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Final Report

Ultra-clean Fischer-Tropsch (F-T) Fuels Production and Demonstration Project

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I. Abstract

The objective of the DOE-NETL Fischer-Tropsch (F-T) Production and Demonstration Program was to produce and evaluate F-T fuel derived from domestic natural gas. The project had two primary phases: 1) fuel production of ultra-clean diesel transportation fuels from domestic fossil resources; and 2) demonstration and performance testing of these fuels in engines. The project also included a well-to-wheels economic analysis and a feasibility study of small-footprint F-T plants (SFPs) for remote locations such as rural Alaska.

During the fuel production phase, ICRC partnered and cost-shared with Syntroleum Corporation to complete the mechanical design, construction, and operation of a modular SFP that converts natural gas, via F-T and hydro-processing reactions, into hydrogen-saturated diesel fuel. Construction of the Tulsa, Oklahoma plant started in August 2002 and culminated in the production of over 100,000 gallons of F-T diesel fuel (S-2) through 2004, specifically for this project. That fuel formed the basis of extensive demonstrations and evaluations that followed.

The ultra-clean F-T fuels produced had virtually no sulfur (less than 1 ppm) and were of the highest quality in terms of ignition quality, saturation content, backend volatility, etc. Lubricity concerns were investigated to verify that commercially available lubricity additive treatment would be adequate to protect fuel injection system components.

In the fuel demonstration and testing phase, two separate bus fleets were utilized. The Washington DC Metropolitan Area Transit Authority (WMATA) and Denali National Park bus fleets were used because they represented nearly opposite ends of several spectra, including: climate, topography, engine load factor, mean distance between stops, and composition of normally used conventional diesel fuel.

Fuel evaluations in addition to bus fleet demonstrations included: bus fleet emission measurements; F-T fuel cold weather performance; controlled engine dynamometer lab evaluation; cold-start test-cell evaluations; overall feasibility, economics, and efficiency of SFP fuel production; and an economic analysis.

Two unexpected issues that arose during the project were further studied and resolved: variations in NOx emissions were accounted for and fuel-injection nozzle fouling issues were traced to the non-combustible (ash) content of the engine oil, not the F-T fuel.

The F-T fuel domestically produced and evaluated in this effort appears to be a good replacement candidate for petroleum-based transportation fuels. However, in order for domestic F-T fuels to become a viable cost-comparable alternative to petroleum fuels, the F-T fuels will need to be produced from abundant U.S. domestic resources such as coal and biomass, rather than stranded natural gas.

II. Acronyms

ACERT	Advanced Combustion Emissions Reduction Technology
AETDL	Arctic Energy Technology Development Laboratory
ARCO	Atlantic Richfield Company
ASTM	American Society for Testing and Materials
bbl	barrel
bpd	barrels per day
BTU	British Thermal Unit
CDF	Catoosa Demonstration Facility
CH_4	methane
CN	cetane number
CO	carbon monoxide
CTA	Chicago Transit Authority
DC	DaimlerChrysler
DDC	Detroit Diesel Corp.
DOC	diesel oxidation catalyst
DOD	Department of Defense
DOE	Department of Energy
DPF	diesel particulate filter
DPX	diesel exhaust particulate filter
ECM	electronic control module
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
FTP	Federal Test Procedure
F-T	Fischer-Tropsch
g/bhp-hr	grams per brake horsepower hour
g/kWhr	grams per kilowatt hour
GTL	gas-to-liquid
H_2	hydrogen
H_2O	water
HC	hydrocarbon
HC-CO	hydrocarbon and carbon monoxide
HCCI	homogeneous-charge compression-ignition
HFTL	heavy Fischer-Tropsch liquid
kW	Kilowatt
lb-ft	pound-feet of torque
LFTL	light Fischer-Tropsch liquid
LNC	lean NOx catalyst
LNT	lean NOx trap
LSD	low sulfur diesel
MIT	Massachusetts Institute of Technology

mmscfd	Million standard cubic feet per day
MY	model year
N_2	nitrogen
N-m	Newton-meters of torque
NAC	NOx adsorber catalyst
NETL	National Energy Technology Lab
NOx	nitrogen oxides
NP	National Park
O_2	oxygen
OEM	original equipment manufacturer
PM	particulate matter
PPM	parts per million
PSI	pounds per square inch
R&D	research and development
pS/m	picoSiemens/meter
S-1	Syntroleum F-T fuel comparable to No. 1 Conventional Diesel
S-2	Syntroleum F-T fuel comparable to No. 2 Conventional Diesel
SAE	Society of Automotive Engineers
SCR	selective catalytic reduction
SEM	scanning electron microscope
SFP	small-footprint plant
SOF	soluble organic fraction
SOL	start of injection
SOPO	Statement of Project Objectives
TDC	top dead center
UAF	University of Alaska-Fairbanks
ULSD	ultra-low sulfur diesel fuel
VW	Volkswagen
WMATA	Washington Metropolitan Area Transit Authority
WVU	West Virginia University

III. Executive Summary

By using pipelined natural gas as a relatively easy-to-access surrogate for stranded natural gas, this project has shown, at a demonstration-plant scale approaching that of a small commercial operation, that stranded gas could be processed in a small-footprint Fischer-Tropsch (F-T) plant into premium-quality F-T diesel and jet aircraft fuels in a remote location. The design, construction, and operation of the fuels-production demonstration-plant by project-partners Syntroleum and Marathon was a $70 million undertaking, with $12 million provided by DOE-NETL through this project. The plant produced over 100,000 gallons of F-T fuels specifically for this project, and this fuel was evaluated by project-leader ICRC and other project-partners, primarily in over twenty different diesel engines.

The 20-plus diesel engines used in this project for demonstrating and evaluating F-T fuel operated in a broad range of vehicles and laboratory facilities, including:

- Three buses in each of two fleets, the Washington DC Metro Transit Authority (WMATA) bus fleet and the Denali National Park (Alaska) bus fleet owned and operated by Doyon/Aramark, with emissions measured at both fleet locations by West Virginia University using WVU's field-portable, heavy-duty vehicle emission-measurement dynamometer-laboratory;
- An additional WMATA bus with a diesel particulate filter (DPF), used by WVU to compare emissions with F-T and conventional diesel fuels, both with and without the DPF;
- Two dynamometer engines (a Detroit Diesel Series 50 and a Caterpillar C-7, the same two engine-types as in WMATA and Denali bus fleets, respectively) at AVL Powertrain Engineering's Ann Arbor, MI, Laboratory, used for both fuel-system durability testing on F-T fuel, and back-to-back laboratory-measurements of the effects of F-T and conventional diesel fuels on engine-out emissions and on catalytic exhaust aftertreatment effectiveness;
- One of the above bus engines (the Detroit Diesel Series 50) in a cold-start test-cell at AVL in which the unassisted cold-starting characteristics of F-T and conventional No. 1 and No. 2 diesel fuels were directly compared;
- A diesel generator-set, typical of those used for electric power production in rural Alaskan villages, set up at the University of Alaska Fairbanks (UAF), used to compare performance and emissions with F-T and conventional diesel fuels;
- Ten diesel snow-removal vehicles used during the winter at Denali National Park, operated on arctic-grade F-T diesel fuel; and
- In a highly instrumented laboratory diesel engine at the Massachusetts Institute of Technology (MIT), used for fundamental combustion, emission, and exhaust aftertreatment studies on F-T, conventional diesel fuels, and blends of F-T with conventional fuels.

Through the fuel-production and fuel-evaluations described above, the project has shown that F-T diesel fuel could make excellent use of otherwise useless stranded natural gas, and could be directly substituted for conventional diesel fuels in diesel vehicle engines, while reducing engine emissions, especially diesel particulates, and modestly increasing U.S. energy security at the same time. Furthermore, F-T diesel fuel could be a locally produced, more environmentally friendly alternative fuel for rural Alaska, where conventional diesel fuel is currently transported long distances through extremely challenging terrain, and stored in hundreds of leak-prone tanks for long periods of time, in order to provide electric power in remote areas.

A potential problem associated with the use of F-T fuels in existing diesel engines, namely that the fuel-lubricity level would need to be supplemented with lubricity-improver additive-technology, was recognized in advance. Much of the project's original technical and experimental focus was on the lubricity issue, and the project demonstrated conclusively that commercially available fuel-lubricity additive-technology, which was developed for ultra-low sulfur-conventional diesel fuels, is indeed also fully capable of protecting diesel-engine fuel-systems using F-T fuels.

The project also discovered two unexpected effects of using F-T fuel in one type of new-technology diesel engine, the Caterpillar C-7 used in the Denali National Park buses. These unexpected effects are almost certainly preventable, but they were discovered late in the project when insufficient time and budget remained to investigate preventive measures within this project. These unexpected effects, which may be directly related to each other, are covered in more detail in later sections of this Report, and include:

- NOx emissions can increase with extremely high-Cetane F-T diesel fuel under some low-to-moderate-load operating conditions because the engine control strategy (including early fuel-injection) allows combustion to begin sooner (similar to an injection-timing advance in an older technology diesel engine) than would occur with normal (i.e. lower-Cetane) conventional diesel fuel; and
- Deposits originating from the non-combustible (ash) components of the engine oil, not from the F-T fuel, can accumulate in the fuel-injection nozzle-orifices and reduce fuel-flow, and thus reduce maximum engine power output, when using hydrogen-saturated F-T fuel which has lower inherent solubility for many materials than do conventional aromatic-containing diesel fuels.

The project's economic and feasibility studies emphasize that in order for F-T fuels to become a viable domestically produced supplement or alternative to petroleum fuels, they must be produced and sold at a comparable cost to end users. Furthermore, to make a significant contribution to supplementing petroleum on a large scale, F-T fuels will need to be produced from U.S. domestic resources such as coal and biomass that are much more abundant, but which are also more expensive to process to F-T fuels, than stranded natural gas. This situation illustrates why the U.S. and most of the rest of the world have become so dependent upon petroleum to fuel transportation, because despite recent price increases, it is still less expensive than the alternatives, including F-T fuels.

IV. PROJECT OVERVIEW

The driving force behind the DOE-NETL Fischer-Tropsch Production and Demonstration Program was to chart a coherent and feasible future path that can extend beyond this project to progressively increase both the quantity and quality of liquid fuels available for U.S. transportation, and help reduce exhaust emissions at the same time.

The objective of the program was to produce and evaluate F-T fuel. The project had two primary activities; 1) fuel production, and 2) fuel demonstration, including overall evaluation of F-T fuel compatibility with diesel engines. The project also included a study of the overall feasibility of small-footprint F-T plants (SFPs) for remote locations, including Alaska, and a well-to-wheels economic analysis.

A. RATIONALE FOR MAJOR PROJECT ACTIVITIES

1. Benefits of Small Footprint Plant (SFP) Fuel Production Technology

The Syntroleum fuel production technology demonstrated in this project has several features that can contribute to the overall goal of increasing both the quantity and quality of liquid fuels available for future transportation. First, the technology uses air rather than oxygen in the process of making F-T fuels. This means that a plant using this technology can be less expensive and more transportable than a plant that must include air-separation capability to make oxygen for its process. Furthermore, this project's technology can be made modular, which also improves transportability. These features can enable transportation of modules, and assembly of a production plant from them, at the source of otherwise unusable feedstock (such as stranded or associated gas, for example) in a remote area, or even offshore. These features are also the reason that the plant built as part of this project is referred to as a Small Footprint Plant (SFP). Since the primary product of such a plant is high quality finished liquid fuel, it can be transported to where it is needed relatively easily. In fact, it may be needed locally, and thus this scenario could also reduce the transportation cost of finished liquid fuels to some remote areas, such as Alaska.

Another feature of SFP technology is that the "air" that has flowed through the process, and become a stream consisting primarily of nitrogen and carbon dioxide, with a little oxygen remaining in it, is still a valuable resource. This gas is at elevated pressure and temperature, and the temperature can be raised further by burning an additional amount of fuel in it to consume the remaining oxygen. Then the gas can be expanded through a gas turbine to generate electricity, which is a long-standing commercial technology. This feature makes the plant self sufficient in electricity for both processing, and for the domestic needs of the people who operate the plant. It is even possible to configure the plant to export electricity, if this is desirable in a particular situation.

Even after passing through the gas turbine and producing power, the exiting stream of nitrogen and carbon dioxide from the SFP is still a potentially valuable resource. This gas can, for example, be injected into an oilfield to help maintain oil yield over time.

2. Potential F-T Feedstock Resource Bases

Associated Gas

Oil is produced in an extremely large number of places around the world. In virtually every case, at least some, and often a great deal of gas, called associated gas, is produced along with it. In some cases, it is economically feasible to gather this gas by building a pipeline (or possibly by other means) so the gas can be transported to a market, such as through the gas transmission system of the U.S. Much of the cost of pipelined natural gas is attributable to the relatively high cost of its transportation system. However, in many cases the combination of the relatively small amount and/or poor quality of the associated gas being produced, the distance to a market, and other factors, make it prohibitively expensive to gather associated gas and transport it to a market. However, if oil is produced, something must be done with the associated gas. In many areas of the world, associated gas is flared, or even vented to the atmosphere, which poses obvious dangers. In others, such as the North Slope of Alaska, for example, the associated gas is pressurized using expensive machinery, and re-injected into the oilfield to help maintain oil yield over time.

Associated gas that is currently being vented, flared or re-injected is a prime, but only one, example of potential feedstock for SFP's. This high-energy gas is either wasted outright by venting and flaring, or contributes only marginally to future oil production if re-injected. Therefore, such gas has low (or even negative) value under present circumstances, but it could be ideal feedstock for SFP's. The finished liquid fuel from SFP's could, in many cases, be transported by the same means as the crude oil being produced. In virtually all cases, the liquid F-T fuel can be transported to market much more economically than the original associated gas could have been, because the F-T fuel can be used within the existing liquid fuel infrastructure.

Other Potential Feedstocks

Other examples of potential SFP feedstocks include already known remote or offshore gas that was discovered when searching for oil far from any existing gas pipeline infrastructure. SFP technology could promote the active search for such gas resources. In summary, there is no shortage of ideally suited potential gas feedstocks, either at present or in the intermediate (several decades) term. The program has produced a study that quantifies the costs, risks, opportunities and potential economic alternatives associated with these resources, and their exploitation by using SFPs. As part of the project, the feasibility of SFPs for Alaska has been evaluated on a location-specific basis.

In the long term, many other feedstocks, including coal and even biomass, can be gasified and converted to ultra-clean liquid transportation fuel using the same basic SFP technology, with some additional front-end processing. The decision of whether to move a particular feedstock to a plant (such as moving a small portion of the vast resource of remote Alaskan coal, for example, to distant conventional power plants), or to move SFPs to the feedstock source to make ultra-clean liquid transportation fuel, would depend upon the relative overall economics of such alternatives.

3. Initial and Longer-Term Commercial Uses of F-T Fuel

Emissions Reductions

Diesel bus fleets have begun using ultra-low-sulfur conventional diesel fuels to reduce emissions as required by law, and would conceivably use F-T fuels to obtain even greater emission reductions if F-T fuels were generally available at comparable cost. Two bus fleets that elected to use the lowest sulfur diesel fuels available in their respective areas before it was required participated in this project by making available three buses from each of their fleets to demonstrate the use of, and measure exhaust emissions using, F-T fuel. The two participating fleets were the Washington DC Metro Area Transit Authority (WMATA) bus fleet, and the Denali National Park (NP) bus fleet, which is owned and operated by Doyon/Aramark.

One of the consequences of reducing fuel sulfur and aromatics to low levels, whether in conventional or F-T fuels, is a reduction in fuel lubricity. Experience has shown that low sulfur diesel fuels need to be treated with appropriate lubricity additive technology to assure fuel injection system durability. Therefore, since relatively long-term bus fleet tests of the zero-sulfur F-T fuel are part of this project, 1,500-hour dynamometer tests of fuel-system durability were conducted by ICRC and AVL Powertrain Engineering in using additive-treated F-T fuel and engines of the type used by each bus fleet, to validate the effectiveness of the lubricity additive technology in a controlled dynamometer laboratory environment.

F-T fuels have virtually zero sulfur, virtually zero aromatics, and are hydrogen saturated. Such blending components are likely to be in great demand from the current decade onward, as Federal Requirements already in place require the sulfur level of all on-road diesel fuel to be no more than a maximum of 15 ppm. The initial uses of F-T fuel will almost certainly include it as a final-step blendstock to meet the sulfur level requirement for diesel fuel that is primarily petroleum derived, and that has undergone intensified refinery processing to remove sulfur down to the minimum practical and economic level.

The reason that the sulfur level of on-road diesel fuel has been reduced is ultimately to reduce overall diesel exhaust emissions. Sulfur level reduction contributes to this goal directly, especially for particulate emissions, and it enables the use of exhaust aftertreatment emission control devices, which would be quickly rendered ineffective by fuel sulfur levels above ~15 ppm. For reduction of diesel particulate emissions to virtually zero levels, catalyzed particulate traps have been developed and applied to 2007 model-year diesel engines, and have been retrofitted in a few fleets of earlier heavy-duty diesel vehicles. Exhaust aftertreatment devices for NOx emission reduction are not as well developed yet, but they do show promise. One of the advantages of F-T fuel, with its near-zero aromatic level, is a significant reduction in engine-out NOx emission level, even when compared to ultra-low-sulfur conventional fuel. In this project, West Virginia University has determined the magnitude of such potential reduction in NOx emissions, and other emissions as well, using the two real-world bus fleets from WMATA and Denali.

F-T Fuel as an Enabler for Improved Diesel Engine Design

When F-T fuels reach a sufficient total volume to become commercially available on a widespread basis, maintained separately from the rest of the diesel fuel supply, it will be possible to design and build future diesel engines to take advantage of their premium properties, and thus improve diesel engine performance and reduce emissions further.

Diesel engines rely upon their fuel to have sufficient ignition quality for the engines to start and run acceptably. Diesel fuel ignition quality is normally quantified as Cetane Number, and a specification of 40 Cetane, minimum, is typical for conventional diesel fuels. Virtually all aspects of both the performance and emissions of a given diesel engine design respond positively to an increase in the Cetane number of the fuel. In fact, compromises are made in the design of current diesel engines so that they will perform acceptably on the available 40 Cetane fuel.

F-T fuels have a Cetane Number of 70, or higher. Although the effort to reduce the sulfur level of petroleum derived diesel fuels has had some beneficial effect on their Cetane Numbers, values greater than about 50 are rare. Therefore, F-T fuels offer the promise of truly revolutionary advances in the design of future diesel engines to make them smaller and lighter, but still powerful, less-noisy, easier-starting and lower-emitting. These are among the potential advantages of F-T fuels that have been investigated through the project by the MIT Sloan Automotive Laboratory, in addition to their research on the effects on injection timing on NOx and particulate emissions.

F-T Fuels as Enablers for Mobile Fuel Cells

When F-T fuels become commercially available on a widespread basis, maintained separately from the rest of the diesel fuel supply, they can assist the development and commercialization of mobile fuel cells.

It is well known that fuel cells can be very efficient, and that they produce virtually zero emissions. Fuel cells are not limited by the thermodynamic constraints that put a cap on the maximum efficiency an engine can achieve. Therefore, it is anticipated that fuel cells could be efficient and environmentally friendly power sources for vehicles of the future. But fuel cells “convert” hydrogen directly into electricity, so the vehicle must either carry hydrogen on-board as fuel (challenging, but potentially achievable economically in the future), or produce hydrogen on demand from some other fuel or energy source that is carried on-board. Hydrogen-saturated F-T fuels are ideally suited both to be carried on-board a vehicle, and to be reformed on demand to produce the hydrogen needed by a fuel cell.

A major concern in the ongoing development of reformers for fuel cell applications is the impurities that are contained in conventional hydrocarbon fuels. Impurities such as sulfur and metals must be removed, either in advance, or on-board, or they can quickly disable the system. Even some hydrocarbons, such as heavy aromatics for example, can cause deposition and other problems in reformers over time. A major advantage of F-T fuels is that they contain virtually zero levels of all such impurities, greatly improving the long-term performance and reliability of fuel-cell reformers. The University of Alaska-

Fairbanks conducted an evaluation of F-T fuel in a reformer/fuel-cell system as part of this project.

4. Economics

Although F-T has many technical advantages, none of them will be put into use if it does not make sense economically. As such, the project conducted an economic analysis. The major thrust of the analysis is a well-to-wheels economic and market analysis of SFPs and their potential feedstock resources, and of the commercial applications in future transportation markets for ultra-clean liquid F-T fuels from these plants.

B. PROJECT ORGANIZATION AND TIMELINE

Figure 1 shows the overall organizational structure of the project's participating organizations under the leadership of ICRC. The overall flowpath of the project was that ICRC's primary partner Syntroleum designed, built, and operated the plant to produce F-T fuel, and the other partners worked in parallel to evaluate the fuel. Figure 2 shows the timelines during which the "main-portions" of the project tasks were performed.

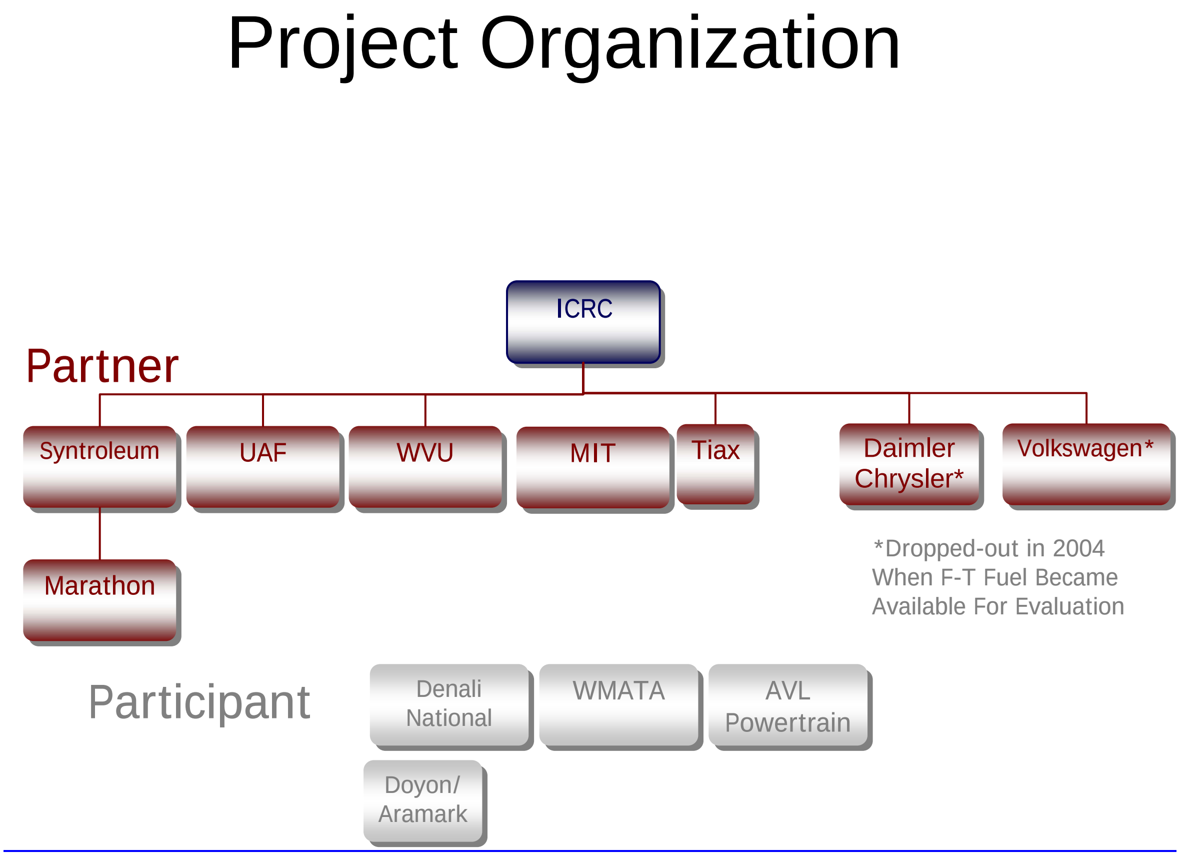


Figure 1: Project Organizational Structure

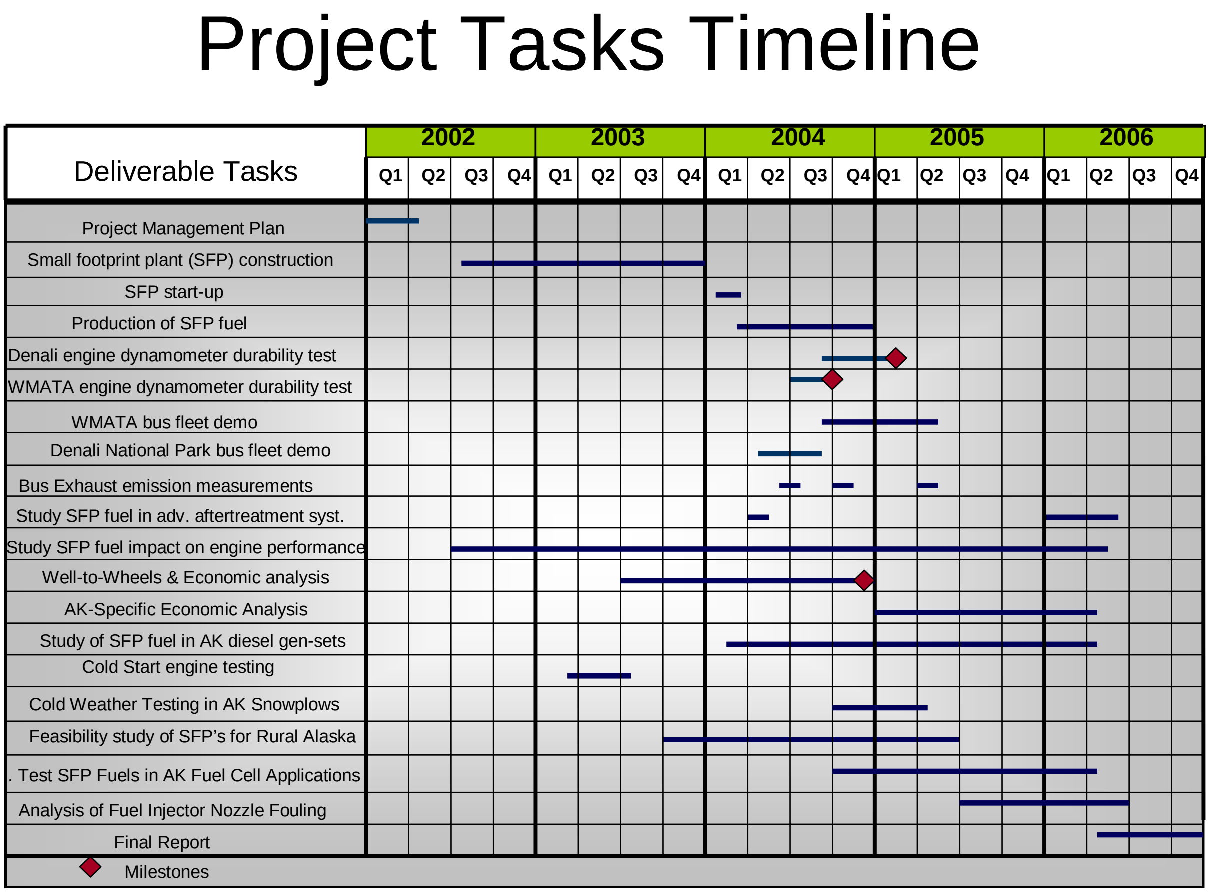


Figure 2: Project Task Timelines Chart

C. SUMMARY OF PROJECT ACTIVITIES AND RESULTS

1. Fuel Production Task

Plant Design, Construction, Startup and Operation

Plant design, construction, startup and operation were, by far, the most expensive aspects of this project. Out of the total $18.8 million provided by the Department of Energy, approximately $12 million was used in the design, construction and operation of the plant. In addition to the $12 million provided by DOE, over $20 million was provided by Syntroleum and partner Marathon as project cost-share. An additional $38 million was provided by Syntroleum and Marathon over and above the required cost-share for plant construction, operation, etc., for a total plant cost of over $70 million. The following table shows the relative costs of the various functional areas of the plant for construction only (not operation).

Construction Cost

SFP 100 BPD Construction Cost	
Total Installed Cost	
Syngas Generation	$6,800,000
F-T Conversion	$15,000,000
Product Upgrading	$11,500,000
Utilities	$5,900,000
Total	$39,200,000
Cost Estimate Assumptions	
Book value for Cherry Point facilities $8,000,000	
Cost of buildings, roads, and infrastructure is distributed between the plant sections	

Figure 3: SFP 100 BPD Construction Cost

Overview of Plant

Construction of the Syntroleum Catoosa Demonstration Facility (CDF) took place during the last half of 2002, and throughout 2003. Syntroleum designed, assembled, and operated a demonstration-scale F-T fuel production plant in Catoosa, Oklahoma, with significant technical and financial assistance from its licensee and project-partner, Marathon Oil Company. The plant is based upon Syntroleum's F-T technology, the Syntroleum® process, and its associated product upgrading technology, Synfining®. Prior to its subcontract for this effort, Syntroleum had previously demonstrated its Syntroleum® process technology in a joint development project with one of its licensees, the former Atlantic Richfield Company (ARCO), at ARCO's Cherry Point facility in the State of Washington. Under the Syntroleum subcontract to the Cooperative Agreement, Syntroleum was tasked with constructing a plant that would utilize this demonstrated technology for synthesis gas production, F-T conversion, and product upgrading to produce both ultra-clean diesel and Jet A-1 fuel for evaluation by project participants.

Improvements of SFP from Cherry Point Plant

The CDF is designed to be modular, meaning that the three primary functional areas of the plant, while integrated, can operate independently if necessary. These three functional areas are: synthesis-gas production by autothermal reforming of natural gas; production of syncrude (an intermediate stream of light F-T liquids and heavier, F-T wax) by the Fischer-Tropsch conversion process; and refining of the syncrude to produce finished fuels. This modularity was demonstrated when Syntroleum dismantled, moved, design engineered and assembled each of these Syntroleum modules from the Cherry Point site to the CDF site at the Tulsa Port of Catoosa. The modular design was intended to show that F-T plants have the potential to be "portable," and could be mobilized in remote areas to produce and provide F-T fuels. This project further explores situations where remote F-T fuel production would be beneficial, such as remote military field locations where vehicle fuel is not readily available, and rural areas where electricity is typically provided by generators. While this initial CDF design is modular, it would obviously need large-scale design changes and size reductions beyond the scope of this project in order to construct the smaller-scale plants that could be deployed to these remote locations.

Several improvements have been made to the Cherry Point Plant. The addition of a second Fischer-Tropsch Reactor and reducing the operating pressure of the autothermal reformer has improved conversion and overall carbon efficiency. The addition of a product upgrade unit allows production of finished ultra-clean products such as naphtha, diesel, and jet fuels. Syntroleum Fischer-Tropsch diesel (S-2) produced with the product upgrade unit has been provided for fleet testing.

Plant Operation

SFP Operating Cost	
Natural Gas (based on $6.00/mmBtu)	$2,700,000/yr
Electricity	$ 770,000/yr
Water	$ 26,000/yr
Hydrogen	$ 640,000/yr
Nitrogen	$ 170,000/yr
Catalyst	$ 1,600,000/yr
Staffing, including operations, maintenance, and overhead. Based on actual costs from DOE plant and therefore includes additional costs as compared to a commercial facility due primarily to additional technical support (For example Engineering & Analytical support) typically seen with a new facility.	$ 4,900,000/yr
Note: Above annual costs based on 93% on-stream factor	

Figure 4: SFP Operating Cost

Process Description

The Syntroleum$^{®}$ Process uses proprietary technology to convert natural gas into synthetic oil which can then be further processed into fuels and other hydrocarbon-based products. The Syntroleum Process can be optimized for location requirements. Overall material balances for the Syntroleum SFP GTL process producing conventional and arctic diesel are shown in Figures 5 and 6.

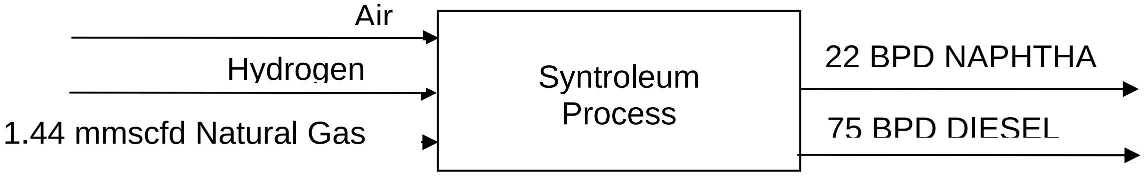


Figure 5: SFP Mass Balance for Conventional Diesel

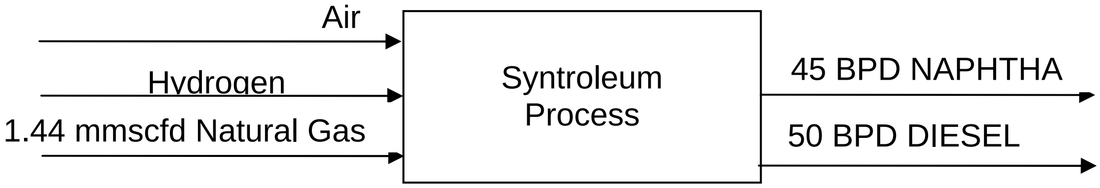
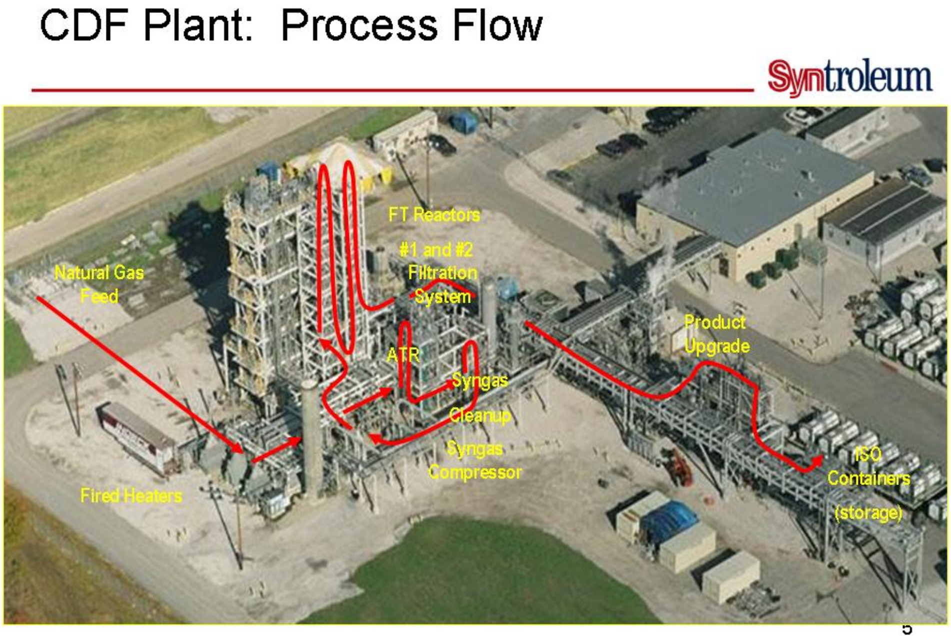


Figure 6: SFP Mass Balance for Arctic Diesel

The SFP plant can be divided into four sections by process function using the existing demonstration plant as a basis for discussion. The syngas generation section reacts natural gas with compressed air to produce syngas. The Fischer-Tropsch synthesis section recombines the syngas to varying chain length paraffinic hydrocarbons. The product upgrade section refines the raw F-T material / product into the required finished products to specification as naphtha or diesel. Hydrogen and typical process utilities provide support to the other three sections. Figure 7 highlights the individual areas of Syntroleum's 100 BPD demonstration plant located near Tulsa, Oklahoma at the Port of Catoosa.



CDF Plant: Process Flow

Figure 7: Syntroleum Catoosa Demonstration Facility

Syngas Generation

Pipeline quality natural gas is combined with hydrogen and heated prior to treatment for removal of sulfur compounds such as mercaptans or carbonyl sulfide. After sulfur removal, the residue gas is combined with high pressure steam, heated and fed to the autothermal reformer along with additional steam and compressed air. In the autothermal reformer, the mixed feeds pass over a catalyst where partial oxidation, steam reforming, and shift conversion reactions occur simultaneously. The overall reaction for the formation of syngas is represented by the equation in Figure 8. Syngas leaving the autothermal reformer is cooled by the generation of high pressure steam, scrubbed for impurities, and compressed prior to entering Fischer-Tropsch synthesis.

Fischer-Tropsch Synthesis

The Fischer-Tropsch section has two reactors in series containing proprietary catalyst to convert syngas to Fischer-Tropsch products. Overhead vapors from the first F-T reactor are cooled, condensed and separated into light Fischer-Tropsch liquids (LFTL), water, and tail gas. Tail gas from the first F-T reactor feeds the second F-T reactor. Overhead vapors from the second reactor are again cooled, condensed and separated into LFTL, water and tail gas. Nitrogen associated with the syngas passes through the reactors and is removed as tail gas. The overall reaction for the formation of hydrocarbons via the Fischer-Tropsch process is represented by the equation in Figure 9. Large amounts of medium pressure steam are generated in this section which can be used in the plant or for export.

Each F-T reactor utilizes a Heavy Fischer-Tropsch Liquids (HFTL) withdrawal system that allows catalyst free product to be withdrawn from the reactor. Fischer-Tropsch liquids represent a variety of hydrocarbon products with varying molecular weights. Fischer-Tropsch liquids are primarily paraffinic hydrocarbons, with minor olefin content. Light Fischer-Tropsch liquid is most similar to naphtha while heavy Fischer-Tropsch is a high purity wax. Both LFTL and HFTL require additional processing for use as fuels. The F-T liquids are sent to the product upgrading unit for processing into naphtha and diesel. The tail gas is burned in an incinerator.

Product Upgrading

The product upgrading section of the plant refines the F-T liquids into the diesel and naphtha, each according to required specification. The operation is analogous to refining of crude oil, but is conducted under much less severe operating conditions than conventional crude oil refining. This is due to the high quantities of paraffin and the absence of sulfur and other contaminants in the F-T liquids. The product upgrade unit includes several sections to process the F-T liquid. The primary sections are Feed Fractionation, Hydroprocessing (Hydrotreater and Hydrocracker), and Product Fractionation. The product upgrading process has a flexible design that enables production of a wide range of distillate products and product adjustment to meet seasonal requirements.

Utilities

Process utilities for the SFP plant are shown below:

- Instrument and utility air
- Fuel gas
- Purchased Hydrogen
- Raw Water
- Cooling water
- Imported Electricity
- Startup steam and condensate
- Potable water and sewage

Fuel Production

The plant began producing fuel in the first quarter of 2004 and operated throughout 2004 before shutting down.

Syntroleum Corp. produced 110,800 gallons of fuel as part of this project. This fuel was made up of S-2 synthetic No. 2D diesel, S-1 synthetic No. 1D diesel, and S-8 synthetic JP-8 fuel. The diesel fuels were produced to meet ASTM D975 requirements and additional engine manufacturer and customer requirements typical for conventionally sourced diesel fuels. An additive package provided by Lubrizol Corporation was blended with the synthetic diesel fuel to allow the fuel to meet critical lubricity requirements as well as corrosion inhibition, foam control, water dispersion, oxidation stability and conductivity requirements. The synthetic jet fuel was treated with an approved antioxidant additive only to assure that reaction with atmospheric oxygen was minimized during transportation and storage of the jet fuel before delivery to the DOD for evaluation as a replacement fuel for conventionally produced JP-8 turbine engine fuel.

Conversion Process

The conceptual chemistry involved in understanding the conversion of natural gas to synthetic hydrocarbon distillates can be summarized by two general chemical reactions.

The first general reaction is the partial combustion of natural gas to form a mixture of hydrogen and carbon monoxide, commonly known as syngas (Syntroleum). A general reaction for the formation of syngas from methane is shown in Figure 8.

$$\overset{\text{Methane}}{CH_4} + \overset{\text{Air}}{O_2 + N_2} + \overset{\text{Steam}}{H_2O} \xrightarrow{\text{Catalyst}} \overset{\text{Syngas}}{CO + H_2} + N_2 + \overset{\text{Water}}{H_2O}$$

Figure 8: Syngas Reaction

The second general reaction is known as the Fischer-Tropsch (F-T) reaction and is shown as Figure 9. The Fischer-Tropsch reaction recombines the carbon monoxide and hydrogen in syngas to form a variety of hydrocarbons of varying molecular weight and hydrocarbon chain length (Syntroleum).

$$\overset{\text{Syngas}}{H_2 + CO + N_2} \xrightarrow{\text{Catalyst}} \overset{\text{Hydrocarbons}}{C_nH_{(2n+2)}} + \overset{\text{Nitrogen}}{N_2} + \overset{\text{Water}}{H_2O}$$

Figure 9: Fischer-Tropsch Reaction

Hydrocarbons formed can range from ethane to heavy waxes. The raw Fischer-Tropsch product from the reactor contains what is typically described as a light Fischer-Tropsch syncrude (liquid at room temperature) and a heavy Fischer-Tropsch syncrude (solid at room temperature). Additional process equipment converts raw F-T material/product to synthetic versions of traditional hydrocarbon products such as naphtha, diesel, and jet fuel. Carbon distribution of the raw Fischer-Tropsch product and the final products are represented by the following charts.

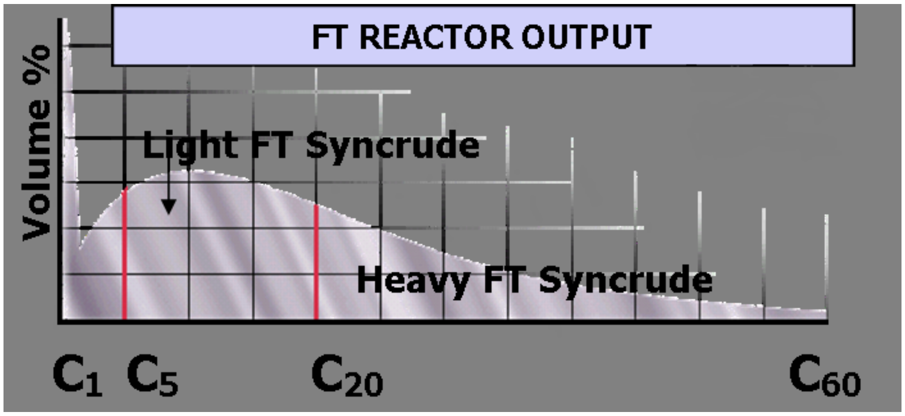


Figure 10: Raw Fischer-Tropsch Product Carbon Distribution

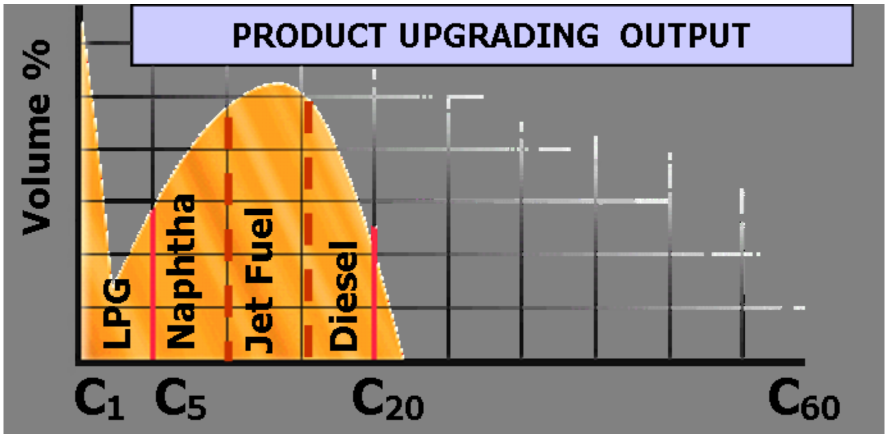


Figure 11: Refined Fischer-Tropsch Product Carbon Distribution

Fuel Production and Formulation

Syntroleum's demonstration facility is capable of producing 70 bbl/day of GTL products. The facility utilizes pipeline natural gas as feed to an autothermal reactor which produces synthesis gas of an appropriate ratio of hydrogen to carbon monoxide for use in the Fischer-Tropsch reaction. The Fischer-Tropsch reactor utilizes a proprietary catalyst technology for conversion of synthesis gas into paraffinic hydrocarbons. (Freerks).

Diesel fuel and jet fuel must meet requirements specified in several documents such as ASTM D975 Standard Specification for Diesel Fuel Oils or ASTM D1655 Standard Specification for Aviation Turbine Fuels. These specifications set the distillation ranges appropriate for each fuel as well as numerous other requirements critical to the successful use of a fuel in an application. These specifications are not exhaustive, however, and they do not cover all issues that make a fuel "Fit for Purpose." In the case of diesel fuel, it is often left to the fuel supplier to determine what additional performance requirements are necessary to make the fuel fit for use in customer's engines.

Syntroleum Corporation has developed technology for converting raw F-T reaction products into commercially viable products utilizing conventionally available hydroprocessing techniques. Although these techniques are well known in the industry, adaptation of these techniques to paraffinic feedstocks is not as well known. In order to make Ultra Clean Transportation Fuel using F-T feedstocks, several physical and chemical processes must take place. The broad carbon distribution of the F-T reaction must be distilled into appropriate feeds for hydroprocessing equipment. The proper feed is then subjected to hydrocracking catalysts and conditions sufficient to convert all of the F-T feedstock into material boiling in the diesel of jet fuel range along with some material boiling below that range which has use in other chemical processes.

As part of the project, Syntroleum provided fuels that met several different diesel product requirements spanning the ASTM D975 No. 2D and No. 1D ranges. Fuel meeting D975 No. 2D specifications are known as Syntroleum S-2 and fuels meeting No. 1D specifications are known as S-1. Within D975, there are various climatic requirements outlined. Syntroleum provided S-2 meeting relatively severe low temperature requirements so that no problems with filter plugging would occur during any of the testing programs. This "summer diesel" fuel met a maximum Cloud Point of -20°C which is well below the minimum temperature that would be seen during the two bus field demonstration programs. To demonstrate utilization of the fuel in arctic climates, Syntroleum provided No. 1D fuel meeting the most stringent climatic requirements specified in D975. Syntroleum S-1 met a Cloud Point of -50ºC maximum, below the Tenth Percentile Minimum Ambient Air Temperature for Northern Alaska in winter.

Diesel fuels that are highly hydroprocessed to meet ultra low sulfur requirements established by the EPA will not provide sufficient lubricity to fuel handling components of a diesel engine. These fuels will require a lubricity additive that will replace the naturally occurring lubricity components of diesel fuel which are removed by hydroprocessing. Ultra Clean Transportation Fuels will also need lubricity additives and can utilize the same technology developed for ULSD fuels. These additives are commercially available. Syntroleum has partnered with Lubrizol Corporation to develop an additive system that will meet lubricity requirements of all world diesel fuels and engine manufacturers. At the time this program was initiated, ASTM did not include lubricity as a part of D975 specifications. However, the European specification EN590 did have a requirement and this was set as the target for Syntroleum S-2 and S-1 fuels. Subsequently, ASTM has adopted lubricity requirements into D975 which are not as stringent as those in EN590, so the development work is still valid. The additive system developed by Lubrizol also addresses other aspects of fuel performance which are not included in specifications such as EN590 and D975. These include oxidative stability (prevention of peroxide accumulation), foam stability (prevention of aeration of the fuel), demulsibility (prevention of emulsion formation with water), and corrosion prevention. Also included was an additive that improves the electrical conductivity of the fuel. This is considered a safety issue as accumulation of static charge in fuel has been associated with electrical discharge in some situations. The conductivity of the fuel is used as a quality assurance measurement to ascertain the presence and amount of the additive package in the fuel.

Fuel Specifications

Syntroleum bases its specifications for fuel on ASTM D975 as several other fuel specifications have density minimums which are above the typical density for highly paraffinic fuels such as GTL Ultra Clean fuel. D975 does not specifically set winter properties for diesel fuel but does address Cloud Point requirements.

It is unrealistic to specify low temperature properties that will ensure satisfactory operation at all ambient conditions. In general, cloud point (or wax appearance point) may be used as an estimate of operating temperature limits for Grades Low Sulfur No. 1; Low Sulfur No. 2; and No. 1 and No. 2 diesel fuel oils. However, satisfactory operation below the cloud point (or wax appearance point) may be achieved depending on equipment design, operating conditions, and the use of flow-improver additives.

Syntroleum has designated several quality grades of diesel fuels to address low temperature performance of the fuel. Summer fuel should meet climatic minimum temperatures for the lower 48 states through the Fall months. The November 10th Percentile Minimum Ambient Air Temperature for the Lower 48 states is -20ºC (Freerks). Syntroleum has therefore defined three grades of Summer Diesel Fuel with average cloud point requirements of -5ºC, -15ºC, and -25ºC. Winter diesel fuels should satisfy customer performance requirements under all winter conditions except Arctic Climates. Two Winter Diesel Fuel grades have been defined with average cloud point requirements of -35ºC and -45ºC. To meet winter arctic conditions, a fuel must meet the 10th Percentile Minimum Ambient Air Temperature for Northern Alaska for all winter months, which is -49ºC (Freerks). Arctic Diesel Fuel is therefore defined as having a cloud point below -50ºC. Specific ranges for these grades of S-2 and S-1 are shown in the table below.

Product Name	Product Grade	Flash, °C	KV 40, cSt	Cloud, °C
		D 93	D 445	D 5771
S-2	S0	125 min.	1.9-2.5	0 to -9°C
S-2	S1	125 min.	1.9-2.5	-10 to -19°C
S-2	S2	125 min.	1.9-2.5	-20 to -29°C
S-2	W3	125 min.	1.9-2.5	-30 to -39°C
S-2	W4	125 min.	1.9-2.5	-40 to -49°C
S-2	A5	125 min.	1.9-2.5	-50 to -59°C
S-1	S0	100 min.	1.3-2.4	0 to -9°C
S-1	S1	100 min.	1.3-2.4	-10 to -19°C
S-1	S2	100 min.	1.3-2.4	-20 to -29°C
S-1	W3	100 min.	1.3-2.4	-30 to -39°C
S-1	W4	100 min.	1.3-2.4	-40 to -49°C
S-1	A5	100 min.	1.3-2.4	-50 to -59°C

Figure 12: Flash Point, Kinematic Viscosity and Cloud Point ranges for Syntroleum Fuels.

Fuel Additization and Quality Control Testing

In order to simplify production, handling and delivery of fuel from the Catoosa Demonstration Facility, the output from the hydroprocessing unit was fed directly to ISO containers. These containers are suitable for international transportation of liquid products. They can contain 24,000 liters of liquid and were usually filled to 6,000 gallons. During filling, additive concentrate was placed in the container so that mixing could occur. At the end of filling, a sample was taken for quality assurance testing.

Blending additives with fuels and lubricants is a well practiced art. Quality assurance of these blends involves testing those properties that can vary during the production and blending of the product and not testing those properties that are invariant. For Syntroleum S-2, production variables include distillation range, density, flash point, viscosity, ash, cloud point, specific gravity, appearance and conductivity. All the variables except for conductivity are related to production of the fuel. Conductivity is related to the presence of the additive package at the proper concentration. Since sufficient testing has been conducted to know that the additive system provides the required lubricity function in the fuel, simple tests to verify that the additive is present in the fuel will suffice for quality assurance. Syntroleum S-2 has essentially no conductivity as produced. Addition of the Lubrizol additive to the fuel increases the conductivity to 300-450 pS/m. Therefore conductivity is used as the measure of the presence of additive in the fuel prior to shipping.

Fuel Shipments

The majority of fuel shipped under this contract was done by ISO container. Approximately 93,000 gallons of fuel were shipped to project participants by this method. Both field test locations were able to receive bulk fuel and transfer the fuel to on-site fuel storage tanks. Project partner AVL Powertrain Engineering has an underground tank and also received bulk fuel. Project partner MIT Sloan Automotive Laboratory received drum quantities of fuel as they did not have bulk storage capabilities.

Syntroleum S-8 Synthetic Jet fuel produced under this program was drummed prior to shipment since many of the locations receiving this fuel did not have bulk fuel storage capabilities. In addition, this fuel will be stored for a substantial period of time in some cases, and sealed epoxy lined drums are preferable to bulk storage to reduce degradation of the fuel. To further improve storage of the fuel, drums were flushed with nitrogen prior to and during filling to reduce the amount of oxygen available in the drums. Two separate production runs of S-8 Jet Fuel were conducted. The shipment volume was 10,000 gallons.

Syntroleum S-2 and S-1 fuel was also shipped in epoxy lined drums, but these drums were not purged with nitrogen prior to filling as the fuel would be consumed within a short time period.

The CDF constructed under this project, although currently shutdown and mothballed, is the only F-T facility in the U.S. with the capability of producing both finished diesel and jet-aircraft fuels from natural gas.

2. Fuel Demonstration and Evaluation

Throughout this five-year project, the F-T fuel from the plant was demonstrated and evaluated in more than 20 diesel engines under a wide range of operating conditions, and in a reformer/fuel-cell system.

i. Bus Fleet Demonstrations of F-T Fuel

ICRC demonstrated F-T diesel fuel in two different bus fleets - urban transit buses run by the Washington Metro Transit Authority (WMATA) in Washington, DC, and wilderness tour buses owned and operated by Doyon/Aramark in Denali National Park, Alaska. These two test sites and their fleets were chosen to evaluate the fuel primarily because they represent nearly opposite ends of several spectra, including climate, topography, engine load factor, mean distance between stops, and composition of normally used conventional diesel fuel. Both demonstrations were kicked off at large press events, reported subsequently in the media, and were highly visible to passengers. The overall intention of these bus demonstrations was make the general public and national leaders more aware of the F-T fuel's potential as both a domestically-produced source of transportation fuel, and also as lower-emissions alternative to traditional diesel fuel. In general, both demonstrations ran smoothly with F-T fuel being praised at both locations by bus depot personnel and drivers for producing reduced smoke and odor emissions.

Participants

ICRC used its internally-developed wireless data acquisition system to collect engine operational data on these buses, monitoring and comparing the three buses at each site running on F-T fuel, and three buses at each site running on the conventional diesel fuel typically used at that site. The University of Alaska Fairbanks supported the Denali bus fleet demonstration. West Virginia University (WVU) conducted emissions tests on all of the buses run on F-T fuel at WMATA and at Denali National Park, as well as on the baseline buses at each location. F-T fuel reduces particulate emissions significantly compared to conventional diesel fuel.

Denali

Denali National Park is a six million acre national park located in the middle of interior Alaska (U.S. Department of Interior, National Park Service website http://www.nps.gov/dena/). There is only one road servicing the entire park, and as private vehicles are not allowed on this road after about 15 miles into the park, Denali provides bus services to visitors from that point on, mostly in the form of tour buses (Bluebird buses) that allow visitors to view area wildlife. These wildlife tour buses, which take eight-hour tours nearly every day in the summer months, were the source of the demonstration vehicles for this project. The Denali National Park bus fleet demonstration began in May 2004 with the kickoff at the 2004 Alaska Clean Energy Symposium in Anchorage. The demonstration continued until the Park stopped tours for the season in September 2004.

Three Denali buses were run on Denali's normal No. 1 diesel fuel (Jet-A fuel with its sulfur content reduced to no more than 500ppm) as control buses, and three were run on Syntroleum S-2 fuel as demonstration vehicles. All six followed similar duty cycles. ICRC used its internally-developed wireless data acquisition system to collect engine operational data on all six buses, monitoring and comparing the three buses running on F-T fuel, and three buses running on conventional diesel fuel. Analysis of the data collected revealed no significant problems with or differences in the data collected from the demonstration and control vehicles.

Denali Park bus drivers and vehicle maintenance personnel reported no problems with the buses running on the F-T fuel. Their main comments focused on the reduced odor and smoke associated with the buses running on the F-T fuel. In fact, Park personnel liked the fuel so much that they requested to continue the evaluation of the Syntroleum Fuel into and through the winter of 2004-2005 in their snow removal vehicles.

Figure 13: Denali Syntroleum Fueled Bus with Caterpillar C-7 engine

WMATA

The WMATA demonstration took place in urban-cycle buses running in the Washington, DC metropolitan area. It was officially kicked-off with a press-conference event on Capitol Hill on September 22, 2004 hosted by House Transportation Committee Chairman Don Young of Alaska and Congressman John Sullivan of Oklahoma. Three Orion buses (of the approximately 800 total WMATA buses) ran on WMATA's normal low-emission, conventional petroleum-derived ultra-low sulfur No. 1 diesel fuel (ULSD1) and were considered the three control vehicles. Three more Orion WMATA buses ran on Syntroleum S-2 fuel as the demonstration vehicles. Because of the large WMATA bus fleet, and complex logistics and fuel distribution systems, WMATA fuel distribution included three specialized fuel filler adapters. These adapters were fitted to the S-2 test vehicles and one specialized mating nozzle fitted to the S-2 Fuel tank supply. This system was successfully used to maintain control of S-2 fuel used in the three WMATA test buses.

As it did in Denali, ICRC used its internally-developed wireless data acquisition system to collect engine operational data on all six buses, monitoring and comparing the three buses running on F-T fuel, and three buses running on the conventional ULSD1 fuel. As in Denali, analysis of the data collected revealed no significant problems with or differences in the data collected from the demonstration and control vehicles.

Figure 14: WMATA Syntroleum Fueled Bus with Detroit Diesel Series 50 engine

However, the WMATA demonstration was not entirely free of problems. Near the end of the demonstration program, one of the buses running on F-T fuel, Bus 2056, experienced a failure of its turbocharger, a component of the engine that had been recalled by the manufacturer at the U.S. Environmental Protection Agency's behest. ICRC conducted a thorough investigation into this problem, which began with the replacement of the turbocharger. After replacement of the turbocharger the engine was still not running properly, so all four fuel injectors were removed and inspected. One injector, in cylinder No. 4, had a broken tip, so all four injectors were replaced. The bus was then returned to service without any further testing or diagnosis to verify that it was in road-worthy condition. Subsequent problems ensued on the road, and a compression check showed that cylinder No. 4 had no compression. Teardown of the engine revealed a burned exhaust valve in cylinder No. 4.

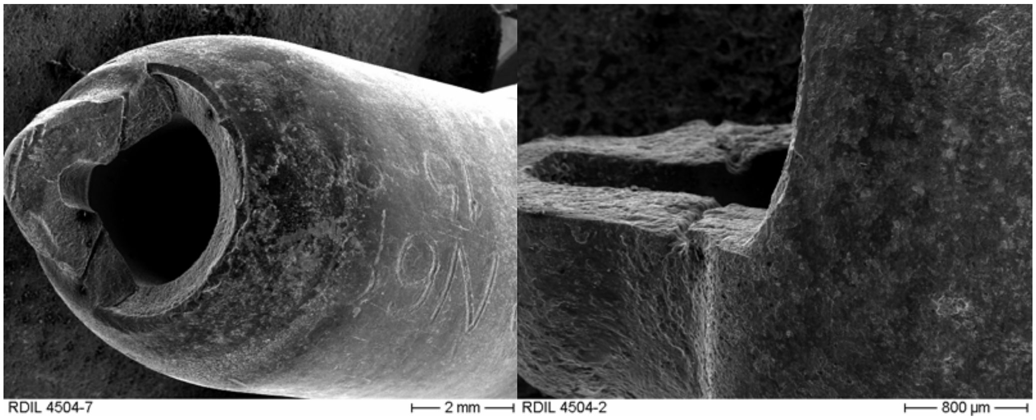


Figure 15: Broken tip of cylinder No. 4 nozzle

The failure of the turbocharger's oil seal introduced oil into the engine's intake manifold. This oil likely contributed to the failure of cylinder number 4's fuel injector tip; although it is possible that the failure of the fuel injector, which is by no means a rare occurrence for these engines in the WMATA fleet, may have been unrelated. Regardless of the cause, the broken nozzle tip resulted in a concentrated and undispersed jet of fuel being directed at one of the cylinder No. 4 exhaust valves that eventually burned through the valve. The broken fuel injector was replaced, but with the valve burned–through, the cylinder no longer had enough compression to ignite and burn the diesel fuel when the bus was put back in service. This unburned fuel was pumped out of cylinder No. 4 and down the exhaust system where it collected in the diesel oxidation catalyst. Once the catalyst became hot, the collected fuel burned within the exhaust system of the bus.

To investigate the condition of Bus 2056's three used, but unbroken, fuel injectors, the injectors were sent to Southwest Research Institute for flow testing. Southwest Research Institute compared the fuel flow rates from the three "good" injectors and one new baseline injector. They found that one used injector had a 20% reduction in flow, and the others showed no degradation of their flow rates. Syntroleum examined all four of Bus 2056's injector-nozzles (including the broken-tip injector from cylinder No. 4) using a Scanning Electron Microscope (SEM) at the University of Tulsa. Syntroleum found that deposits, with a composition consistent with the non-combustible (i.e. ash) components of the engine oil additive package had accumulated and partially restricted some of the nozzle holes in some of the injectors, a condition that was discovered in some nozzle holes of injectors run in dynamometer-based fuel-system durability tests as part of this project. It is possible that such deposits could have lead to an increase in pressure within the nozzle sac, which may have contributed to the nozzle-tip failure in cylinder No. 4.

The injector nozzle-hole deposit phenomenon, and the indirect role that fuel properties and/or dispersant fuel additives may play in reducing or promoting the tendency for such deposits to accumulate in the nozzle holes of some engines, is the subject of follow-on project work, which is discussed below in the section titled "Unexpected Fuel-Evaluation Results, Fuel-Injector Nozzle Fouling."

ICRC's analysis of the series of events surrounding and leading up to the engine problems of Bus 2056, as well as the replaced parts themselves, lead to the conclusion that the turbocharger, plus a fuel-injector and exhaust-valve in the same cylinder, which needed replacement at 227,480 odometer miles on WMATA Bus 2056, constitute an unremarkable or commonplace event in light of the overall experience of the WMATA bus fleet with DDC Series 50 engines.

Some fuel-injector nozzle holes in the engine of Bus 2056 had engine-oil-ash derived deposits in and around their outlet ends, but not enough deposits to prevent or greatly restrict injected fuel from flowing. As was also observed with the dynamometer-tested DDC Series 50 engine in this project, the level of these deposits varied from essentially none to moderate accumulation, from cylinder to cylinder and from hole to hole of a given cylinder's injection nozzle.

The on-road operational problems that occurred after the turbocharger and fuel injectors were replaced were caused by insufficient follow-up testing and diagnosis. Had the service personnel re-tested the vehicle after the repair, they would have noticed that the number 4 cylinder was not producing any power. Under further investigation the burned exhaust valve would have been found. If the valve had been replaced before the bus went back to WMATA, there would have been no subsequent failure.

ii. Bus Fleet Emissions Measurements

During the WMATA and Denali bus demonstrations, West Virginia University measured exhaust emissions on the six WMATA and six Denali buses that were used in the project. Use of the Syntroleum S-2 synthetic diesel produced reductions in NOx and PM emissions of the WMATA transit buses and reductions in PM, HC and CO emissions of the Denali tour buses.

During the fall of 2004 and spring of 2005, West Virginia University measured exhaust emissions on the six WMATA buses participating in project. The 2000 model year transit buses are equipped with 1999 model Detroit Diesel Corporation Series 50 engines and diesel oxidation catalysts. Three buses were operated on Syntroleum S-2 F-T fuel and three control buses were operated on ultra-low sulfur No. 1 (ULSD1) petroleum derived diesel fuel. Emissions were measured shortly after the test buses were converted to Syntroleum S-2 fuel and then repeated six months later.

The three WMATA transit buses fueled with Syntroleum S-2 fuel demonstrated apparent emission reductions of between 16% and 22% for NOX and 35% for PM compared to three control buses running on ULSD1. HC and CO emissions from the WMATA buses were low for both fuels with no significant differences noted between the Syntroleum S-2 and ultra-low sulfur fuel, given vehicle-to-vehicle variation.

Emissions measurements were also conducted back-to-back with both S-2 and ULSD1 fuels on a single WMATA transit bus equipped with an Engelhard DPX^{TM} passive catalyzed diesel particulate filter. Tests were conducted with the DPX installed and with the OEM oxidation catalyst installed. Installation of a catalyzed particulate filter in conjunction with the Syntroleum S-2 fuel reduced PM emissions to less than 0.01 g/mile. HC and CO emissions were also reduced to at or below ambient levels by the catalytic action of the DPX filter.

During summer of 2004, West Virginia University measured exhaust emissions at Denali National Park. The six Denali buses used for the project were 2004 model year Thomas buses equipped with new-technology 2004 model Caterpillar C7 ACERT engines and diesel oxidation catalysts. Three "test" buses were operated on Syntroleum S-2 fuel and three "control" buses were operated on the Denali fleet's normal No. 1 diesel fuel which is actually Jet A fuel. (This road-legal Jet-A fuel is sometimes referred to by fuel suppliers as "low-sulfur" because to be used as road-diesel fuel its sulfur content must be no more than 500 ppm, considerably lower than the maximum limit of 3000 ppm that would be acceptable for aviation use of Jet-A fuel.) The Jet-A fuel is used because ultra-low sulfur fuel is not economically available in Alaska. Due to time and travel constraints, the Denali Park buses were only tested on one occasion, rather than twice within a year, like the WMATA buses.

Three Denali Park buses fueled with Syntroleum S-2 showed apparent emissions reductions of 25% for PM, 81% for HC and 68% for CO compared to three identical buses running on the "baseline" Jet-A fuel typically used as No. 1 diesel fuel at Denali Park. However, NOx emissions from these Denali buses, equipped with new-technology Caterpillar C-7 engines which were calibrated for the "normal 40 to 45 Cetane" level of conventional fuels rather than for the much higher Cetane level of the Syntroleum fuel, showed an apparent increase of approximately 23%.

The combination of extremely high Cetane fuel and a "normal" (i.e. not matched to the high Cetane level) calibration of the Caterpillar C-7 engine apparently resulted in combustion beginning earlier in the cycle with higher in-cylinder temperatures than for a calibration better-matched to the fuel, similar to an increase in injection timing advance in an old-technology diesel engine. During the emissions testing, fuel economy was computed from exhaust emissions data using a carbon balance. The Syntroleum S-2 fuel did not result in significant changes in fuel economy in either bus fleet.

iii. F-T Fuel Cold-Weather Performance

An additional demonstration of the S-2 fuel in cold-weather conditions was required by the project scope. ICRC did not have any problem finding a site to conduct this demonstration, as Denali personnel were so pleased with the S-2 fuel's performance during the Summer 2004 bus demonstration that they requested an extension of the demonstration, and ran 4,000 gallons of arctic-grade F-T diesel fuel in the Park's snow-removal equipment through the Alaskan winter and during springtime road-opening, during which time the fuel's performance impressed its users extremely favorably.

Since F-T fuels are hydrogen saturated, it is sometimes incorrectly assumed that they must consist almost entirely of normal paraffins (i.e. wax), and accordingly that their low-temperature flow properties must be poor, causing flow-problems in cold climates. However, Syntroleum's F-T fuels are hydro-isomerized to the extent required to meet whatever the cold-flow requirements of the application may be. Hydro-isomerization maintains both hydrogen saturation and approximately the same carbon-number distribution of the isomerized F-T fuel, but adds methyl-branches to otherwise straight-chain paraffin molecules. The resulting structure causes the molecules to resist the formation of wax crystals as the temperature drops, greatly improving their cold-flow properties compared to normal paraffins. Therefore, there were no low-temperature flow problems, or any other problems for that matter, with the arctic-grade Syntroleum F-T diesel fuel used by the Denali National Park snow-removal vehicles through the Alaskan winter.

iv. Dynamometer-Lab Testing

ICRC and project-partner AVL Powertrain Engineering tested the durability of the fuel systems of the same two types of engines used in the WMATA and Denali demonstration buses, a Detroit Diesel Corp. (DDC) Series 50 and a Caterpillar C7 engine respectively, running each for 1,500 hours on F-T fuel. These tests showed conclusively that commercially available fuel-lubricity additive technology developed for low-sulfur conventional diesel fuels is fully capable of protecting diesel engine fuel systems with zero-sulfur F-T fuel. The DDC Series 50 performed 1500 hours of Syntroleum fueled repetitive Chicago Transit Authority (CTA) cycles without incident. There was no indication of any fuel system performance problem at the end of the test. The Caterpillar C-7 performed 1500 hours of Syntroleum fueled repetitive CTA cycles. Engine peak power decreased approximately 20% over the 1500 hour duration. The cause of this reduction in the Cat C-7's peak power was later determined to be accumulation of deposits derived from the non-combustible (ash) components of the engine oil, not from the fuel, in some of the fuel-injection nozzle-orifices.

AVL also made dynamometer-based emissions measurements on the two bus engines described above, primarily as a follow-up to the unexpected NOx emission results obtained with the Denali NP buses with new-technology Caterpillar C-7 engines. The emission investigation compared Syntroleum, Denali and WMATA fuels on a time and power weighted emission test cycle. WMATA fuel, a conventional low-sulfur No. 1 diesel, is defined in this study as the 'reference' fuel. For each engine, three AVL 8 Mode emission tests were performed on each of the three fuels. The AVL 8-Mode is a hot start test originally designed to correlate with exhaust emission results of the U.S. Federal Test Procedure (FTP) Heavy-Duty Transient Cycle. The weighted brake specific emissions were compared for each pollutant by averaging three emission tests to a one value result. NOx and particulate matter (PM) were the pollutants of primary interest. For the CAT engine an AVL 472 SPC 'Smart Sampler', a partial flow exhaust sampling system, provided tailpipe PM mass emissions. The following results were obtained:

- Syntroleum NOx decreased 12% (DDC) and 19% (CAT) from the reference WMATA fuel.
- Syntroleum PM decreased 42% (CAT only) from the reference WMATA fuel.

v. Cold-Start Test-Cell Evaluation of F-T Fuel in an Engine

The F-T fuel was evaluated alongside No. 1 and No. 2 diesel fuels for its unassisted cold starting characteristics. All testing was done in a Detroit Diesel Series 50 four-cylinder heavy-duty diesel bus engine in a refrigerated test cell at AVL Powertrain's test facility in Ann Arbor, MI.

Cold-starting performance of S-2 F-T fuel in this engine was shown to be superior to that of conventional petroleum derived No. 1 and No. 2 diesel fuels.
As cold-soak temperature decreased, each fuel was found to have:

1) A range of cold-soak temperatures where additional engine cranking (beyond a single ten-second crank) would usually be needed in order to start the engine;

2) A lower range of cold-soak temperatures where cold-starting was sometimes possible (by using up to three cranking events of ten seconds each), but starting did not always occur, so cold-starting was termed unreliable in this cold-soak temperature range; and

3) An even lower cold-soak temperature, at which and below cold-starting was no longer possible, even after three cranking events of ten seconds each.

The test proceeded as follows. The test engine was installed in a refrigerated test cell capable of cold soaking the engine to -36°C (-33°F). The engine was allowed to cold soak overnight at the test temperature. The stabilized temperature of the engine was tracked using the engine coolant temperature. The starting test consisted of the engine being cranked until start, or until ten seconds had elapsed. If the engine failed to start, the cranking procedure was repeated, after a five-second interval, no more than two additional times. Since experience has shown that cold-starting behavior from one attempt to another of an engine/fuel combination at a particular low temperature cannot be predicted (or repeated) with absolute certainty, the test was designed to characterize the temperature range where the fuel and engine would begin to experience difficulty in starting and finally fail to start.

Three temperatures were considered to be important for characterizing the region with difficult or unreliable cold-starting. The highest temperature of interest is where additional cranking events were required to have the engine start. The next highest temperature of interest is the highest temperature at which a non-start was recorded. The final or lowest temperature of interest is the coldest temperature at which a start was recorded. Relatively quick, reliable starting can be expected above this region and no starting can be expected below this region. The temperatures of interest are provided in the table below, which presents the temperatures for the three fuels that define the area of difficult or unreliable starting.

	Diesel No. 2	Diesel No. 1	Syntroleum S-2
Additional cranking required	-14.39°C (6.10°F)	-15.84°C (3.49°F)	-23.66°C (-10.59°F)
Highest temperature non-start	-18.68°C (-1.63°F)	-16.65°C (2.03°F)	-29.63°C (-21.33°F)
Lowest temperature start	-21.96°C (-7.52°F)	-16.75°C (1.85°F)	-31.68°C (-25.03°F)

Figure 16: Temperatures of Interest °C (°F)

Figure 17 below shows graphically the regions of difficult or unreliable cold-starting for the No. 2 diesel, No. 1 diesel, and the Syntroleum S-2 fuels.

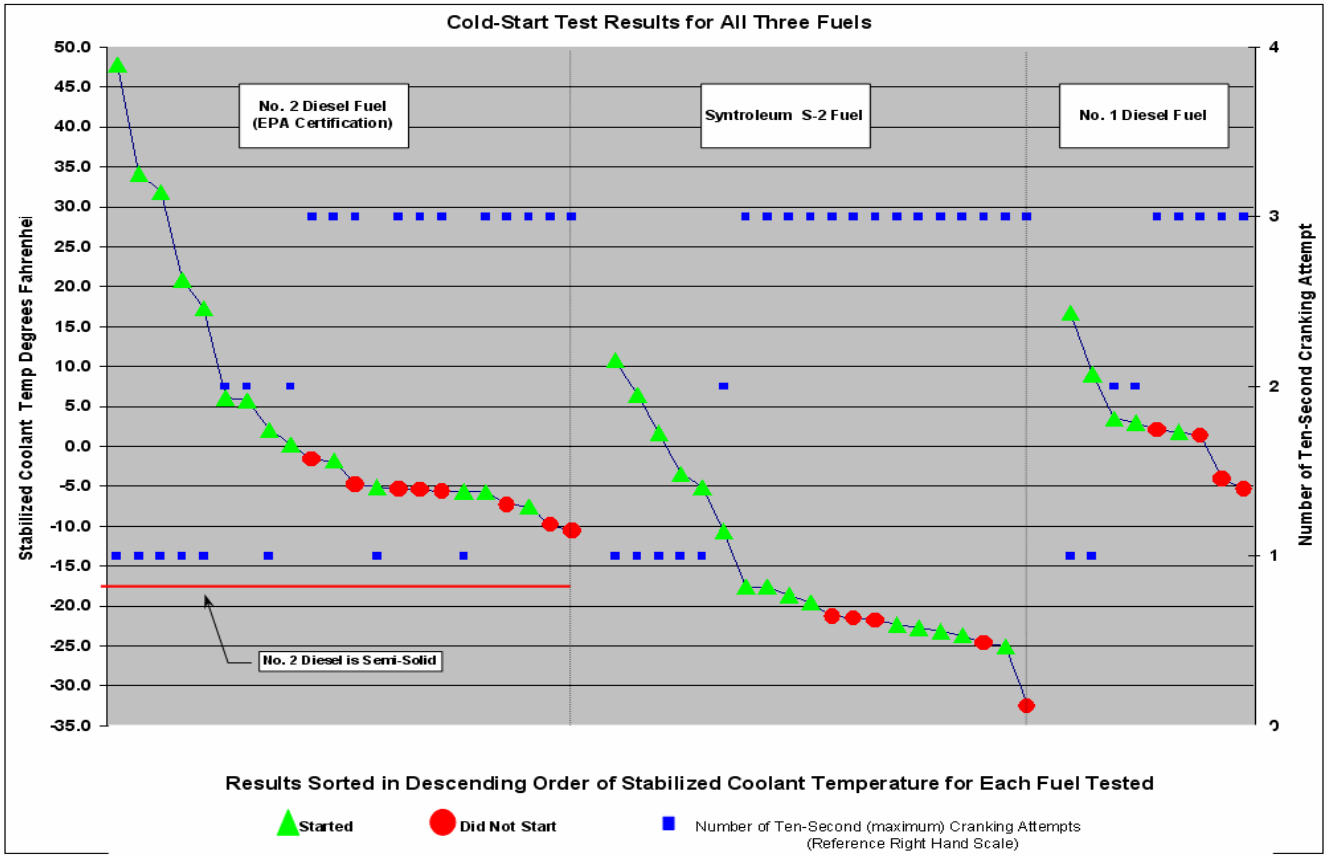


Figure 17: Complete Cold Start Testing Results

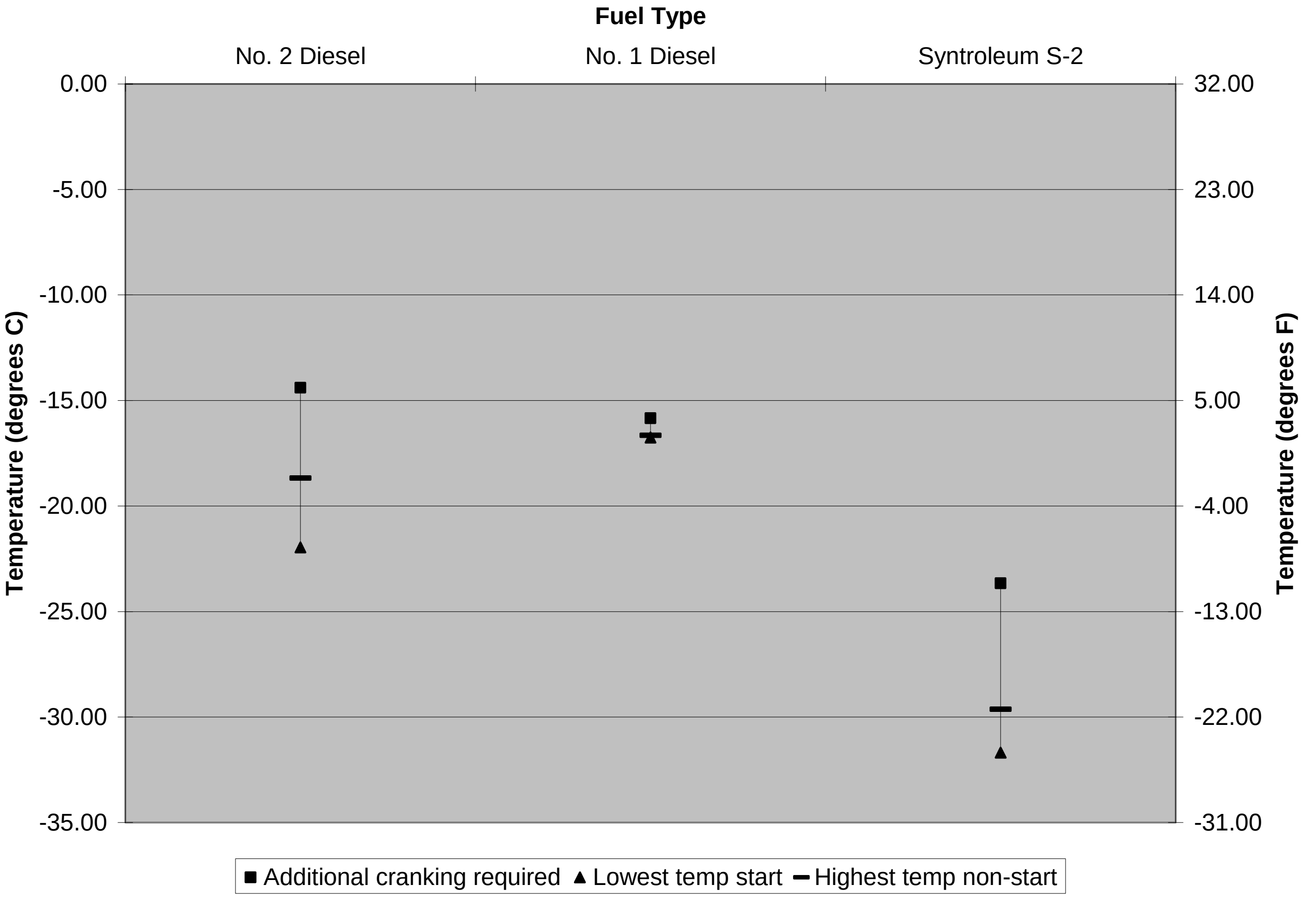


Figure 18: Regions of Difficult and Unreliable Starting for Each Fuel

When compared with No. 2 diesel fuel, the Syntroleum S-2 fuel exhibited the following results:

- The S-2 fuel did not require additional cranking events until the temperature was 9.27°C (16.69°F) lower.
- The S-2 fuel did not experience its highest temperature non-start until the temperature was 10.95°C (19.7°F) lower.
- The S-2 fuel started at a 9.72°C (17.5°F) lower temperature.

When compared with No. 1 diesel fuel, the Syntroleum S-2 fuel exhibited the following results:

- The S-2 fuel did not require additional cranking events until the temperature was 7.82°C (14.08°F) lower.
- The S-2 fuel did not experience its highest temperature non-start until the temperature was 12.98°C (23.36°F) lower.
- The S-2 fuel started at a 14.93°C (26.88°F) lower temperature.

It is of note that conventional No. 1 diesel fuel does not exhibit a lower minimum starting temperature than No. 2 diesel fuel. This is despite No. 1's improved cold-flow properties and increased volatility. Future testing could investigate the capability of the fuel–engine-vehicle system to continue running at extremely low temperatures. ICRC speculates that No. 1 diesel fuel would allow the engine to continue running at lower temperatures than No. 2 diesel fuel. The No. 2 diesel fuel used in this program exhibited gelling at temperatures below -27°C (-18°F), while No. 1 diesel and Syntroleum S-2 showed no gelling down to -36°C (-33°F), the lowest test temperature.

This testing program was designed to characterize the cold-starting behavior of the fuels in question to allow an evaluation of whether or not ultra-clean F-T diesel fuels can allow diesel engines to start at lower temperatures. The characterized improvement over No. 2 and No. 1 Diesel successfully demonstrates that this ultra-clean F-T diesel fuel does exhibit better cold-starting characteristics.

vi. Advanced Diesel Combustion Analysis

The Massachusetts Institute of Technology (MIT) conducted a dynamometer laboratory evaluation of F-T fuel's effects on the performance and emissions of a highly instrumented Cummins 5.9 liter diesel engine. The main findings were:

- Ultra-clean F-T fuel reduces emissions of both particulates and NOx compared to conventional fuels, which is consistent with the consensus of all the emission measurements on the larger bus engines, in the bus fleets, and in AVL's dynamometer laboratory;

- Blends of F-T and conventional fuels provide greater emissions benefits than in proportion to the amount of F-T fuel in the blend;

- F-T fuel removes the sensitive dependence of PM production on EGR rate, allowing significant NOx reductions through the use of higher EGR rates before PM levels become unacceptably high.

Over the duration of this study, the differences in the measured combustion characteristics, PM chemical composition, and fuel properties were compared to the emissions variations between the fuels studied, and an explanation for the observed emissions behavior of the fuels was developed. The effects of various engine operating parameters, namely injection timing and EGR rates, on emissions with Fischer-Tropsch and conventional diesel fuels were explored, and strategies were proposed to take full advantage of the beneficial properties of Fischer-Tropsch fuels. A detailed investigation into the effects of GTL fuels on the performance of diesel particulate traps was also conducted.

The engine used in this study was a pre-production development engine based on the Cummins 2002 ISB 300 platform. The Cummins ISB 300 is a turbocharged, 6-cylinder, 5.9-liter, four-stroke, direct injection diesel engine. The engine was rated at 224 kW (300 hp) at 2500 rpm and 890 N-m (660 lb-ft) at 1600 rpm. The ISB300 was certified to meet 2002 EPA emissions standards, and employed a number of advanced subsystems such as a Bosch common rail high-pressure fuel injection system, Holset variable geometry turbocharger, and cooled EGR. In addition to these subsystems, the engine also utilized a multiple fuel injection strategy to further optimize the combustion process with three injection events (pre-, main-, and post-injection) per cycle. All of the advanced subsystems were electronically controlled by an electronic control module (ECM) (version CM 850) calibrated to meet 2002 emissions limits when operating with an EPA No. 2 diesel fuel. The table below lists the engine specifications.

Number Of Cylinders	6
Combustion System	Direct Injection
Aspiration	Turbocharged
Stroked (Displaced) Volume [liters]	5.9
Bore/ Stroke [mm]	102/120
Connecting Rod Length [mm]	192
Crank Radius [mm]	60
Compression Ratio	17.2

Figure 19: Engine Used in Advanced Diesel Combustion Research

The ISB 300 engine, provided by Cummins, was fully electronically controlled and came equipped with an unlocked ECM. In addition, Cummins also provided their proprietary in-house software, Calibration Terminal (CalTerm) version 7.63, allowing for engine calibration changes and real-time monitoring and modification of engine parameters. Throughout the duration of this study, the engine was operated using the stock 300-horsepower calibration provided by Cummins. This calibration was based on a standard No. 2 diesel fuel and was used for the following two reasons: (1) to ensure the engine would run on the 2002 EPA-emission-certified performance maps, and (2) to evaluate the performance of the Fischer-Tropsch fuels and blends in a modern engine running on the stock control system.

Testing included the use of various (experimental) fuels. The three neat fuels under investigation in this study were low-sulfur diesel (LSD) containing 400 PPM sulfur, ultra-low sulfur diesel (ULSD) containing 15 PPM sulfur, and Fischer-Tropsch synthetic diesel, produced from natural gas, containing zero sulfur. A blend of 25% F-T and 75% low sulfur diesel by volume and a blend of 25% F-T and 75% ultra-low sulfur diesel were used as well.

Goals for this portion of the study included:

(1) Assess how gas-to-liquid fuels impact engine performance and emissions, directly and in blends; to evaluate tradeoffs among fuel properties and blending ratios; to evaluate engine modifications in further improving engine emissions; and to determine combustion and emission characteristics.

(2) Explore opportunities of injection strategy control and exhaust-gas-recirculation in pushing limits of NOx/particulates reduction using Syntroleum Fischer-Tropsch fuels produced from a small footprint plant. The engine will be modified for various injection control and EGR systems. Since particulates are expected to be substantially lower with the GTL fuel, limits of NOx reduction via EGR and injection variables will be explored as well.

(3) Evaluate exhaust aftertreatment systems performance and design tradeoffs available using gas-to-liquid fuels. Optimize the fuel/engine/emission-control system.

The NOx and particulate emissions trends were measured and correlated with the combustion characteristics for a modern diesel engine (Cummins MY 2002 ISB 5.9 liters). Different injection timing strategies as well as EGR rates were explored. Initial results using limited quantities of the F-T fuel and 400 PPM sulfur fuel showed NOx reductions of 6-13% and particulate reductions with the F-T fuel up to 75% compared to the 400 PPM sulfur diesel fuel.

Subsequent tests explored changes in fuel injection timings and EGR rates from the standard factory settings and included 15 PPM and 400 PPM sulfur diesel fuel, as well as F-T/diesel blends (25% F-T/75% 400 PPM and 15 PPM diesel by volume). While NOx reductions were still limited to 20% or less, the bulk of the data showed particulate reductions between 25-50%. Particulate reductions of up to 75% with F-T fuel compared to the standard diesel were observed at extremely retarded timing and light load conditions, primarily due to the increase of particulate emissions of the regular diesel fuel at those extreme conditions.

Comparison with the ultra-low sulfur fuel indicates that the particulate reduction benefit of F-T fuel originates beyond the zero sulfur content of the F-T fuel. The analyses suggest that the F-T fuel maintains its combustion rates, even as injection timings are severely retarded and EGR rates heavily increased to reducing NOx. This is in contrast to conventional diesel fuel, where these conditions result in an increase in particulates.

Detailed chemical analyses of the particulate composition confirmed the results obtained in previous tests. Furthermore, the analyses provided conclusive evidence for the contribution of significant non-sulfur effects to the observed emissions trends. Fuel sulfur may actually have very little influence on the observed differences in PM emissions for the fuels studied. The combustion analysis, carried out over a much larger range of engine operating conditions than in earlier stages of the study, provided additional insight into the combustion characteristics and differences in observed emissions trends.

The impact of using the F-T fuel on emission control via exhaust aftertreatment was also investigated. A prototype and full-flow diesel particulate trap was designed, fabricated, and tested using the F-T and low sulfur diesel fuels. The F-T fuel significantly extended the trapping period and reduced the regeneration frequency as compared to the LSD. Furthermore, the absence of sulfur in F-T fuels permits the use of more aggressively catalyzed traps, as sulfur poisoning is not an issue. Moreover, the reduced particulate emissions of F-T fuels lead to increased time between trap regenerations, which in conjunction with advanced catalyst formulations reducing the temperatures required to initiate regeneration, may provide substantial improvements in trap durability and performance.

An investigation into the relationship between fuel properties, combustion characteristics, and exhaust emissions was carried out using a pre-production 2002 Cummins ISB 300 direct injection turbo-diesel engine. Current results confirm the results presented in previous reporting periods that the Fischer-Tropsch gas-to-liquid diesel fuel from the Syntroleum small footprint plant performs better and with lower emissions than regular diesel fuel in a modern (MY 2002) direct injection diesel engine. Further improvements in performance and emissions can be realized by configuring the engine to take advantage of F-T diesel fuel's properties, and the addition of exhaust aftertreatment systems. A small fraction of F-T fuel blended with regular No. 2 diesel (low sulfur and ultra-low sulfur diesel) can offer significant PM emission reductions more than shown by its proportion in the blended fuel. Furthermore, the F-T diesel significantly extended the trapping period and reduced the regeneration frequency of an un-catalyzed cordierite diesel particulate trap as compared to the baseline low sulfur diesel.

The modern engine technology and related subsystems employed by the Cummins ISB have a profound effect on the manner in which the fuel properties affect engine out emissions. The Cetane number (CN) of a fuel is commonly believed to control NO_x output by dictating the amount of fuel that auto-ignites in the initial premixed burn fraction. However, the modern engine tested is designed to have small premixed burn fractions, such as those with high injection pressures to promote good mixing along with late injection in hot cylinder conditions around TDC. Thus, NOx emissions are less sensitive to the value of a fuel's CN. On the other hand, combustion data show that the F-T fuel burns faster during the latter part of combustion, in back-to-back comparisons with No. 2 diesel. This helps to oxidize particulates, and when combined with retarded injection timing past TDC provides an optimal combination of both NOx and particulate reduction. Furthermore the multiple injection strategy, employed in the Cummins ISB, also has a significant effect on the in-cylinder combustion process and plays a significant role in reducing NOx and PM emissions.

Additional tests performed investigated the relationship between fuel properties, emissions, and diesel particulate trap performance characteristics. Uncoated Cordierite ceramic substrates were loaded using Fischer-Tropsch and a conventional 400 PPM sulfur diesel fuel for 25 hours each. Pre- and post-trap emissions, temperature, pressure drop, and trapping efficiency were measured under steady-state engine operation. Furthermore, a detailed analysis of the particulates was carried out to provide further insight into the differences in the trap loading and performance characteristics. The data collected over the duration of this study leads to the following updated conclusions:

Fuel Effects on Combustion and Emissions

- For a modern MY '02 heavy-duty diesel engine, F-T fuel reduces particulate emissions substantially, mostly in the range of 25-50% for a variety of steady-state conditions tested. Under light load, low speed conditions typical of urban driving, particulate reductions can reach up to 75%.
- A blend of 25% (by volume) F-T fuel with 75% 400 PPM sulfur fuel showed that the 25% F-T fuel in the blend produced about half of the particulate reduction of using neat F-T fuel alone.
- Significant non-sulfur effects are responsible for the large reductions in PM emissions observed for the F-T fuel and blends. The results of the PM analysis carried out at the emissions-chemistry laboratory of a major engine manufacturer

confirmed these findings, and demonstrated reductions in the range of 40% to 60% in SOL and SOF for the blend when compared to the reductions observed for the neat F-T fuel alone.

- For the same modern engine, F-T diesel fuel reduces NOx emissions consistently from 6-20% versus No. 2 diesel fuel. The more recent results are consistent with previous results of 6-13% reduction and with overall results reported in the literature. F-T fuel's higher Cetane number and a shorter ignition delay allow fuel injection to be further retarded for NOx control.
- The reduction in NOx emissions for the F-T fuel and blend was directly correlated to the measured reduction in exhaust temperatures and shorter diffusion burn. This data confirms that a temperature sensitive extended Zeldovich type mechanism is primarily responsible for NOx formation in the power cylinder.
- While emissions of hydrocarbons were low, and typically within acceptable limits, the significantly higher rate of HC emissions from the ultra-low sulfur diesel fuel is most likely due to the fuel's higher volatility and significantly different distillation curve. These two factors may also be responsible for the relatively higher sulfur to sulfate conversion rate observed for the ULSD.
- The increased cetane number of the F-T and blend decreased the ignition delay compared to the baseline fuel. The shorter ignition delay and lower density of the F-T fuel and blend contributed to a significant reduction in the maximum heat release of the pilot injection, thus reducing initial particulate formation.
- F-T fuel burns faster during the latter part of combustion, especially when combustion occurs predominantly during the expansion stroke. The faster 50% to 90% burn duration of the F-T fuel may lead to additional particulate oxidation. Therefore, late injection timing retard, at or after TDC, can be employed for large NOx reduction in modern engines.

Interaction of Fuel Effects and Influence of Engine Parameters on Emissions

- For a modern MY 02 heavy-duty diesel engine, steady-state results indicate that F-T fuel reduces particulate emission substantially (50-75%) over the entire timing and EGR sweep compared to the baseline low sulfur diesel fuel (400 PPM sulfur). Favorable combustion effects for the F-T fuel for late injection timings also contributed significant particulate reduction.
- From examining exhaust mole fractions of water, CO, and CO_2, the higher H/C ratio of F-T fuel appeared to have a small but perceptible effect on products of combustion that may make it more difficult to produce NOx.
- Conventional diesel fuel normally produces more particulate matter as EGR increases. F-T fuel removes the sensitive dependence of PM production on EGR rate, allowing significant NOx reductions through the use of higher EGR rates before PM levels become substantially large.
- Injection timing has no adverse effects on emissions with F-T fuel. F-T diesel fuel follows the same trends as the petroleum-based No. 2 diesel fuel used in the experiments. As timing is advanced, both fuels show increases in NOx while timing retard results in NOx reductions, showing both fuels have the same NOx production mechanisms. With PM, both fuels show reductions in emissions as timing is changed from the stock timing point.

- Increases in PM output from increased EGR rates can be controlled by aftertreatment systems without concern of system performance deterioration from fuel sulfur, as F-T diesel fuel is virtually sulfur free.
- In addition, as established elsewhere but not within the current scope of this work, sulfur-free fuel does not poison catalysts in NOx aftertreatment systems with sulfur originating from the fuel. Sulfur in the lubricant presents a different problem.

Fuel Effects on Particulate Aftertreatment Systems

- The diesel particulate traps loaded using F-T diesel exhibited a slower rate of increase in pressure drop and a reduction in trap pressure drop of 14.5% on average.
- The reduced pressure drop for the traps loaded using F-T fuel is primarily due to the significant reduction in PM emissions of the F-T diesel.
- The slower initial increase in trapping efficiency of the F-T fuel is due to the slower rate of PM accumulation in the trap.
- The differences in trap temperature profiles, NO_2, CO, and CO_2 emissions all suggest that some slow soot oxidation via NO_2 is occurring.
- F-T particulates may oxidize at a slower rate in the presence of NO_2 as compared to particulates generated from conventional diesel fuel.
- The slower rate of F-T particulate oxidation may contribute to the smaller than expected difference between the pressure-drop profiles for the two fuels.
- F-T fuels may present a slight fuel economy advantage at elevated trap loading levels.
- Fischer-Tropsch fuels extend the trapping period and reduce regeneration frequency due to their lower PM emission rates.
- The use of zero sulfur F-T fuels may also allow the use of more aggressive exhaust after-treatment systems.

In summary, F-T fuel gives greater freedom to engine designers when trying to optimize the engine/emission-control/fuel system in modern engines, by providing the fuel properties as another flexible set of variables that affect the combustion and emission processes. Furthermore, the zero sulfur nature of the F-T fuel allows for the use of additional and more aggressive exhaust aftertreatment devices, previously impossible due to the deleterious effects of fuel sulfur on the catalyst.

vii. F-T Fuel for Electric Power Generation

The Arctic Energy Technology Development Laboratory (AETDL) of the University of Alaska-Fairbanks conducted testing of both S-1 (winter-grade) and S-2 F-T fuels in a diesel generator-set similar to those typically used to power rural Alaskan villages. In most parts of the U.S., the majority of diesel fuel (90%) is used for transportation, in trucks and busses, but in Alaska, the majority (about 95%) is used in diesel generators for the production of electricity in remote areas (Witmer). Diesel generators typically use the same engines as used in trucks and busses, but operate them in a different manner (constant speed at 1,200 or 1,800 rpm, continuous operation.) In addition, cold winters in

Alaska require the use of Arctic Grade fuels, capable of flowing at temperatures of -50F (Witmer).

Primary findings of the testing were:

- Gaseous exhaust emissions, including NOx, were reduced by S-1 and S-2 fuels compared to conventional diesel fuel.
- After running for over 2,200 hours on S-1 and S-2 fuels without any dispersant additive treatment, fuel injector nozzles of the gen-set's Detroit Diesel Corp. Series 50 engine (basically the same as in the WMATA buses) were flow-tested and showed no reduction in flow compared to a new nozzle.
- Early in the program, the gen-set's Series 50 engine turbocharger failed, "dumped" oil into the engine induction system, and was replaced under warranty, the same basic scenario as with the turbocharger on WMATA bus 2056 in the program.
- Waste-heat recovery for space heating from both the engine coolant and exhaust is typically a vital aspect of the overall efficient operation of gen-sets in rural Alaskan villages. Accordingly, AETDL evaluated the corrosivity of exhaust condensate and found it to be reduced significantly when using F-T fuels compared to conventional diesel fuels.

The study plan for this project included a 2,000-hour test on clean fuel, emissions measurements, and a test of a new arctic grade fuel. Fuel was supplied by Syntroleum in three lots. The first batch of fuel had properties somewhere between that of conventional S2 fuel and the arctic grade S1 (delivered in June, 2004), the second batch met the specifications of S2 (delivered in August, 2004), and the third lot met the specifications for S1 fuel (delivered in October, 2004).

Highlights of the testing program included:

- 2,200 hours of operation of the Detroit Diesel Series 50 generator with no issues traceable to the fuel.
- Emissions testing indicated that no change to injection timing map necessary with the Detroit Diesel engine.
- Emission measurements indicated that the synthetic fuel burned cleaner than conventional diesel fuel
- Exhaust condensate from clean fuels is less corrosive than those from conventional fuels.

Several operational issues occurred during the testing. These included

- Turbocharger failure at 962 hours, not traceable to the clean diesel fuel
- Low lubricity values as measured in the scuff ball test, but no resulting operational issues
- A leak at the bulk fuel pump in cold weather (-8 C) traceable to the lack of arctic grade seals in the pump
- High CO measured in emissions test, traceable to the high intake air temperatures inside the generator shed.

Our conclusions indicate that the clean fuel could be used in diesel generators with no significant changes in operational or maintenance procedures.

AETDL, in conjunction with Idaho National Engineering and Environmental Laboratories, also conducted a short test of F-T fuel in a 5-kW (kilowatt) reformer/solid-oxide fuel-cell system, and concluded that the system ran "as well or better" on F-T fuel as it did on conventional fuel.

viii. Overall Feasibility, Economics and Efficiency of SFP Fuel Production in Alaska

Tim Bradner, an Alaska-based consultant, investigated the overall feasibility of constructing small-scale F-T plants at specific sites in rural Alaska to take advantage of the state's vast supplies of underutilized natural resources that could potentially provide feedstock for F-T plants. These potential local-feedstock F-T plants could meet local energy needs while reducing the need for expensive imported petroleum products. Two types of locations were analyzed in the study: SFPs in more populated (for Alaska) locations near resource deposits, from which rural communities could be served; and SFPs in selected rural locations that are already near natural resource deposits.

SFPs in Regional Locations

Best Rural Alaskan Plant Locations

The study found that medium-sized (6,000 to 12,000 bbls/day) plants at regional locations, from which F-T products can be distributed to locations in and outside Alaska, offer the best possibilities.
The four best locations are:

1. Healy: There is a producing coal mine at Healy, industrial facilities have been built there, and an F-T plant would have access to the Alaska Railroad for product transportation and the regional power grid for sales of electricity generated with waste heat.
2. Beluga: There is a large coal resource and a tidewater location. The opportunity to ship products efficiently in bulk, and near-proximity to the regional power grid makes this location of interest. The major drawback is that a coal mine has not been developed.
3. Nikiski: There is a functioning GTL demonstration plant that could be converted, and because local biomass resources are available. The existing GTL plant is too small for commercial use, and using natural gas as a raw material is too expensive in Cook Inlet. There are possible limits to the size of a bio-mass F-T plant.
4. Bristol Bay**:** The Bristol Bay basin is very gas-prone and the possibilities of a gas discovery are good. A medium-sized GTL plant is a possible option to commercialize a gas discovery that is too small to support a conventional gas pipeline or a liquefied natural gas project.

Of the four sites listed above, the plants that could be developed on the fastest schedules are at Nikiski and at Healy because a source of resource feedstock is available, as well as utility support facilities, transportation infrastructure to move products to market and the existence of a local or regional construction workforce

Site Study Conclusions

*F-T plants in Alaska will require government support***.** In almost every scenario studied, a temporary government support mechanism was crucial in reducing the "tailgate" cost of F-T fuels to levels that might approach economic viability even if crude oil prices remain high. There are several ways the Government could support such plants: (1) an energy credit on F-T fuels for an amount similar to tax credits granted to biodiesel, ethanol, and compressed natural gas; (2) a Government grant to pay the capital costs of a plant; and (3) a Government fixed-price purchase contract for F-T fuels to make the plant economic. This study assumed a federal energy credit similar to existing energy credits for biodiesel, ethanol, and compressed natural gas as a plausible form of federal support.

*Higher oil prices could make F-T plants more feasible***.** The continuing rise in crude oil prices and the price of conventional diesel make the possible economics of Alaska F-T plants much more feasible. What must also be taken into consideration are the extra costs required after 2006 and 2010 to supply ultra low-sulfur (ULS) diesel, or conventional diesel with sulfur reduced to 15 parts-per-million (ppm), on top of the cost of conventional diesel. Since F-T fuels will meet the EPA requirements in the 2006 and 2010 regulations, the true comparison will be to weigh possible costs of F-T diesel against conventional diesel with the ultra-low sulfur cost added.

*F-T fuels would meet the requirements of new EPA ultra-low sulfur diesel***.** New U.S. Environmental Protection Agency rules requiring the use of 15 ppm ULS diesel are effective in 2006 regarding transportation fuels and 2010 regarding diesel used in off-road (construction, mining, etc.) and stationary diesel engines (Bradner). These rules will have considerable impacts in rural Alaska, mainly because of the cost of making winter-grade ULS diesel, and transportation and storage problems that arise if the ULS fuels are segregated from conventional diesel. It is predicted that by 2010 all diesel used in rural Alaska will be ULS because of the high costs of shipping and storing separate fuels. There will still be a premium charged for this fuel in rural Alaska, beyond the cost of conventional ULS diesel--various estimates, ranging from 15 cents per gallon to 70 cents per gallon depending on the location (Bradner). These high ULS fuel costs help make a better case for the use of F-T diesel: while F-T diesel is currently cost-prohibitive as compared to conventional winter diesel fuel, when the cost of F-T diesel is compared to the increasingly expensive ULS fuel that will be used in the very near future, the feasibility of F-T diesel (which already meets the EPA requirements) greatly increases.

*Low-toxicity and biodegradability of some F-T fuels is an advantage***.** The low toxicity and biodegradable nature of F-T fuels is an advantage: many F-T fuels have low toxicity and are certified as biodegradable by EPA. If these fuels were spilled during handling or because of a rupture of a tank, the environmental impact would be less than that of conventional diesel. The study did not attempt to quantify this advantage, but there is a real cost imposed on small rural storage and distribution facilities by spill containment, training and other requirements that arise from the toxic nature of conventional crude oil-based diesel. Use of F-T fuels may not eliminate these requirements, but the nature of the fuel would be weighed by the state and federal government agencies in considering a spill plan and other requirements for a bulk fuel storage facility.

Uncertanties

While the study shows that there are several advantages to using F-T fuel instead of conventional diesel and even ULS diesel in rural Alaska, there are still uncertainties that must be explored. The study uncovered four major risk factors. They are:

1.) Technology risks. F-T technology works at large scale, such as at 50,000 barrels/day, but there is insufficient industry experience with smaller scale F-T plants, such as those at the 200 bbls/day range. This is a major area of uncertainty.
2.) Location risks. There are no guidelines for estimating project construction costs in rural Alaska, or even the state as a whole. Project cost estimation was based on past experience and familiarity with site conditions by the project team. Study authors discussed each location with local experts and, within the means at their disposal, attempted to make reasonable assumptions as to local construction costs. However, a realistic quantitative assessment of a particular site would take a greater and more focused effort, and is beyond the means of this project.
3.) Resource risks. The study includes a range of estimates for the cost of supplying given resources (coal, biomass, gas) to the locations discussed above, but the actual cost will remain unknown until a project is developed. The study authors are confident in the estimated costs of biomass and coal at Nikiski and coal at Beluga and Healy, but the estimates for natural gas, coal, biomass and coalbed methane at the Bristol Bay, Galena, and Fort Yukon sites are very speculative.
4.) Operations risks. This is an unquantifiable risk, but a serious one in remote or rural settings. An F-T plant is really a kind of chemical plant--operations are complex and require skilled personnel and substantial off-site support. As such staffing and operating such a plant in a remote or rural setting could be quite a challenge, and have proved to be a challenge in rural Alaska in the past.

Smaller-Scale Plans in Rural Communities

As larger plants would require an extensive transportation system to move the fuel products out of the immediate region, the study also analyzed two rural community locations in Interior Alaska, assuming small-scale 300 bbl/day F-T plants. Galena and Fort Yukon were selected because these communities are on the Yukon River, which offers a good, if seasonal, transportation option for the fuel not used by the immediate community. Resource deposits near the communities could supply feed for small F-T plants, coal and biomass near Galena and bio-mass and coal bed methane near Fort Yukon.

Although the state of research and development in smaller-scale F-T plant technology is not as advanced as that of larger scale plants, the study was able to provide general assessments of the potential for such plants in rural community settings, and came to the following conclusions.

Government funding would greatly improve economics. Study authors were initially skeptical that a small plant (300 bbl/day) would be even remotely feasible at any rural community locations, and in general the analysis supported this view. However, depending on the project and what type of feedstock is used, it may be possible to obtain government funding to cover capital costs of the F-T plant and equipment (~$65 million). Such startup awards could lower the required price of diesel products from the plant to at or below diesel prices in late 2004 and early 2005. The study did not consider a case like this for the larger projects because the prospects for government funding for the larger projects – involving several hundred million dollars – seem remote. The conclusion is that alternate ways of financing small F-T projects in rural areas may be worthy of further study.

Using bio-mass as a feedstock could stimulate rural industry. In the case of a small rural plant supported by bio-mass from regional timber harvesting, the operation of the plant and the harvesting could provide a considerable economic stimulus to the region, particularly if the harvesting is integrated with a sawmill or some other way to use higher-value wood**.**

More support is needed for SFP research and development. More support should be given to research and development of SFP F-T technologies. Because the military has shown such great interest in SFP F-T technology, the federal government should take the lead in providing support. Private industry's F-T research and development is directed toward larger plants which enjoy economies of scale. Little effort is being made, within the private sector, on smaller plants, and very little in the micro-plant category (200-600 bbl/day).

ix. Economic Analysis

Tiax LLC (formerly A. D. Little, Inc.) performed a general well-to-wheels economic analysis, estimating the economics, emissions, and overall energy efficiency associated with using small footprint plants to produce F-T fuel from relatively small-scale deposits or accumulations of natural resources such as stranded gas, biomass, coal, etc., which might be used as feedstocks for producing F-T fuel.

The study confirmed that the SFP approach is more likely to succeed in Alaska than in most continental U.S. locations. However, a primary conclusion from both the foregoing feasibility studies is that even in rural Alaska, where conventional diesel fuel is typically moved long distances under difficult conditions at high cost to provide for virtually all energy needs, this existing approach is projected to remain less costly overall than producing F-T fuel from underutilized local resources in the absence of subsidies or technological breakthroughs.

The study identified stranded natural gas and biomass as potentially viable feedstocks for the production of GTL fuels from small footprint plants. Both exist in sufficient quantities but in small enough streams to warrant the construction of small footprint plants. For natural gas, when the plants produce power as well as fuel, the study found conditions under which the internal rate of return for plants with a 20-year lifetime ranged as high as 9% to 146%, depending on plant size and the cost of feedstock and the price at which the products could be sold. For biomass, which requires a significantly larger capital investment than natural gas, conditions that led to positive returns could not be identified, implying that this type of plant would need subsidies to make it viable.

Other resources, coal, shale oil and coal bed methane, either were available in reservoirs large enough to support large facilities that are more cost effective when run at scale or they were too far from markets to offer the benefits of local supply.

To estimate the economics of fuel production with small footprint plants the study considered scenarios that included wide ranges for future prices for the principal products of GTL, fuel ($24-$55 per barrel) and electricity ($0.03 to $0.11 per kWh). At the low end, which corresponds roughly to consensus projections prior to the end of 2005, a small footprint plant constructed using conventional unit operations appears to be unprofitable in the absence of subsidies that might accompany the production of the ultraclean fuel. However, a hypothetical plant that employs a novel, modular, packaging of the production technologies appears to offer significant economic benefits, particularly at production capacities less than 1,000 barrels per day. At the high end, which corresponds roughly to consensus projections that take into account the recent increases in petroleum costs, profitably, overlapping economics are estimated for both a conventional plant and the hypothetical, modular plant.

To compare the emissions and fuel economy for vehicles fueled with Fischer-Tropsch diesel and conventional diesel, the well-to-wheels analysis includes the effects of fuel generation, transportation and use. The benefit of GTL fuels with respect to criteria pollutants, NOx, CO, and PM, is complicated by the mandated introduction of very clean diesel engines nearly simultaneously with the earliest practical introduction of small footprint plants. Thus, in the analysis the benefits of GTL fuels were applied only to the older fraction of the vehicle fleet and can therefore be expected to diminish as those vehicles are taken out of service. The study took into consideration, but did not attempt to quantify, other potential advantages of GTL fuels. For example, with sophisticated engine control systems, it is likely that approaches can be found, if they are sought, to take advantage of a fuel with inherently less tendency to produce emissions. In that case, or if the improvements presaged by EPA regulations are not fully realized, additional benefits would accrue from the availability of a very clean fuel.

Even under the conservative assumptions made, significant savings in NOx and PM—15% and 35%, respectively—were projected for two heavier vehicle classes, buses and utility trucks, if fueled with GTL fuels, because in 2015 (the year that small footprint plants could be commercialized) almost 80% of those fleets will consist of vehicles purchased prior to 2010 (Weber). Because there are so few light duty diesel vehicles in the current fleet, the benefits of using GTL-derived fuels are projected to be very small in this category (<5% decreases in criteria pollutants) since the future fleet will consist primarily of modern, low emission vehicles at the start of the study period. Since the GTL process consumes a much larger portion of the feedstock for just the operation of the plant than does a conventional refinery (60% in the model versus about 20% for a refinery), there is a significantly larger CO_2 burden for using GTL compared to that of using petroleum-derived diesel. However, biomass-derived GTL fuels can, in principle, exhibit net zero CO_2 emissions, leading to as much as 75% reductions in CO_2 from the projected fleet.

In addition to potential emissions benefits, the production of GTL fuels offers the promise of energy security associated with using non-conventional, domestically based resources. Such considerations are now fostering the development of large scale GTL plants that might supply a significant fraction of the U.S. fuel demand. Moreover, the GTL process produces its carbon dioxide in fairly rich streams that therefore facilitate CO_2 sequestration or carbon recycling schemes. The value of the energy security afforded by small footprint plants was explicitly considered in the calculations that took into account the cost of alternative sources of energy in remote regions. The possibility of CO_2 sequestration for the small footprint plants was not considered because the confluence of a remote market, an adjacent source of feedstock and an adjacent CO_2 sink seemed improbable.

In a second task of this study these same methods were applied to the feedstocks, conditions and opportunities that pertain in Alaska. Three sizes of plants were investigated: 600 and 6,000 barrels per day, corresponding to feedstock availability for small and medium sized plants, and a 19,000 barrel per day facility, such as might be constructed to use coastal reservoirs of natural gas known to exist in the Kenai Peninsula. Because the study assumed that the small footprint plants to be constructed in remote areas would be mostly prefabricated and would be operated by a small staff, the estimates were only modestly higher for the remote plants for both the capital costs of the plants (2-10%) and the operating costs (1-7%), depending on plant size. The higher price of conventional fuel in Alaska therefore contributed significantly to the economic performance of GTL plants at all size ranges: the economic value, estimated as internal rate of return, could be greater than 100% for natural gas-fueled plants, providing that markets could be found at the higher prices for all of the products (naphtha, GTL fuel and electricity). It is noted, however, that even the smallest sized plant would supply fleets as large as 10,000 light-duty vehicles or 800-900 heavy duty vehicles, which is a larger range than would likely be found in remote communities. Therefore, to realize the full emissions and economic benefits of a small footprint plant will require export of fuel. The analysis indicated that biomass-fueled plants would be much more expensive to construct than natural gas-fueled plants, implying that, even in Alaska, the products from a small footprint GTL plant would require significant subsidies ($3-$5/gallon) to compete with conventional fuel and power.

The picture that emerges is that there are resources and conditions under which a SFP can be operated profitably. In particular, high cost of oil, long distances from conventional sources, and underutilized resources all contribute to the economic viability of the plant. The addition of credits for electricity, steam, water, and, in some instances, criteria pollutants, only serve to improve the economic outlook. However, achieving autonomy and profitability require matching the scale of the SFP to local needs and dealing with all of the side products, including naphtha.

The study identified particular resources to refine the economics for constructing and operating small footprint plants. Interestingly, the conditions favorable to the economic viability of SFPs could prevail in Alaska. However, additional study to refine the parameters for specific resources and markets in Alaska would be necessary to develop specific case-by-case applications.

The well-to-wheels analysis estimating the overall economic and environmental impact of the production and use of SFP-produced fuels suggests that the primary benefits of employing GTL fuels derive from both the energy security they confer and the emissions reductions from older vehicles. Emissions benefits from newer vehicles (post 2010) will require tuning of the engines to extract maximum effect. If for some reason this tuning of the engine control systems is not, or cannot be, done, this benefit of GTL fuels from small footprint plants would have only about a 10-15 year window of opportunity (commissioning of the first plants, assumed to be in 2015, until the pre-2010 vehicles have been retired).

V. MAJOR ISSUES THAT EMERGED DURING THE PROJECT

Several inter-related issues impacting the project emerged during the project, and these issues cannot be covered comprehensively by the Topical Reports, which focus primarily on individual project tasks that were defined at the outset. Therefore, this section describes in detail the project's changes in emphasis and the follow-up investigations that were required in the wake of: fuel-lubricity being less of an issue than originally assumed; discrepancies between different sets of emission tests; unexpected emission and engine-operational results; unexpected trends in the development progress of diesel-engine exhaust-aftertreatment emission-control systems; and the interrelationships of these issues as they affected the overall project.

A. FUEL LUBRICITY CONCERNS WERE PUT TO REST

Diesel engine fuel systems typically rely on the fuel being pumped and injected to lubricate the fuel-wetted parts of the system. Lubrication can be a demanding challenge, because many diesel-engine fuel-system parts operate under conditions of high pressures, stresses, speeds, temperatures, etc. Conventional diesel fuels have significant contents of sulfur and aromatics, which provide natural lubricity, but the F-T fuels produced and evaluated in this project contain virtually no sulfur or aromatics. Therefore, the overriding technical concern with respect to F-T fuel evaluation when this project was being developed was fuel lubricity, and whether or not commercially available lubricity additive treatment technology, developed for ultra-low sulfur and reduced aromatic content conventional diesel fuels, would be adequate for a fuel such as F-T with no sulfur or aromatics.

1. Initial Fuel-Lubricity Evaluation Plan

When the project was proposed in 2000, the original plan was actually to do some of the initial F-T fuel "evaluation" before the CDF was even built, started-up, or capable of producing any F-T fuel. It was assumed back then that it would be feasible to obtain F-T "material" from an existing source, the Shell Bintulu plant in Malaysia. Furthermore, it was assumed that this Bintulu material, which is similar to diesel fuel, but is not a finished fuel capable (neat) of meeting the specified low-temperature flow requirements, would be "close enough" to the expected fuel composition that the CDF would produce for at least one type of accelerated evaluation.

Specifically, it was assumed that one of the dynamometer-based fuel-system durability tests could be run on the Bintulu F-T material. The objective of the test was to evaluate the acceptability of fuel lubricity, which is thought to be controlled almost entirely by the additive treatment applied to a hydrogen-saturated F-T fuel, rather than by small differences in the composition of the base-fuel. This approach of using Bintulu material was considered primarily to allay the potential fears of bus fleet managers that "new and unproven" (at the time) F-T diesel fuel might pose a risk to the fuel systems of their bus engines in planned bus fleet demonstrations of F-T fuel.

However, the managers of both bus fleets already had experience using the lowest-sulfur No. 1 diesel fuels available in their respective areas as a means to reduce bus-engine exhaust emissions. And these fleet managers had, in fact, already experienced initial lubricity problems with the fuel systems of some of their engines. They had repaired these fuel systems, and then verified that the problems were solved permanently by the use of improved lubricity fuel-additive technology in their low-sulfur No. 1 fuels. Therefore, these bus fleet managers were already aware from first-hand experience of the effectiveness of commercial lubricity additives for fuels with low natural lubricity, and they were not particularly concerned about this potential risk to their equipment with F-T fuel.

It was not possible to obtain Shell Bintulu material in the quantity required for a fuel-system durability test at a reasonable cost. Several factors made Bintulu material cost prohibitive, including changes after September 11, 2001 in some of the worldwide distribution patterns of blending components, such as Bintulu material, used to make finished petroleum products in various refineries around the world.

2. Fuel-Lubricity Findings

As described above, Syntroleum S-1 and S-2 diesel fuels with their normal, commercially available lubricity additive treatment, were run in a total of 20-plus diesel engines in this project with no indication of any operational problems related to fuel lubricity. But even though there were no operational issues related to fuel lubricity, the test-plan of dynamometer-based fuel-system durability tests on the bus engines included post-test inspection of all fuel-lubricated fuel-system components specifically to look for any possible lubricity related issues. Accordingly, the tests were begun with "new" fuel-system components (fuel-injectors and pumping elements), which were then removed, disassembled and inspected after 1,500 running hours on each of two engines, a Detroit Diesel Series 50 and a Caterpillar C-7. It was later learned, as will be described, that the "new" DDC fuel-system fuel-injector assemblies, purchased through the DDC Service Parts System, had in fact been re-manufactured.

Of all the fuel-system parts inspected, only one, a spill-valve or poppet-control-valve in one of the four DDC Series 50 injectors from the dynamometer engine, "looked" like it might have (or might not have) had one of its fuel-lubricated surfaces somehow degraded, even though it had functioned normally throughout the engine-dynamometer test. Electron microscope analysis concluded that although one surface of the valve "looked somewhat distressed," the valve was within specifications and indeed would have been re-used and built into a re-manufactured fuel injector in that condition at the re-manufacturing facility. In essence, despite the appearance of the valve, it was ultimately concluded that this was not an indication or insufficient lubricity of F-T fuel, but rather a false alarm attributable to the fact that these valves are reused over and over.

B. UNEXPECTED FUEL-EVALUATION RESULTS

The most interesting fuel-evaluation results obtained in this project were those few that were not expected. Part of the reason is that the vast majority of results from all experiments, measurements, etc., did indeed turn out about as generally expected. With respect to emissions, in every instance F-T fuel significantly reduced diesel particulate emissions compared to conventional fuel. In general, NOx emissions were also reduced, except as described below. With respect to engine operation, commercial fuel lubricity additive technology proved to be fully capable of protecting diesel engine fuel systems using F-T fuels as described above. However, it was determined that diesel fuel-injector nozzle-orifice deposits can form under some conditions, as described below.

The first unexpected result was an apparent increase in NOx emissions with Fischer-Tropsch, clean-diesel fuel, compared to conventional fuel, from one (new) type of diesel engine, the Caterpillar C-7 used in the Denali National Park buses, when operating over one type of transient test cycle. Follow-up investigation lead directly to discovery of the second unexpected result: the injector nozzle holes of this same type of engine can accumulate deposits (that originate from the lubricating oil, not from the clean-diesel fuel), under a different operating cycle, in sufficient amount to partially foul the injector nozzle holes, reducing fuel flow and thus reducing maximum power output of the engine. These phenomena may indeed be related, and may be attributable in part to the engine's operating strategy.

The objective of the sections that follow is first to describe both of the unexpected results, then to provide an overview of the step-by-step course taken by the project partners to understand their validity, meaning, implications, etc.

1. NOx Emissions from Caterpillar C-7 diesel engines in Denali NP Buses

As an initial step in this project, partner West Virginia University measured emissions from a single bus with two fuels, and with either a catalyzed diesel particulate filter (DPX) or a diesel oxidation catalyst (DOC), at the Washington Metro Area Transit Authority. As shown in the following Figures, emission results were consistent with previous experience with F-T clean-diesel fuels: emissions were reduced by using F-T fuel, especially particulate matter (PM) and NOx emissions, even when compared to results for Ultra-Low Sulfur No. 1 Diesel (ULSD1) conventional fuel.

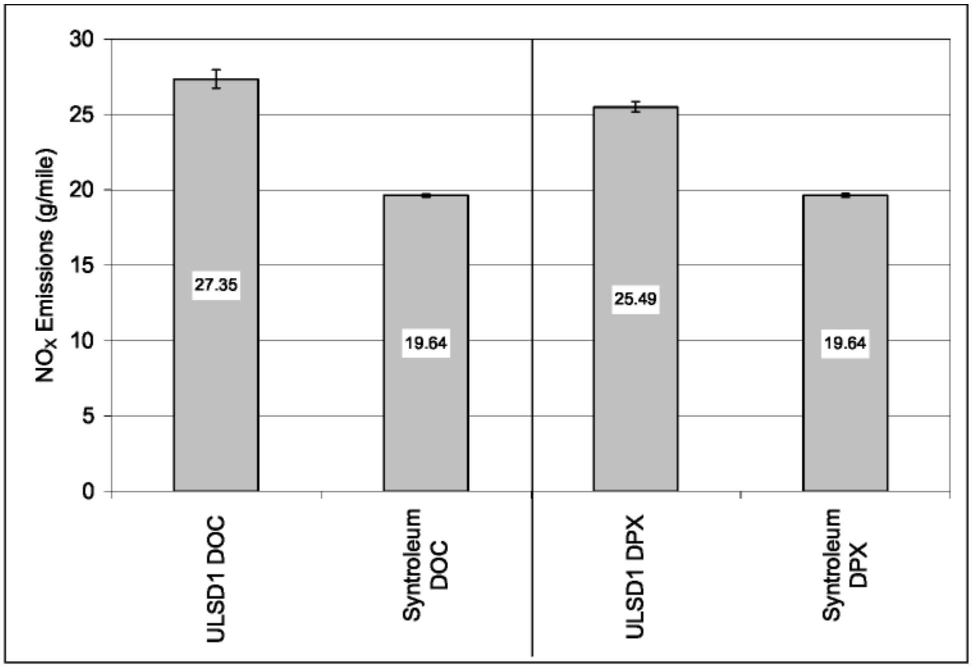


Figure 20: NOx Emission from WMATA Bus Used for Diesel Particulate Filter (DPX) Fuel Evaluation

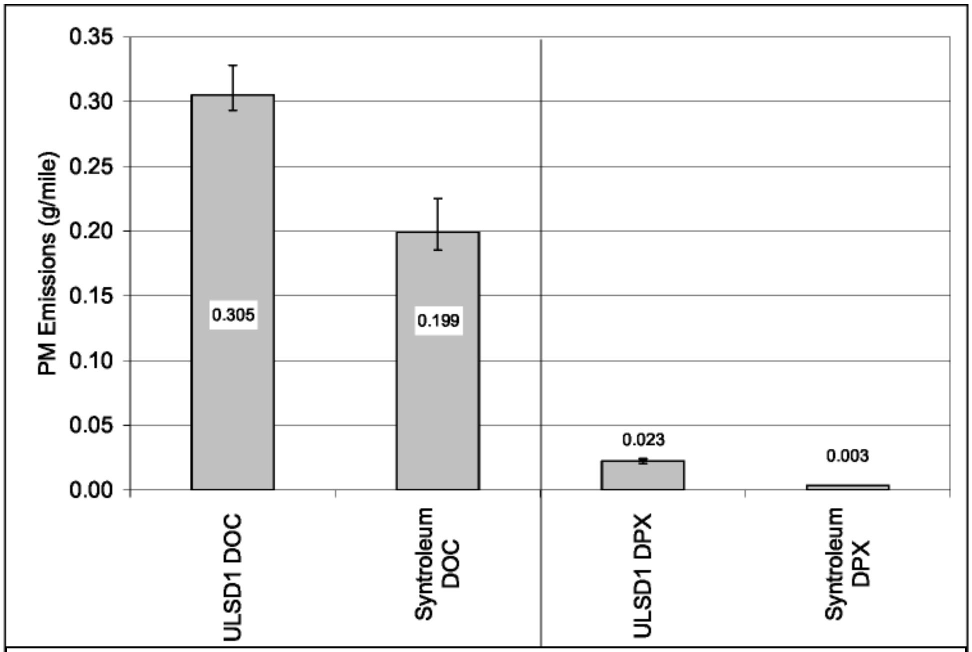


Figure 21: PM Emissions from WMATA Bus Used for DPX Fuel Evaluation

However, there was a surprise in store for the project team when WVU performed the same type of emission testing on the Denali National Park buses. Although particulate emission results for the F-T fuel and conventional fuel (No. 1 diesel fuel in most of Alaska is actually Jet-A fuel) were about as expected, NOx emissions appeared to increase with the F-T clean-diesel fuel, as shown in the following two Figures. (The numbers on the figures represent the bus numbers. The buses running on JET-A are the control buses, and the buses running on SYNTRO are the experimental buses running on F-T.)

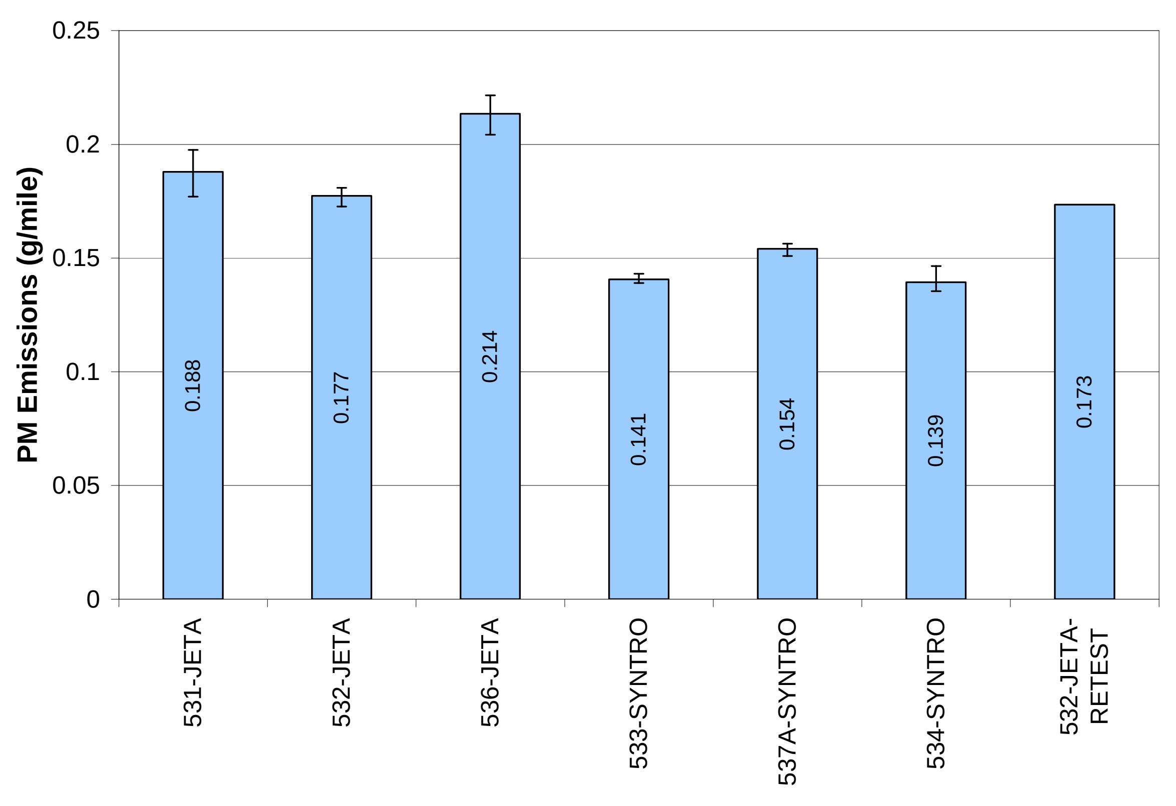


Figure 22: PM Emissions from the Six Denali National Park buses

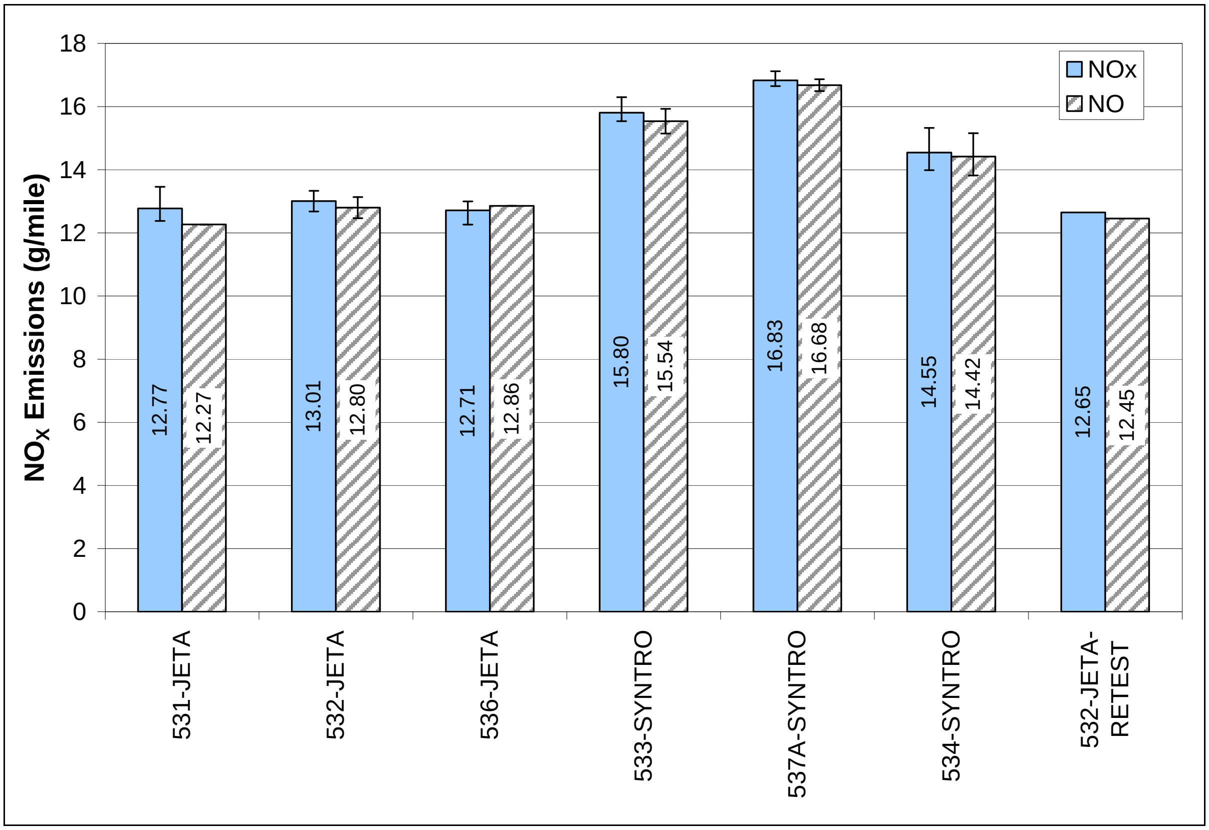


Figure 23: NOx Emissions from the Six Denali National Park buses

The project team began immediately to try to understand the results better. The first step, taken during the on-site testing, was to retest Bus 532 as shown in the Figures to rule out the possibility of major instrument drift, inaccuracy, etc. The other factors that might have influenced the results were also considered by the project team, as will be reviewed here briefly.

Problems with Initial Bus Demonstration Emission Test Plans
While the WMATA fuel-comparison emission results referred to first above had been obtained with one bus, the initial design of the subsequent WMATA and Denali National Park Bus Fleet F-T Fuel Demonstrations included the use of three "control" buses running on conventional fuel, in addition to the three F-T fueled "demonstration" buses. Since F-T fuel was "new and unproven" when the program was designed about seven years ago, "control" buses running on conventional fuel were included as a means to investigate, understand, compare, etc., any potential operational problems that might have occurred with F-T fuel. Emission testing all the buses in both demonstrations on their "assigned fuel" flowed rather naturally from the initial design of the program. However, in hindsight this was a poor choice, because it introduced another variable, the buses themselves, into a program that was really intended to compare fuels and their effects on emissions.

The six Denali buses in the Denali National Park bus fleet that were used for this demonstration program were all brand-new models with new 2004 Caterpillar C-7 engines. The all-new Denali buses and engines undoubtedly contributed to the consistency, from bus to bus, in the emission results obtained on the two fuels at Denali National Park.

By contrast, the six WMATA buses with Detroit Diesel Series 50 engines used in the WMATA bus fleet demonstration, while nominally all the same, had all been in service for almost five years and had each accumulated approximately 200,000 odometer miles before the WMATA demonstration began. During the initial round of emission testing of these six WMATA buses (each on its assigned fuel), emission results, especially hydrocarbons and CO, varied so much from bus to bus that the effect of the fuel on these emissions could not be determined with any certainty. This situation lead to the decision (by ICRC, WVU and WMATA in consultation with NETL Contracting Officer's Representative) to modify the testing approach and conduct the second round of demonstration-bus emission testing at WMATA by comparing emissions obtained with the two fuels in the same three buses. These tests of F-T and conventional fuels "head-to-head" in the same buses demonstrated conclusively that F-T fuel reduces both particulate and NOx emissions from the Detroit Diesel Series 50 engines used in these WMATA buses.

Dynamometer-Lab Follow-up on Increased CAT C-7 Engine NOx Emissions

In an effort to understand the unexpected Denali NOx emission results better, engine dynamometer-based emission testing, using the same fuels as had been run in both bus fleet demonstrations, was added to the fuel-system durability testing program at AVL Powertrain's Ann Arbor Validation Laboratory. Two drums each of the conventional fuels that both the Denali and WMATA fleets use were obtained, from the actual bus-fueling tank at Denali National Park, and from WMATA's fuel supplier, respectively. ICRC also decided to include the more typical ultra-low sulfur No. 1 diesel fuel (ULSD1) used by WMATA in these dynamometer emission measurements since Jet-A fuel, which is the fuel that is regularly used at Denali Park, is somewhat "atypical,". The older-technology DDC Series 50 diesel engine used by WMATA was also run on the same three fuels to provide yet another set of reference data on the effects of fuel properties on NOx emissions. A test sequence consisting of eight steady state modes designed to simulate EPA's transient test cycle for heavy-duty diesel engines was selected for the emission measurements.

The primary focus of this engine dynamometer-based emission measurement program was to compare NOx emission levels from the same new-technology Caterpillar C-7 engine when the only variable was fuel type. The goal was to determine whether or not S-2 fuel caused an inherent increase in NOx emissions from this engine compared to the conventional No. 1 diesel fuel (Jet-A) used at Denali National Park. Since NOx and particulate emissions are known to "trade-off" in some instances, average (over all eight modes) particulate emissions were also measured from the Caterpillar engine.

Interpretation of Emission Measurement Results
The dynamometer emission test results show that S-2 fuel causes a reduction, not an increase, in both NOx and particulate-soot emissions from both engines, and in comparison to both conventional fuels. The results also show high variability in the Caterpillar engine-out NOx and hydrocarbon-CO (HC-CO) emissions from run-to-run on all three fuels at the two lowest-load conditions tested. In low-load runs with NOx emissions very low, corresponding Caterpillar engine-out hydrocarbon and CO emissions are very high, and vice-versa.

This low-load NOx/HC-CO emission behavior is fully consistent with new approaches being taken by several diesel engine manufacturers to achieve low NOx and particulate emissions simultaneously by allowing the engine ECM to sense that the demand for engine power is low, then vary the injection timing and schedule greatly in an attempt to achieve partial premixed combustion, or partial homogeneous-charge compression-ignition (HCCI) combustion, at the appropriate low-load conditions the engine encounters during a driving cycle. The associated increase in engine-out HC and CO emissions can then be controlled relatively easily by exhaust aftertreatment, either by a diesel oxidation catalyst, or even more effectively by the catalyzed diesel exhaust particulate filter, which is required to meet model year 2007 and later requirements for particulate emissions.

The group of engine OEMs pursuing HCCI combustion technology prominently includes Caterpillar, based upon their recent HCCI technical session organization activity and technical presentations within SAE and other forums. Every effort was made to engage Caterpillar engine-emissions technical personnel in discussion and resolution of the NOx emission results and related issues of this project, including “buttonholing” them at technical meetings, follow-up e-mails, phone calls and messages, etc., but Caterpillar has remained resolutely unresponsive.

The very early start of fuel injection events needed to achieve partial HCCI combustion can be disadvantageous for a very high cetane fuel such as S-2 if the engine control system is not somehow made “aware” that a much higher cetane fuel is being used (Wang). The net effect is that very early injection of very high cetane fuel can result in an earlier start of combustion than would occur with a conventional fuel, resulting in an effective “timing advance” and increased NOx emissions (Lepperhoff).

The apparent increase in NOx emissions with high cetane S-2 fuel indicated by WVU’s results at Denali National Park is likely attributable to the combination of relatively low-load conditions within the dynamometer test cycle used, and the new-technology Caterpillar engine attempting to operate with early fuel injection in an HCCI-like mode at the low load conditions.

2. Fuel-Injector Nozzle Fouling

As stated previously, follow-up investigation of the unexpected NOx emission results WVU measured at Denali National Park lead directly to discovery of the second unexpected result: the injector nozzle holes of this same type of engine can accumulate deposits (that originate from the lubricating oil, not from the clean-diesel fuel), under a different operating cycle, in sufficient amount to partially foul the injector nozzle holes, reducing fuel flow and thus reducing maximum power output of the engine.

The entire focus in the design of the fuel-system durability tests was fuel lubricity, and more specifically verifying the ability of commercial lubricity additive technology to prevent damage to bus-engine fuel-system mechanical components that might result from low natural lubricity of the un-additized F-T fuel. Deposits, of any kind, were simply not expected to be an issue with ultra-clean F-T fuel.

Reduced Power Output

Therefore, the ~20% reduced power output of the Caterpillar engine at the end of the fuel system durability test was thought to be some kind of "computer or ECM" problem. This view was reinforced by the fact that during the initial setup and cycle-programming of the brand-new Cat engine, there had been a period of time when the engine would produce only about 80% of its rated power (apparently operating in some type of "limp-in" mode), and this was, indeed, a "computer" problem that Caterpillar-authorized service technicians were eventually able to resolve. The entire initial set-up and programming of the Cat engine to run the CTA cycle was much more difficult and time consuming than had been originally anticipated, because of a fundamental difference in the approach to engine control taken by the DDC and Cat ECMs.)

The original test plan had been to remove the Caterpillar fuel system components, especially the hydraulically activated fuel injector assemblies, for inspection of any distress, wear, malfunction, etc., (expected to be primarily lubricity related, if any occurred), and replace the removed fuel-system components with new ones from the Caterpillar parts supply system so that the engine could be returned to Doyon/Aramark at Denali National Park in ready-to-run condition.

Accordingly, with brand-new new fuel injectors installed after the fuel-system durability test had been completed, the Cat engine was dynamometer-tested again and was now found to be capable of producing its rated power. But even at this point, the assumption was that some kind of "computer, ECM or communication" problem must have existed when the used (1,500 hours) injectors had been in the engine. The new injectors were used for the dynamometer-based emissions measurements on three fuels as described above.

Recognition of the Deposition Issue and Follow-up Investigation

When the used (1,500 hours) injectors were disassembled and thoroughly inspected, it became apparent that two of the six injectors were almost completely fouled with some unknown type of deposit on the outside surface of the nozzle-tips and in the nozzle fuel-spray holes. The fouled nozzles were flow-tested using a low-pressure test rig (2,000 psi vs. ~20,000 psi in the engine) and their flowrates were minimal (dripping). However, much higher injection pressures would have been occurring in the engine, indicating that fuel flow would not have been zero to the two cylinders with these injectors.

In an attempt by dynamometer laboratory personnel to understand the reason for the reduced fuel flow, the two fouled nozzles were subjected to cleaning in an ultra-sonic cleaner using laboratory solvent. When this approach did not increase flowrate significantly, a wire brush was used to remove the deposits from the outside surface of the nozzle tip. Physical removal of most of the deposits did allow the flowrates to return to approximately that of a new nozzle, but provided little information on the composition or source of the deposits. One of the two fouled nozzles was also sectioned through the sac area, which showed that there was no accumulation of deposits within the internal nozzle sac.

After the “damage had been done” to the accumulated nozzle deposits, it was recognized that the nozzle deposits were not merely an annoyance that had been interfering with the dynamometer-based emission measurement test schedule, but could in themselves be a finding of major importance in the overall project. Accordingly, all nozzles from both engines that had been run in fuel-system durability testing were sent to Syntroleum for further analysis at the University of Tulsa using a scanning electron microscope with fully quantitative energy dispersive X-ray analysis.

The deposits were shown to:
1.) Originate from the mineral (ash) elements added to the lubricating oil,
2.) Form on the outside of the nozzles, and
3.) “Creep into” the nozzle fuel-spray orifices.

Figure 24 shows a highly magnified portion of the outer surface of one of the nozzles that was cleaned at the dynamometer laboratory with a wire brush. The scratches from cleaning the nozzle tip surface are visible, and some of the deposit can be seen remaining in the fuel-spray orifice shown (one of six).

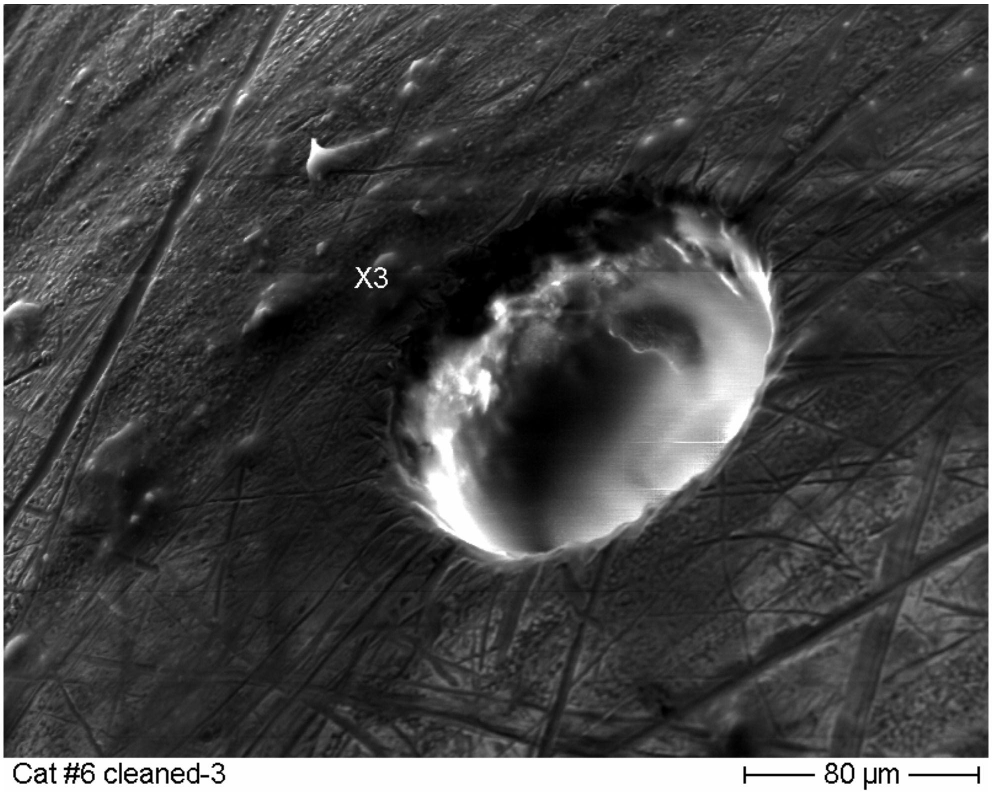


Figure 24: Highly magnified view of a single Caterpillar C-7 nozzle spray orifice or hole (one of six) in the nozzle tip that was previously fouled virtually completely with deposits. Note scratches on the nozzle tip surface from wire-brush cleaning and some deposit remaining inside the nozzle hole's inside diameter

Deposits of identical composition, but in nowhere near as great an amount as on two of the Cat injectors, were also found on the outside of the nozzle tip surface and "creeping-into" the fuel-spray orifices of the Detroit Diesel Series 50 injector nozzles that had been run in the 1,500 hour fuel-system durability test. The DDC nozzle orifices did not have enough deposit formation in the aggregate to cause a noticeable reduction in fuel flowrate or in engine power output. There is the possibility that similar deposits may form in small amounts on some diesel fuel injector nozzles when conventional fuel is being used. However, if deposit accumulations sufficient to reduce engine power output by double-digit percentages (as occurred with the Cat engine) were at all common using today's diesel fuels, this would certainly be common knowledge within the heavy-duty diesel engine industry.

Potential Deposit Formation/Accumulation Mechanisms

As described previously, the fuel injection strategy associated with attempting to achieve HCCI-type combustion, i.e. injecting early and in several discrete events, could have an effect on the type of nozzle deposit formation considered here. And although the deposits do not originate from the fuel, fuel properties may play a role in either the ability of deposits to gain an initial "foot-hold" or in their ability to continue to grow and accumulate, or both.

For example, hydrogen-saturated F-T fuels produce inherently low levels of soot compared to conventional fuels, and the greater amounts of soot particles likely to adhere to combustion chamber surfaces with conventional fuels may impede the initial deposition mechanism. Furthermore, hydrogen-saturated F-T fuel is known to be a poor solvent for polar compounds, and thus hydrogen-saturated F-T fuel may not “wash-away” initial deposits as well as conventional fuels which contain aromatics.

WMATA bus 2056 had a turbocharger failure near the end of the WMATA demonstration. The turbocharger was the subject of a DDC recall and was replaced under warranty. Furthermore, at the time of the turbocharger replacement, one of the fuel injectors was found to have a broken tip, so all four fuel injectors were replaced in the engine of bus 2056. ICRC retrieved all four of the replaced injectors for further analysis. This showed some accumulation of similar deposits, which had originated from the metals in the oil-additive package, in the nozzle-orifices, but in no case enough to severely restrict fuel flow.

Recommended Future Work on the Fuel-Injector Nozzle Fouling Issue

Based upon the foregoing nozzle-orifice deposit findings, Syntroleum has worked with Lubrizol Petroleum Chemicals Co., technology leader of the Fuels and Lubricants Industry and the supplier of the additive package in S-2 (which includes lubricity improvers, among other things), to incorporate commercial fuel-dispersant additive technology into Syntroleum’s future F-T diesel-fuel additive package as well.

Such fuel-dispersancy additive technology was not thought to be needed originally in an ultra-clean F-T fuel which contains virtually no deposit precursors in its own right. However, with the benefit of 20:20 hindsight, inclusion of dispersancy additive technology might now be considered “cheap insurance,” since it is commercially available and relatively inexpensive compared to everything else required to produce F-T fuel. This dispersant technology is expected to eliminate the diesel-injector nozzle fouling issue, and is being evaluated in other F-T fuel demonstration-type projects.

However, this project has identified an engine, the Cat C-7, and a dynamometer cycle, the Chicago Transit Authority Cycle, that together appear to “bring-on” significant levels of fuel-injector nozzle fouling from oil-metals when using S-2 fuel that does not contain dispersant additive treatment. Furthermore, the accumulation of these oil-ash-derived nozzle-orifice deposits can apparently be monitored during testing by comparing, over time, the maximum steady-state power output of the engine, a condition which is an integral part of each CTA cycle.

In evaluating, understanding, and ultimately solving many potential field-problems in the fuels and lubricants industry, finding a controlled, repeatable laboratory procedure that can “produce” the problem is critical to evaluating the effectiveness of potential remedies and solutions, especially if fuel or lubricant additive-technology is likely to be needed as part of the solution. The nozzle-fouling issue is also likely to arise with other future fuels, possibly even with conventional fuels, if they have a very high saturate content without fuel-dispersant additive-technology. Therefore, follow-up testing is recommended, starting with the fuel, engine, oil, and dynamometer-cycle identified in this project to "map-out" the extent of the issue, to determine the relative contributions of the various factors, and to quantify the effectiveness of potential solutions.

C. PROJECT IMPLICATIONS OF DEVELOPMENT PROGRESS IN EMISSION CONTROL SYSTEMS

When the project began in 2001, it was widely expected that exhaust aftertreatment emission control technology for both NOx and particulate emissions would be required for virtually all U.S. on-road heavy-duty diesel engines to meet the 2007 model year emission requirements. It is now clear that this expectation was only half-right, because while particulate filters will be used, NOx aftertreatment will not.

Year	HC	CO	NOx	PM
1998	1.3	15.5	4.0	0.10
2004	0.5	15.5	2.5	0.10
2007	0.14	15.5	1.2	0.01
2010	0.14	15.5	0.2	0.01

Figure 25: U.S. Emission Ceilings, U.S. Heavy Duty Transient Cycle, g/bhp-hr (Hinz)

Year	HC	CO	NOx	PM
2000 (Euro III)	0.66	2.1	5.0	0.10
2005 (Euro IV)	0.46	1.5	3.5	0.02
2008 (Euro V)	0.25	1.5	2.0	0.02

Figure 26: European Emission Ceilings, European Stationary Cycle, g/kWhr (Hinz)

An original goal when this project was being developed was to evaluate the improvements in both the effectiveness and the service-life that would be expected to occur with F-T fuel compared to conventional diesel fuel in diesel exhaust aftertreatment emission control systems, for both particulates and NOx. However, such exhaust aftertreatment systems for NOx are not yet commercially available in the U.S., as will be discussed in detail below.

Catalyzed diesel exhaust particulate filters (DPFs), or catalyzed particulate traps, will indeed be required for new on-road heavy-duty diesels to meet the U.S. model-year 2007 emission limit of 0.01 g/bhp-hr. This limit is a tenfold reduction from the current limit for 2004 and later model-year U.S. vehicles, and a particulate level that is below that of typical gasoline engine exhaust. Furthermore, at this overall emission level, diesel exhaust particulate concentrations are even below that of the ambient air in many instances.

However, the U.S. 2007 particulate limit is reasonably comparable to the 0.02 g/kWhr diesel particulate limit that has been in effect in Europe since the 2005 model year (note that the European limit is expressed in g/kWhr, not in g/bhp-hr, and it is based on a different test cycle). In summary, diesel particulate filters are virtually certain to be a "fact of life" for diesel engines worldwide into the future. Regeneration, or burning off accumulated particulate matter at the appropriate times, is the key to maintaining long-term DPF or particulate trap effectiveness.

As will be described in detail below, NOx emission control will be accomplished for U.S. heavy-duty on-road diesels in the 2007 model year without the use of any NOx-specific exhaust aftertreatment technology.

1. Technical Readiness of Diesel Particulate Aftertreatment Technology

The catalyst "coating" of the ceramic particulate filter material aids regeneration by starting the process at a lower temperature than would otherwise be possible without somehow "forcing" regeneration. The catalyzed particulate trap is also reduces CO and hydrocarbon emissions very effectively as well, but has no significant effect on NOx emissions. Frequent regeneration is desirable to prevent the build-up of too much particulate, which could damage the filter when regeneration did finally occur because too much heat would be released by the combustion of too much accumulated particulate matter.

Even with frequent relatively low-temperature regeneration, the trap's lifetime of high efficiency particulate emission control is usually limited by thermal cycling durability considerations to some (large) total number of regeneration cycles. Furthermore, ash and some sulfur compounds in the exhaust gas, which can originate from both the fuel and the engine oil, tend to accumulate in the particulate filter requiring filter replacement, typically after hundreds of thousands of miles. It may be possible to chemically clean "used" particulate filters so that they can be used again. A fuel such as F-T with virtually no ash or sulfur would be expected to extend the life of the particulate filter with respect to such accumulation.

Reducing engine-out particulate emissions, and the rate at which particulate matter accumulates, and thus the frequency with which the trap needs regeneration, would also be expected to increase the overall effectiveness and lifetime of the catalyzed particulate filter. Lower engine-out particulate emissions is therefore another anticipated long-term benefit of F-T fuel for diesel vehicles equipped with catalyzed particulate filters. Study of this effect was one of the original objectives included within the WMATA bus fleet demonstration of F-T fuel.

2. Evaluation of F-T Fuel & Exhaust Aftertreatment Technology in this Project

WMATA bus with retrofitted diesel particulate filter

Attempts to retrofit catalyzed particulate filter technology to engines already in the field have demonstrated that while the overall DPF technology is quite robust, it absolutely must be fully integrated into the engine control system to "force" regeneration when necessary and thus avoid plugging or related problems that can otherwise occur under some service conditions. Such problems have been observed in several retrofitted buses at WMATA, to the extent that WMATA has greatly scaled back their original objective of retrofitting catalyzed particulate filters to approximately half of their current diesel buses.

Thus, despite WMATA's originally stated intention to retrofit the test buses in this program with particulate filters, the project partners decided against it as the F-T fuel demonstration program was about to begin. One reason for this decision, in addition to the potential operational problems from filter plugging, was to be able to accurately measure the emission impact of the F-T fuel on particulate emissions rather than having the particulate filter obscure the fuel effect. Although the field retrofit of particulate traps was originally endorsed by Detroit Diesel Corp., there have been significant challenges with field retrofits and DDC no longer recommends or supports such retrofits.

In view of the decision not to retrofit the test buses with particulate filters, ICRC and partners WMATA and West Virginia University decided that to meet the objectives of the overall program, some data on the effect of the catalyzed diesel particulate filter (DPF) on emissions with both F-T and conventional fuels should be obtained. Therefore, a direct emission comparison test was conducted on a single WMATA bus, equipped alternately with its "stock" diesel oxidation catalyst (DOC) or with the retrofit DPF, using both F-T and conventional fuels. This additional testing was accommodated within the existing project budget, motivated in part by the previously discussed less-than-ideal original emission test plan that did not initially include back-to-back testing of the same buses on both fuels.

Dynamometer Emissions Measurements

A diesel oxidation catalyst was included in the dynamometer test-cell set-up of the Caterpillar C-7 engine at AVL, and gaseous emissions were measured both before and after the DOC in the follow-up to the NOx emission results at Denali. The results show that, as expected, the DOC has little effect on NOx emissions, but the DOC was included in the dynamometer test-cell set-up for consistency, because identical DOCs had been installed on all the Denali buses. The results also show that the relative effectiveness of the DOC in reducing CO and hydrocarbon emissions under some low-load conditions is greater when using F-T fuel than conventional fuels.

Particulate Trap Loading Studies

MIT's role in the project included both studies of F-T/conventional fuel-blends, and a comparative evaluation of F-T and conventional fuels in terms of their effects on particulate trap loading rate under dynamometer laboratory conditions. Figure 27 shows the relative rates of particulate matter accumulation with 400-ppm sulfur conventional diesel fuel and F-T diesel fuel. These trap-loading studies showed that reduced engine-out particulate emissions with hydrogen-saturated F-T fuel do indeed translate into extended operating time before the particulate trap needs regeneration.

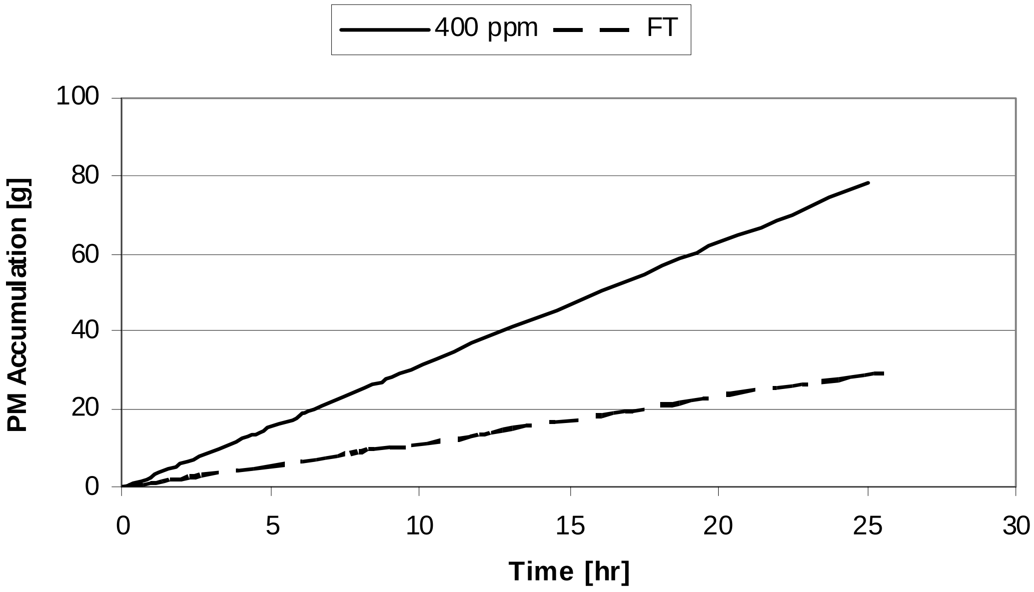


Figure 27: Conventional Diesel v. F-T PM Accumulation.

DaimlerChrysler and Volkswagen Prototype Diesel Engine Evaluations

When the overall F-T fuels program was developed and proposed by ICRC and its partners, and was subsequently approved by NETL, both DaimlerChrysler (DC) and Volkswagen (VW) had expressed their willingness to participate by evaluating F-T fuel in prototype diesel engines and their exhaust-aftertreatment emission control systems, in comparison to ultra-low sulfur diesel fuels made from conventional crude oil. Around that time in 2000, and even into late 2001, the 2007 model year seemed to be "a long way off," and there was at least an "academic interest" in these organizations in the effects that ultra-clean F-T fuel would have both on immediate engine-out emissions, and on the long-term effectiveness and durability of whatever exhaust aftertreatment emission control systems might be needed in the near future.

However, as the deadline for compliance with the 2007 model year emission requirements approached rapidly, the entire diesel-engine and emission-control-supplier industries became focused on demonstrating that 2007 diesel engines and vehicles would meet their emission requirements while maintaining all the other attributes that the customer demands. Since the emission standards must be met using conventional 15-ppm-maximum-sulfur EPA certification diesel fuel that is intended to be representative of the fuel that will be "out there" in late 2006, the industry had no incentive to divert already over-committed test and validation resources to evaluating the effects of a lower-emission fuel that will not be "out there," and which cannot be used for engine/vehicle emission compliance certification. Therefore, when F-T fuel from this program became available for evaluation in 2004, both DaimlerChrysler (which also owns Detroit Diesel Corporation) and Volkswagen declined to participate in the program.

Overtures to Potential "DC- & VW-Replacements"

In attempting to meet the original objectives of the program, ICRC and its project partners approached engineering management contacts at the following diesel-engine and exhaust-aftertreatment emission control system manufacturers, and the U.S. EPA, to determine if they would be interested in participating in the program in the roles originally identified for DC and VW.

Engine/Vehicle Manufacturers:
Caterpillar
Cummins
Ford (uses International diesel engines)
General Motors (uses Isuzu diesel engines)

Emission Control System Manufacturers:
Engelhard
Johnson-Matthey

Federal Agency:
U.S. Environmental Protection Agency, Ann Arbor, Michigan

Ultimately, all of the foregoing potential replacements declined to participate or did not respond to invitations to participate. In addition to the issue of over-committed test and validation resources cited previously, several of the potential replacement companies stated that they believed there are other sources (besides this program) of F-T fuels that they could use for internal research and development purposes without the need to make public any of the data obtained with those other F-T fuels.

3. Long-Term Outlook for Diesel Particulate Filter Technology

As stated above, the U.S. and Europe will have comparable (and extremely low) particulate emission limits requiring particulate filters for on-road diesel engines into the future. Similar on-road diesel particulate emission limits, and corresponding requirements for ULSD fuels, will undoubtedly be adopted worldwide, and will eventually be applied to diesel engines in virtually all other applications as well, thus requiring commonplace usage of diesel particulate filter systems with virtually all non-military diesel engines in the decades ahead.

DPF technology is expected to reduce diesel particulate emissions so effectively, to levels near those of the ambient air, that it is difficult to imagine that lower still particulate emission limits could even be enforceable, since the diesel particulate concentration levels at hand are already at the threshold of being nearly un-measurable compared to the ambient air. As increasing quantities of Fischer-Tropsch fuels are added to the global fuel supply in the decades ahead, they will contribute both to expanding the supply of ultra-low-sulfur diesel fuel, and to extending the service life of diesel particulate filters.

4. Technical Readiness of Diesel NOx Aftertreatment Technology

Unfortunately, the long-term prognosis for future diesel NOx emission requirements, and for the technologies required to meet these NOx limits, is far from being anywhere near as "settled" as the situation appears to be for future diesel particulate emissions. As stated by project partner MIT, "NOx aftertreatment technology has yet to reach the level of maturity and widespread acceptance of diesel particulate traps (Wong)."

According to the announcements made by the major diesel engine manufacturers at technical meetings in 2005, 2006, and early 2007, no major heavy-duty diesel engine manufacturer will be using diesel exhaust aftertreatment technology for U.S. on-road NOx emission control in model year 2007 to meet the 1.2 g/bhp-hr NOx emission limit. However, virtually all these same engine manufacturers have stated that diesel exhaust NOx aftertreatment technology will be required to meet EPA's 2010 model year emission requirements, which call for an additional six-fold reduction in diesel NOx emissions to 0.2 g/bhp-hr.

If NOx aftertreatment technology had been applied in U.S. 2007 model vehicles, it would be "out there" now in the hands of actual U.S. customers. However, since the need for U.S. introduction of NOx aftertreatment emission control technology is still a few years away, competitive considerations make both engine manufacturers and suppliers of emission control systems reluctant to divulge substantive information about their technologies before it is absolutely necessary.

5. Diesel NOx Emission Limits, and Implications for Fuel Consumption

The U.S. 2007 diesel NOx emission limit, at 1.2 g/bhp-hr, is reasonably comparable to the European limit for the 2008 model year (and presumably "thereafter"), which is 2.0 g/kWhr (different units, procedures, etc.). However, the U.S. diesel NOx emission limit for model year 2010 at 0.2 g/bhp-hr is so severe that it is truly in uncharted territory. In fact, such drastic reductions in NOx from heavy-duty diesels might actually be counterproductive to air quality in some urban areas in terms of photochemical smog (California Air Resource Board). In any event, there is no proven technology today that has been accepted by EPA and that can meet the U.S. 2010 heavy-duty diesel NOx emission limit.

Even the U.S. 2007 NOx limit is an extreme challenge, and meeting it has not yet actually been demonstrated within all the other constraints that apply to the heavy-duty diesel-engine and vehicle industries, prominently including customer acceptance and willingness to buy the new engines. For example, these industries are already asking their customers to accept the "new" diesel particulate filter in 2007. Although the DPF has proven to be robust when it is "designed into" the vehicle, engine and control system (as opposed to a retrofit), customers are justifiably wary of buying complicated new technology.

In fact, at the previous transitions between "old" and "new," more restrictive diesel engine emission limits, customers have pre-bought engines with the "old" technology to the maximum extent possible up to the deadline, and then waited as long as possible thereafter (measured in years) before ordering engines with the "new" emission control technology. These "boom and bust" cycles of production and sales have taken a heavy toll on the operations of the heavy-duty engine manufacturers. They have attempted to avoid these cycles by reassuring customers about the reliability, durability and user-friendliness of new technology by getting it into the customers' hands, on a free-trial basis, well in advance of the deadline, which has been accomplished to some extent for the DPF. Furthermore, the DPF's effectiveness in eliminating visible smoke and odor has almost certainly helped to "sell it" to customers.

It is very likely that most of the non-aftertreatment approaches (cooled EGR, timing retard, even HCCI, etc.,) taken by the diesel engine manufacturers to meeting the 2007 NOx emission limit will tend to impact fuel consumption adversely. However, the amount of the overall fuel consumption impact may be difficult to determine and compare among engine manufacturers, because the manufacturers, as a competitive issue, are also likely to do everything (else) that is economically feasible and physically possible to the vehicle and engine to regain as much as possible of the loss in fuel economy that would otherwise be attributed to NOx emission control.

No engine manufacturer will want to be burdened with the label of having "lost" the most fuel economy as a result of meeting the new NOx emission requirements. The "avoided cost" of a NOx aftertreatment emission control system is a counterbalancing factor for the additional costs of other approaches taken to enhance fuel economy.

6. Diesel NOx Aftertreatment Technology

But in 2010, if the currently planned U.S. diesel NOx emission limit of 0.2 g/bhp-hr remains in force (and if it can be met at all), it will almost certainly no longer be possible to avoid exhaust aftertreatment technology for diesel NOx emission control. There are three primary diesel exhaust NOx aftertreatment technologies currently in use (Selective Catalytic Reduction or SCR is being used commercially in Europe) or under development (Lean NOx Catalyst LNC and Lean NOx Trap LNT), and all three could benefit to at least some extent from the properties of the F-T fuels evaluated in this program, compared to conventional ULSD, which is the minimum fuel quality required for all three technologies.

The most fully developed on-road diesel NOx exhaust aftertreatment technology is Selective Catalytic Reduction (SCR), which has been used commercially in Europe for over a year. As normally configured, SCR requires the continuous use of urea, which must be carried as an on-vehicle source of ammonia, which is used in the SCR system to reduce exhaust NOx to nitrogen and water.

SCR's primary advantages are that it is generally quite reliable and effective for NOx reduction, with efficiency as high as 80%; and in a closely controlled U.S. field test on engines without EGR, under the direct supervision of the engine manufacturer and component suppliers, an SCR/DPF emission control system demonstrated compliance with U.S. 2007 diesel emission limits for both NOx and particulates, with no significant increase in fuel consumption from that of same trucks without the SCR/DPF emission control system (Hinz). Therefore, the only increase in operating cost for meeting U.S. 2007 NOx (and particulate) emission control requirements with this system would be the cost of the urea.

However, despite such impressive results, and despite SCR's relatively widespread commercial use in Europe for about the past year, SCR will not be used in the U.S. meet 2007 diesel emission requirements. One of the primary reasons, in addition to likely U.S. customer skepticism of any new complicated emission control system, is that EPA has indicated that they do not favor, and may ultimately not approve for U.S. certification, a technology that would be rendered ineffective for NOx emission control if the operator of the vehicle neglected to maintain the on-board supply of urea.

The total amount of urea needed over the normal engine-oil-drain interval could possibly be carried on-board the vehicle, thus freeing the operator from the need to monitor and maintain the urea supply. However, at the current stage of SCR development, for an engine emitting 4 to 5 g/bhp-hr NOx, with SCR reducing the tailpipe NOx emission level to ~1 g/bhp-hr, the size of urea container needed would be on the order of 100 gallons for a 15,000 mile oil-drain interval, thus reducing truck payload (Hinz).

However, if SCR were to be applied to a future diesel engine with NOx already controlled to a level of only ~1.2 g/bhp-hr engine-out (i.e. the engine-out NOx level anticipated for model-year 2007 U.S. heavy-duty diesel vehicles) the additional reduction of NOx to ~ 0.2 g/bhp-hr (the 2010 limit) by means of SCR might be accomplished with significantly less urea. This assumes that the SCR system would work as well and as efficiently at a lower engine-out NOx emission level, and that the EPA will ultimately accept SCR in time for 2010 model year application.

The primary challenge in controlling a diesel exhaust SCR NOx emission control system is to feed urea to the system at a rate proportional to the instantaneous amount of NOx being produced by the engine. Too little urea leaves NOx unreacted, and too much urea wastes an energy-intensive product (urea) and causes emissions of ammonia. Urea would normally be carried on-board the vehicle in a water solution, which can freeze at temperatures below -11^{o}C. Furthermore, the urea in solution must be hydrolyzed to release ammonia to be effective, and hydrolysis does not occur if temperatures in the exhaust system are below about 200^{o}C. (Hinz)

Urea is a product of the fertilizer industry which has traditionally been made from natural gas. However, the recent steep U.S. price increases for natural gas have put the U.S. fertilizer industry at a significant competitive disadvantage compared to foreign fertilizer producers in those areas of the world which have relatively cheap stranded gas. Fertilizer, like petroleum, is an energy-intensive product which is vital to the U.S. economy, and the U.S. is becoming increasingly dependent on imports of both.

7. NOx Aftertreatment Technologies Under Development

Ammonia from urea is the ideal reductant for NOx emission control in the SCR system, but two other diesel exhaust aftertreatment technologies for NOx emission control that are currently under development offer the promise of using fuel as the reductant instead. Fischer-Tropsch fuels of the type evaluated in this program are likely to provide significant advantages when used in conjunction with these developing technologies compared to conventional ULSD.

The Lean NOx Catalyst (LNC) system under development could be considered selective catalytic reduction by hydrocarbons, rather than by urea/ammonia. The system would operate lean overall, but some additional amount of fuel, analogous to urea/ammonia in SCR, would be added to the LNC to supply the reductant to reduce NOx. The added fuel would ideally be "reformed" to some extent by the catalyst, thus providing more effective reductants than the fuel itself. The LNC system is not likely to be as efficient as SCR with urea/ammonia, and it will need additional catalyst and control system development before it can be used commercially.

The Lean NOx Trap (LNT) or NOx adsorber catalyst (NAC) system under development stores NOx in active sites in the catalyst, then uses a pulse of additional fuel to periodically produce rich (reducing) conditions within the catalyst volume, thus desorbing and reducing the stored NOx, a process referred to as regeneration, somewhat analogous to burning off accumulated particulate matter in the DPF.

A major limitation of the LNT or NAC is that any sulfur oxides in the exhaust will occupy the active sites in the catalyst that are intended to store NOx, thus reducing its ability to adsorb NOx over time. The catalyst must therefore be desulfurized periodically, but much less often if the fuel sulfur level is close to zero. The sulfur can be driven off from the catalyst by burning additional fuel to raise the catalyst temperature to the required high but narrow temperature range for several minutes (Tatur et al).

However, the desulfurization process must be controlled accurately, which may be difficult depending on the potentially highly variable vehicle operating conditions, which are not usually predictable in advance. Furthermore, the thermal and chemical effects that both the regeneration and desulfurization processes of the LNT or NAC may have on the DPF must also be considered and accommodated in developing and implementing an appropriate control strategy, since the DPF may be positioned downstream.

D. PROJECT HELPS ADVANCE DEPARTMENT OF DEFENSE INTEREST IN F-T FUELS

The Department of Defense's Assured Fuels Initiative is intended to bring together the military and commercial industry to produce clean fuels from domestic resources, with the goal of eventually running the entire U.S. military on U.S.-produced F-T fuel.

Although currently shut-down and mothballed, the Syntroleum CDF built as part of this project is the only facility of its kind in the U.S. that has the capability of producing the ultra-clean S-8 F-T version of JP-8 jet aircraft fuel that meets all aircraft low-temperature flow requirements. As such, one of the deliverables for this project was to provide the DOD with 10,000 gallons of S-8 fuel produced at the CDF to be used for testing as part of the DOD Assured Fuels Initiative. The results obtained are not a formal part of this project, but it bears mentioning that the fuel, which was the first significant quantity of military F-T fuel available to the DOD, has been run successfully in laboratory, ground-vehicle and aircraft evaluations. The Air Force was so pleased with the initial 10,000 gallons of F-T fuel provided under this project that it ordered an additional 100,000 gallons of the fuel from Syntroleum, outside of this project

Since F-T fuels can be produced from several U.S. domestic energy resources, they offer the U.S. military the long-term promise of improved energy security. This is especially important considering that imported petroleum and imported petroleum products already make up 70% of U.S. consumption of the primary transportation fuels; middle distillates (mostly diesel and jet fuels), as well as gasoline. Accordingly, the Office of the Secretary of Defense has undertaken the Defense Assured Fuels Initiative.

E. OVERALL CONCLUSIONS AND LESSONS LEARNED

1. Technical and Economic Feasibility of SFPs

This project includes two studies, the well-to-wheels economic analysis and the rural Alaska feasibility study, of the possible "way-forward" for building small-scale F-T fuels plants that could utilize U.S. domestic resources to produce ultra-clean transportation fuels and thus contribute to reducing U.S. petroleum imports. There are some common themes in the findings of the two reports. First, with today's F-T technology and in the absence of unusual benefits such as government subsidies, technological breakthroughs, etc., very small F-T plants of only a few hundred barrels per day (bpd) output of F-T diesel fuel almost certainly cannot compete economically with diesel fuel from petroleum. This is true even in rural Alaska, which has very high and increasing costs for diesel fuel, and even when the small F-T plant would be based upon natural gas, which is by far the "cheapest" and "easiest" resource from which to make F-T fuel, since no oxygen plant would be required.

Small-Scale F-T Plants

A plant capable of producing a few hundred bpd of F-T diesel fuel, plus some by-product electricity, could be about the right size to meet virtually all of the energy needs of a relatively large Alaskan village, provided that the village had access to relatively cheap natural gas, and that it could also "export" some of the excess diesel fuel that would be produced to other villages. Movement of diesel fuel along rivers is the common way Alaskan villages currently get the fuel they need for electricity generation and for several other energy needs.

The economic analysis proposes development of a new compact F-T technology called GTL-in-a-Can^{TM}, which is somewhat speculative and remains to be demonstrated, but that offers the promise of someday building portable and deployable F-T plant-modules that could ideally be set up relatively quickly to produce a few hundred bpd of F-T fuel from locally available natural gas. While development of this technology would be expensive, it could provide the U.S. military with the capability of making significant amounts of military fuel from local natural gas in a war zone. If this technology were developed and made "mass-producible" by and for the U.S. military, it might then also be effectively applied in rural Alaska.

F-T Plants with Greater Production Capacity
The next size-range of F-T fuel production capacity considered by both reports is on the order of 6,000 bpd. As indicated by Figure 27 below, if a sufficiently large stranded gas resource at a low enough cost/price (~$1/Million Btu) could be found to support an F-T plant of this size, its products could certainly be economically competitive with diesel fuel from petroleum. However, such large but low-cost gas resources are likely to be rare anywhere in the U.S., including in Alaska. The challenge will be to build an initial approximately 6,000 bpd F-T plant that can operate on biomass or coal, and thus demonstrate the technology in a lower-risk setting before building huge commercial plants with yet another order of magnitude increase in F-T fuel production capacity.

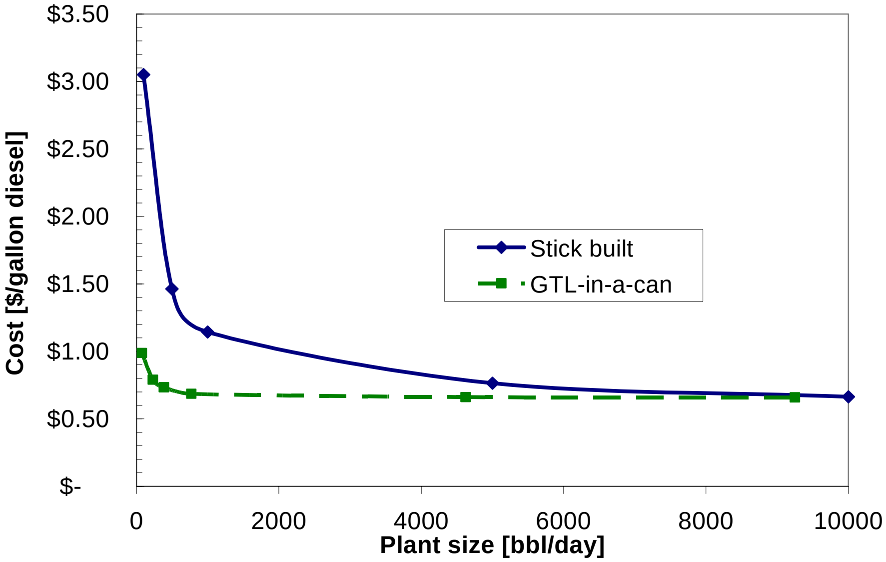


Figure 28: Comparison between GTL-in-a-can™ and stick built plants on the cost of producing one gallon of F-T diesel

Here again, there is a specific military need, driven by national security considerations rather than by economics alone, that can help develop the technology for broader application. A plant of approximately 6,000 bpd capacity that can produce F-T jet-aircraft fuel (as well as diesel fuel) will be needed soon by the U.S. military to support military-aircraft flight-certification under the DOD Assured Fuels Initiative, if this indeed to be an initiative based upon U.S. domestic resources. And while some private (i.e. with no government support or involvement) coal-based F-T fuel production plants may be built in the U.S., they will almost certainly produce only diesel fuel, for which there is a large and rapidly growing market, but not F-T jet-fuel, which costs somewhat more to produce, and for which there will be no large-scale market until after the flight certification process has been completed.

The challenge for the "pioneer" plant that produces approximately 6,000 bpd of F-T jet fuel for military-aircraft flight-certification, will be to remain competitive in the long run, since it is likely to be "too small" in comparison to the large U.S. domestic coal-based F-T plants that should be coming on line over the next few decades. And here again, Alaska is the ideal location for such a pioneer plant, both to meet the immediate military need for F-T jet fuel effectively, and to remain competitive in the long run, since Alaska's conventional petroleum product prices are so high, and rising. Two specific Alaska locations, Healy and Beluga respectively, are most appropriate for such a pioneer plant.

2. Lessons Learned from the Project

Despite the additional effort that went into investigating unexpected NOx emission results at Denali National Park and the engine problems of WMATA bus 2056, which have already been discussed, the overall bus fleet demonstrations were remarkably uneventful. The managerial staffs of both bus fleets were extremely pleased with using F-T fuel in their buses and with their experience participating in the demonstration program, and both expressed their willingness to continue their respective demonstrations if more F-T fuel could be made available.

As described previously, the Cat C-7 engine run in the dynamometer-based fuel-system durability test had exhibited some fuel-injector nozzle-orifice fouling originating from engine oil-ash metals over the 1,500-hour duration of running the Chicago Transit Authority Cycle. The project team informed the manager of the Doyon/Aramark Denali buses about this issue when it was recognized, and asked him specifically if there had been any indication of reduced power output or any other similar problems with any of the buses using C-7 engines that had run on F-T fuel, either during the demonstration the previous summer, or in the interim since all buses and engines had been switched back to conventional fuel. His reply was that there had been no such problems, and he reiterated his offer to continue the F-T fuel demonstration if more F-T fuel could be provided to his fleet.

Additional lessons-learned from this project are:

- F-T diesel fuel can be blended with conventional diesel fuels and thus provide a more than proportional benefit in diesel emission reduction without raising any concerns about equipment durability, unanticipated emissions effects, etc.

- F-T diesel fuel can also be used neat as a means to obtain even greater diesel emission reductions, especially with legacy diesel engine designs, without raising any equipment or emissions concerns. However, for new-design diesel engines with highly sophisticated engine control systems, the effects that F-T fuel's greatly increased cetane number (compared to conventional diesel fuel) may ultimately have on NOx emissions should be determined in consultation with the engine manufacturer.

- Just as this project has demonstrated that commercial lubricity additive technology (developed for conventional fuels) prevents lubricity problems with F-T diesel fuels, the incorporation of commercial fuel-dispersant additive-technology is likely to eliminate any diesel-injector oil-ash nozzle-fouling concerns associated with using aromatic-free F-T fuel neat, even in engines that seem to be more prone to this phenomenon. However, it is recommended that further dynamometer-lab investigation be undertaken (as described previously), with one of the goals being to demonstrate the effectiveness of commercial fuel-dispersant additive-technology in F-T diesel fuels for eliminating fuel-injector nozzle-orifice fouling originating from oil-ash metals.

3. Concluding Comments

The intention of this project was to showcase a clean fuel that can be produced from domestic resources. But despite recent price increases, petroleum is apparently still a cheaper source of transportation fuels than the alternatives, including F-T fuels. And until a cheaper alternative is found, the U.S. and most of the rest of the rest of the world will remain dependent upon petroleum to fuel transportation. As illustrated by the successful technical evaluations described above, F-T fuels are excellent alternatives to petroleum-derived transportation fuels with respect to compatibility with engines, reduced emissions, and exhaust aftertreatment technologies. But as the project's economic analyses reveal, widespread production and use of F-T fuel remains largely out of reach, as the high capital costs associated with building F-T fuel production capacity in the U.S. will be difficult to obtain from private capital sources, since many competing investment opportunities currently appear to offer greater financial return with lower risk.

At some point in the future, global petroleum prices are likely to rise to a sustained level at which F-T fuels from U.S. domestic energy resources will be economically viable without any sort of subsidy. However, the problem for the U.S. is likely to be that the transition to even more expensive petroleum will be very painful for many citizens, and will have severely undesirable effects on the overall U.S. economy as well, if it is simply allowed to occur without any mitigation. By continuing to find a way-forward toward building some capacity to produce F-T transportation fuels from U.S. domestic energy resources in the interim, the U.S. can prepare, both by gaining expertise in F-T technology, and at the same time, helping to establish long-term price limits for imported petroleum and petroleum products.

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VII. APPENDICES

Appendix A: Project Team Contact Information

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Appendix B. Project Deliverables

Task	Deliverable	Location/Report Title	Comments/Description
1	Project Management Plan		Approved on March 25, 2002
2.1	Summary of Plant Improvements	*Syntroleum Small Footprint Plant Study*	
	SFP Process Description	*Syntroleum Small Footprint Plant Study*	
	SFP Construction Costs	*Syntroleum Small Footprint Plant Study*	
	SFP Operation Costs	*Syntroleum Small Footprint Plant Study*	
2.2	Construction and Environmental Permits	*Required Construction and Environmental Permits*	
	Itemized Project Plant Costs	*Cost Breakdown of Building and Operating Plant*	
2.3	Chemical Analysis	*Syntroleum Small Footprint Plant Study*	
2.4	Fuel Production Schedule and Distribution Plan	*Fuel Production Schedule and Delivery Plan*	
3.1	Procurement and Analysis of Similar Fuel		Similar F-T fuel not available for early testing of fuel-system durability before SFP operation. See p. 50-51 of Final Report.
3.2	WMATA Bus Engine Fuel-System Dynamometer Durability Test Report	*AVL Report on Bus-Engine Fuel-System Durability and Emissions*	
3.3	Denali Bus Engine Fuel-System Dynamometer Durability Test Report	*AVL Report on Bus-Engine Fuel-System Durability and Emissions*	
3.4	Fleet Tests Report	*Fleet Demonstration of Ultra-Clean F-T Fuel*	
3.5	Exhaust Emissions Analyses	*Report on Exhaust Emissions Analyses*	
4	SFP Fuel and Advanced Prototype Diesel Engine Emission Systems Report		Particulate Systems evaluated; NOx systems not available. DaimlerChrysler & VW dropped-out. See p. 65-66 of Final Report.
5	Report on Impact of SFP Fuel on Engine Performance	*Ultra-Clean Fuels: Fuel, Blending, and Aftertreatment System Impact on GTL Combustion and Emissions in an Advanced DI Engine*	
6	Economic Analysis	*Supporting Economic Analysis for U.S. DOE-Sponsored ICRC Clean Fuels Program*	
7.1	Additional Dynamometer Durability Tests		Task was subject to funding that was not received—see Final Report Appendix C, Statement of Project Objectives, Task 7.
7.2	Follow-Up Emissions Testing at Denali		Task not funded. Final Report and *AVL Report on Engine Dynamometer Durability and Emissions Tests* describe follow-up emission testing in the wake of Denali results.
7.3	Report on Fuel Cell Testing		Task not funded. UAF performed related fuel-cell testing of F-T fuel in Task 9.2. See *Report on Reformer/Fuel-Cell Evaluation of F-T Fuel*.
8.1	Feasibility Study of SFPs for Rural Alaska	*F-T Small Footprint Plant Economic Feasibility for Rural Alaska*	
8.2	Cold-Start Test Results	*Comparison of Diesel-Engine Cold-Starting*	

		on Syntroleum S-2 and Conventional Diesel Fuels in a Refrigerated Test Cell	
8.2	Cold-Weather Demonstration Report	*Fleet Demonstration of Ultra-Clean F-T Fuel*	
9.1	Report on Use of SFP in Advanced Stationary Power Plants Suitable for Alaska	*Long Term Testing of Syntroleum Synthetic Fuels in a Stationary Generator Set*	
9.2	Testing SFP Fuels in Alaska Fuel Cell Applications	*Report on Reformer/Fuel-Cell Evaluation of F-T Fuel*	

Appendix C: Statement of Project Objectives

This document was taken directly from ICRC's cooperative agreement with the Department of Energy, DE-FC26-01NT41099.

STATEMENT OF PROJECT OBJECTIVES

Background

Solicitation for Ultra-Clean Transportation Fuels stated that DOE was seeking cost-shared applications for research and development in three areas. One of those areas was: "The Production of Ultra-Clean Transport Fuels from Fossil Resources, and the Validation of their Performance by Testing in Engines."

ICRC, Syntroleum and their team partners met the criteria of the solicitation by proposing to:

Complete detail mechanical design, build and operate a modular, small-footprint plant (SFP) to convert natural gas, via Fischer-Tropsch (F-T) and hydro-processing reactions, into hydrogen-saturated diesel fuel. Outside the work program, as defined in the SOPO, Syntroleum will complete the process design for the SFP, and make the process design available to the project at no cost to the project.

Test the:

-- SFP diesel fuel in a variety of engines and vehicles to ensure that use of the product will result in acceptable compatibility with fuel injection system components and improved emissions.

-- SFP diesel fuel in prototype engines to demonstrate compatibility with next-generation exhaust after treatment emission control systems, especially NOx as well as particulate reduction measures.

The final stage of the project is to perform an economic analysis on the data obtained from the project to predict commercial viability of the fuel and SFP process.

Overview

The SFP will be based on synthesis gas production and F-T technology already demonstrated at the Syntroleum Cherry Point plant, and on product upgrading technology demonstrated by Syntroleum in various pilot plant facilities. The proposed plant will produce 70 BPD of fuel, about 54 BPD of Syntroleum diesel and 14 BPD of synthetic naphtha. This technology uses air rather than oxygen in the process, and thus avoids the high cost and added complexity of an oxygen production plant. The SFP will be based on this plant with the following improvements:

The SFP will be modular.

>20% improvement in carbon efficiency from earlier designs.

Reduction in the per/barrel plant capital cost.

Because the SFP will be designed and built to be modular and mobile, it can:
Be moved and easily modified to take advantage of diverse feedstocks
.
Take advantage of future environmental economic incentives by:

- Reducing vented natural gas by using it as a feedstock, and
  Reducing CO2 emissions by simultaneously sequestering the CO2 and using it for CO2 flood to enhance oil recovery.

- Provide strategic fuel supplies: during national fuel shortages, to military bases during emergency mobilization, etc.

The diesel fuel from the SFP will be tested in various engines, including fleet tests in buses. The Washington DC Metropolitan Area Transit Authority (WMATA) and Denali National Park bus fleets were chosen to evaluate SFP fuels for several reasons, but primarily because they represent nearly opposite ends of several spectra, including; climate, topography, engine load factor, mean distance between stops and composition of normally used conventional diesel fuel. Also, the managers of these fleets share the strong desire to participate in a program aimed at minimizing exhaust emissions, especially those emissions that are most apparent to riders, people in other vehicles and by-standers.

Previous research has shown that extremely low-sulfur, high-quality diesel fuels reduce exhaust emissions from current diesel engines significantly. The ultra-clean F-T fuels to be produced in this program have virtually no sulfur (less than 1 ppm), and are of the highest quality in terms of ignition quality, saturate content, backend volatility, etc. However, these fuels lack lubricity, and may cause compatibility problems with legacy fuel injection system components without the use of appropriate additive and formulation technology. With improvements to the diesel engine, this may not be a problem. Tests will be run on prototype diesel engines equipped with prototype exhaust after treatment emission control systems to determine how well these potential engine systems of the future perform with an ultra-clean F-T diesel fuel, both neat and blended.

The fact that the SFP plant will also produce synthetic naphtha (in addition to synthetic diesel fuel) presents an opportunity that could be pursued as an add-on to the proposed program. SFP hydrogen saturated naphtha is an ideal fuel for fuel cell systems that use a reformer to produce hydrogen for the fuel cell. Other common liquid fuels, such as gasoline, methanol, natural gas, and conventional diesel fuel, all have significant disadvantages when compared to this promising fuel cell fuel.

Team Members and General Organization Roles

A joint management team composed of selected ICRC Team members and DOE and NETL staff will oversee and provide overall guidance for the project. The management team will meet or converse on a regular basis and will also meet or converse to address particular or unique concerns or opportunities as needed. Included in these meetings and discussions will be other members of the ICRC Project Team as appropriate. The ICRC management team will be composed of Mr. Kevin Mulrenin, ICRC Operations Manager, Dr. Steve Bergin, ICRC Technical Project Manager, Dr. Branch Russell, Syntroleum Project Director, Mr. R. Andrew Mitchell, Syntroleum Project Manager, and Dr. Lewis Waters, Energy Programs Consultant, to ICRC. Mr. Ken Murphy will act as liaison between the management team and the engine and trucking industries. Dr. Bergin and the DOE COR will be the principal respective technical contacts for this project. Cognizant DOE officials will participate in program review meetings.

ICRC, as the prime contractor, will manage and be responsible for the overall private sector effort. ICRC will conduct dynamometer durability testing of diesel bus engines operating on F-T diesel fuel. ICRC will monitor the vehicle tests at WMATA and will oversee the monitoring of the Denali tests by University of Alaska Fairbanks. Syntroleum will design, build and operate the SFP using Syntroleum’s proprietary natural gas conversion and hydrocarbon product processing and upgrading technology. Marathon will manage natural gas feed stock supply for the plant, and will assist Syntroleum with issues such as plant construction and fuel handling. The WMATA and Denali National Park Bus Fleets will field-test the SFP diesel fuel, with in-service emissions testing performed by West Virginia University. The University of Alaska at Fairbanks will provide support for the Denali testing. Daimler Chrysler and/or Volkswagen will evaluate the SFP fuels in prototype light and heavy-duty diesel engines combined with exhaust after-treatment systems. MIT will take a fundamental approach to the diesel-engine/fuel system to optimize the engine combustion system for SFP diesel, in terms of maximum efficiency and minimum emissions, especially NOx emissions. A.D. Little, Inc. will perform economic and energy analyses of SFP process and fuel market potentials.

TASKS

Task 1. Project Management

Prepare detailed project management plan within thirty days of ratification of this Agreement. The management plan will outline detailed technical and spending schedules, objectives and methodologies for each of the following tasks and subtasks. -The management plan will also include anticipated outcomes and contingency plans. For each task and subtask, the management plan will outline test protocols, data to be collected, and methods of data analysis. Any interaction between tasks, in terms of either timing or results, will also be described.

The management plan will be broken into phases and each phase will correspond to the calendar year to correspond to the NETL's cash flow requirements and the original project plan submitted by the Project Team. The plan will also include a reporting schedule consistent with the DOE reporting requirements, and identification of deliverables such as the DOE requirements for Topical Reports and anticipated submission dates. The budget will include funding for at least one presentation at a DOE-sponsored meeting per calendar year, and annual project review meetings with DOE during the term of the project. These meetings shall be scheduled in concert with the DOE COR.

This project will be managed according to the Project Plan. If necessary, the plan may be modified, with COR concurrence.

Task 2. SFP Construction and Fuel Production

Task 2.1 Economic Impact of Process Improvement

The SFP will be based on synthesis gas production and F-T technology already demonstrated at the Syntroleum Cherry Point plant, and on product upgrading technology demonstrated by Syntroleum in various pilot plant facilities with the following improvements:

The SFP will be modular.

>20% improvement in carbon efficiency from earlier designs.

Reduction in the per/barrel plant capital cost.

While the design improvements are not part of this project, the economic impact of these improvements may be relevant to the Economic Analysis, Task 6, and if so will be provided to DOE.

Task 2.2 SFP Construction

Choose a site for the SFP, obtain all necessary permits (such as air permits, NEPA, etc.), transfer Cherry Point plant equipment to the identified site of the SFP in northeast Oklahoma, and construct the SFP. This is anticipated to take approximately 9 – 12 months after completion of SFP mechanical design.

Task 2.3 SFP Start-up

After construction, the facility will undergo full start-up activities for approximately 2.5 months. Start-up activities will demonstrate the following:

Sustained operations using natural gas.
Operational safety.

Production of continuous, high quality fuels that meet the specification included as an attachment to this SOPO.

Task 2.4 Fuel Production and Distribution Plan

After plant start-up, the SFP shall be run as required (for approximately 4 additional months cumulative) to provide the fuel types and volumes required for program fleet and vehicle demonstration and fuel/engine technology development tasks. At COR direction, up to 10,000 gallons of the fuel product made to the Jet A-1 specification of ASTM D-1655 shall be furnished to NETL. This fuel may be used in test programs with other DOE partners. ICRC will develop a fuel production and distribution plan, including:

Specifications for the types of fuels

Schedule of production types and quantities

Destinations for the fuels, including type and quantity

Fuel storage and distribution for the fleet tests.

Syntroleum reserves the right, from time to time, to designate one or more intervals comprising up to 25% of the operating hours (or greater subject to the prior approval of the DOE's CO) of the plant during each month for purposes outside the program scope as stated in the SOPO. Such intervals will be designated by Syntroleum, and shall not impair the achievement of the project objectives stated in the SOPO. The operating costs of the plant during such intervals shall be borne by Syntroleum.

The participation of the SFP plant in the project shall be deemed complete once Syntroleum has delivered:

10,000 gallons of Jet A-1 fuel, or such lesser amounts as agreed to by the CO, upon the advice of the COR.

150,000 gallons of S-2 diesel fuel meeting the S-2 diesel specification included as an attachment to this SOPO, or such lesser amounts as agreed to by the CO (upon the advice of the COR) and ICRC to satisfy the fuel volumes required to complete the tasks described in this SOPO.

In the event that there is an unforeseen change in the amount of S-2 diesel fuel that is needed to complete Tasks 3 through 5, as described in this SOPO. ICRC agrees to provide the additional fuel. This fuel will meet the S-2 diesel specification included as an attachment to this SOPO, and for purposes of DOE cost share, shall cost no more than the Syntroleum cost of production.

Task 3. Evaluation of SFP Fuels in Current Diesel Engines

Task 3.1. Procurement of Similar Fuel

Small quantities of a representative GTL diesel may be procured. This GTL diesel will be used for preliminary fuel evaluation tests, and will meet the specification included as an attachment to this SOPO.

Task 3.2 Dynamometer Durability Tests

Conduct two 1500-hour dynamometer durability engine tests using two new diesel bus engines, each one representative of the engines that will be used in one of the two fleet tests. The dynamometer testing on the representative engines will be done using fuel produced by the SFP plant, or will be a similar fuel approved by the COR and applicable bus fleet representatives, with the same additive package that will be used during the applicable fleet test. The engine will be inspected during and after the test. The areas that will be especially closely monitored are:

Insufficient fuel lubricity, which would cause damage to fuel-injection system components

Seal compatibility or seal-swell differences between F-T and conventional diesel fuels, which could cause leaks or other problems

Cold-temperature problems such as filter-plugging, etc.

Fuel incompatibility, such as asphaltene precipitation, which may occur when F-T fuels are mixed with conventional diesel, will be monitored with separate equipment.

If any significant problems are found during the tests, they will be resolved and the solutions will be validated before proceeding with the bus fleet tests.

Task 3.3 Fleet Tests

Three buses in two fleets (a total of six buses) will be used to field test the F-T diesel fuels produced by the SFP. The three test buses will be matched to three buses of the same type in each fleet running on conventional diesel fuel and in service that is as similar as possible. Separate fueling facilities and fueling regimens will be set up for the SFP-fueled buses and monitored closely to assure no contamination of the SFP fuel. These buses will also be marked with simple, easy-to-understand panels identifying the project, its sponsors and the purpose of the project, together with web and telephone contacts for more information. During the fleet test, the buses will be closely monitored for any problems that may occur. Data from the fleet tests (including operating time and distance, fuel consumption, engine oil degradation and pertinent ambient conditions) will be cataloged, reduced, and analyzed. Whenever possible, appropriate action will be taken to enable the fleet tests to continue. It is expected that the two bus fleets will be WMATA and Denali, however, another bus fleet may be used with COR approval.

Task 3.4 Exhaust Emission Analysis

The bus exhaust emissions will be tested two times during the fleet tests:

As the buses begin operation on the street, exhaust emissions from each of the six buses in each fleet (12 buses in total) will be measured.

At the end of the fuel evaluation fleet test program, exhaust emissions from all six buses in one of the bus fleet tests will again be measured by WVU.

Task 4. SFP Fuel Assessment with Advanced Prototype Diesel Engines

The SFP diesel fuel will be tested in advanced prototype light duty and heavy-duty engines as follows:

The SFP fuels will be tested and compared to conventional diesel fuels both in terms of emissions and function

.

The performance of SFP fuels compared to other available low sulfur fuels (to be determined in concurrence with the COR) in diesel engines equipped with prototype exhaust after-treatment devices. These devices are used to reduce particulates and NOx.

To provide a basis for comparison to simulated future low-sulfur fuels that may have some significant aromatic content, the effects of various low levels of aromatics added to the SFP fuel will be investigated to determine the level of performance degradation with respect to emissions and emission control systems.

Task 5. Impact of SFP Fuel on Engine Performance

Identify potential engine design improvements to capitalize on benefits of F-T fuel, with particular focus on the reduction of NOx and fine particulate emissions. Research shall include the differences in engine performance, particularly due to changes in injection timing between the SFP diesel and typical diesel fuels.

Task 6. Economic Analysis

A.D. Little will provide a well-to-wheels economic and market analysis of small footprint GTL plants and the commercial applications in future transportation markets for ultra- clean liquid fuels products from these GTL plants. The study will be based upon:

> Data obtained for feedstock resource base, GTL plant construction and operation including non-confidential and non-proprietary data from the SFP, modification (for feedstock and product variations) and mobility costs; fuel types, quality, quantity and manufacturing costs; and commercial usefulness of the resultant fuels.
>
> Other data for the production, type and location of feedstocks. Various feedstock types and locations will be used in the analysis.
>
> Data obtained from the fleet and dynamometer tests.

As part of the final report documenting this analysis, an addendum may be included that gives particular consideration to near term uses of F-T fuels.

Task 7. Additional Tests

The following tests will be performed only if additional funding permits and DOE and ICRC concur:

Task 7.1 Additional Dynamometer Durability Tests

Additional dynamometer testing will be performed on the diesel fuel product of the SFP.

Task 7.2 Follow-up Emissions Testing at Denali

At the end of the fuel evaluation field test program, exhaust emissions from all six buses in the Denali field test will again be measured by WVU, to yield both baseline and ending readings for comparative purposes.

Task 7.3 Fuel Cell Tests with SFP Naphtha

Test the technical viability and commercial feasibility of using Naphtha as a fuel for fuel cells in transportation applications.

Task 8. SFP and SFP Fuel Feasibility in Alaska

Task 8.1 - Feasibility Study of SFPs for Rural Alaska.

Using readily available sources from government and private industry, gather information on various Alaska resources, such as oil, gas and coal, that could be used as feedstocks for local or regional SFP fuel processing plants. Consider the location, quantities, accessibility and other factors of these resources affecting how much clean fuel can be produced and distributed to rural communities in the area. Examine the feasibility of placing SFPs in the most promising areas to serve rural communities around the state, including the general economic and environmental benefits to be derived. The economic analysis should consider the costs of building and transporting the SFPs to Alaska, the cost of accessing and producing the fuels, the costs of transporting the fuels to the surrounding communities and the costs of storing and using the fuels for power, heat and other purposes. Set out findings and draw conclusions about the feasibility of locating SFPs in areas of Alaska to serve the fuel needs of rural Alaska.

Task 8.2 - Cold Weather Testing of Ultra-Clean Fuel

Compare the cold-starting and cold-operation characteristics of the SFP diesel with those of conventional and low-sulfur diesel fuel. Evaluate cold-starting in a cold box in a test cell and cold-operation characteristics in an outdoor vehicle test in Alaska. The cold-starting evaluation will use a dynamometer in a cold-box, and generally accepted measures, to determine cold-start capabilities with SFP diesel and other fuels in a controlled environment. The cold-operation evaluation of the SFP diesel will be set up under controlled fueling and performance monitoring conditions. The test vehicle will be operated during winter months in Alaska and will be compared to a similar vehicle using standard or low-sulfur diesel and operating under similar conditions. Set out findings and draw conclusions about the feasibility of using ultra-clean diesel in engines and vehicles in year-around Alaskan conditions. Arctic grade SFP fuel will be tested in this task. This fuel will be provided by Syntroleum at their cost of manufacture, excluding facility construction costs.

Task 9. Power Production Using SFP Fuels

Task 9.1 - Feasibility of Using SFP Fuels in Conventional and Advanced Stationary Power Plants Suitable for Alaska

Obtain a small diesel generator system, including a storage tank, of a type used in rural Alaska communities and install it under similar operating conditions to those found in such communities. Run the system using SFP diesel and gauge the effects of substituting the SFP diesel for the types of diesel fuel currently used in existing power generators in rural communities. Run the generator for at least 2,000 hours under weather conditions similar to those found in a rural village. Use a test program designed to determine:

- Fuel effectiveness for year-round power generation in rural Alaska.
- Improvement to emissions caused by using the GTL fuels.
- Wear and tear differences between the GTL fuel and conventional fuel.
- KWH/gallon differences for the GTL and conventional fuel.

Set out findings and draw conclusions about substituting GTL fuels for standard diesel fuels in rural diesel gen-sets in Alaska, and the emission benefits and engine durability differences caused by using GTL fuels. The SFP diesel will be provided by Syntroleum at their cost of manufacture, excluding facility construction costs.

Task 9.2 - Testing SFP Fuels in Alaska Fuel Cell Applications

Obtain a fuel cell, one that is either commercially available or a test unit from a fuel cell developer, and run the unit for at least 2,000 hours on SFP fuel(s) under conditions that would be expected in actual use in a rural Alaskan community. Compare the operation to that of a similar diesel generator using standard diesel fuel. Set out findings and draw conclusions about the feasibility of installing other fuel cells using ultra-clean fuels in selected rural communities in Alaska. The SFP fuels will be provided by Syntroleum at their cost of manufacture, excluding facility construction costs.

DELIVERABLES:

Task 1. Project Management

The Project Management Plan shall be provided to DOE.

Task 2. SFP Construction and Fuel Production Task

Task 2.1 Economic Impact of Process Improvement

A non-proprietary summary of the impacts of the improvements made in the SFP over the Cherry Point plant design.

Non-proprietary description of SFP process, including general process description and simple block flow diagrams of plant.

A breakdown of SFP construction costs by plant section.

A breakdown of SFP operation costs by plant section.

Task 2.2 SFP Construction Task

DOE shall have the right to inspect in Syntroleum's offices (but not receive or make copies of) a complete set of: 1) The SFP construction drawings including civil, electric, piping isometrics, instrument and equipment specification sheets, and 2) The SFP as-built drawings.

Copies of required construction and environmental permits.

Itemized costs for new equipment, construction and other project-related expenditures.

Task 2.3 SFP Start-up

A Topical Report providing a detailed chemical analysis of fuels produced, and all other pertinent product information.

Task 2.4 Fuel Production Schedule and Distribution Plan

The Fuel Production Schedule and Distribution Plan.

At COR direction, up to 10,000 gallons of the fuel product shall be made to meet the Jet A-1 specification of ASTM D-1655, unless this specification is modified within 3 months of Award. This fuel may be used in test programs with other DOE partners

.

DOE shall have the right to inspect the SFP with other visitors on a confidential basis. Syntroleum to have 3 day advanced notice of an inspection as well as right to approve or disapprove of proposed visitors who are not government employees.

The DOE shall have the right to inspect in Syntroleum's offices (but not receive or make copies of) 1) plant energy balances, 2) plant material balances, and 3) plant operations data.

Task 3. Evaluation of SFP Fuels in Current Diesel Engines

Task 3.1 Procurement of Similar Fuel

Quantity, source and chemical analysis of the fuel in a Topical Report.

Task 3.2 Dynamometer Durability Tests

A Topical Report for each of the 1500-hr dynamometer durability tests, including all raw data and analyses, conclusions, and the specifications (if available) and identification for all additives.

Task 3.3 Fleet Tests

A Topical Report containing the results of the fleet tests, including all raw data and analyses, and the specifications (if available) and identification for all additives.

Task 3.4 Exhaust Emission Analysis

A Topical Report containing the results of the initial exhaust emission analyses (Denali and WMATA).

A Topical Report containing the results of the final exhaust emission analyses, including all raw data (WMATA, only).

Task 4. SFP Fuel Assessment with Advanced Prototype Diesel Engines

- A Topical Report containing the results of the SFP fuel assessment with advanced prototype diesel engines, including:
  Engine, fuel and aromatics specifications or chemical analysis.
  All raw data and analyses.
  Specifications (if available) and identification for all additives.

Task 5. Impact of SFP Fuel on Engine Performance

A Topical Report containing the results of the engine optimization for superior quality fuels tests, including all raw data and analyses, engine design improvements, fuel specification, and the specifications (if available) and identification for all additives.

Task 6. Economic Analysis

The economic analyses.

Task 7. Additional Tests

<u>Task 7.1 Additional Dynamometer Durability Tests</u>

A Topical Report containing the results of the additional dynamometer durability test, including all raw data and analyses.

<u>Task 7.2 Follow-up Emissions Testing at Denali</u>

A Topical Report containing the results of the final exhaust emission analyses including all raw data.

<u>Task 7.3 Fuel Cell Tests with SFP Naphtha</u>

- A Topical Report containing the results of the naphtha tests, including all raw data and analyses.

Task 8. SFP and SFP Fuel Feasibility in Alaska

<u>Task 8.1 - Feasibility Study of SFPs for Rural Alaska</u>.

- A Topical Report containing the results of the economic analysis.

<u>Task 8.2 - Cold Weather Testing of Ultra-Clean Fuel</u>

- A Topical Report containing the results of the cold start tests, including the specification for the fuel used.
- A Topical Report containing the results of the cold-operation test, including the specification for the fuel used.
- If requested, Syntroleum will provide supporting documentation for the cost of the fuel.

Task 9. Power Production Using SFP Fuels

<u>Task 9.1 - Feasibility of Using SFP Fuels in Conventional and Advanced Stationary Power Plants Suitable for Alaska</u>

- A Topical Report containing the results of the diesel generator system tests, including the specifications for all fuel used, emissions data, and a discussion of the benefits and detriments of using the SFP fuels in place of conventional diesel.
- If requested, Syntroleum will provide supporting documentation for the cost of the fuels.

Task 9.2 - Testing SFP Fuels in Alaska Fuel Cell Applications

- A Topical Report containing the results of the fuel cell tests, including the specifications for all fuel used, the feasibility of using GTL fuels in fuel cells with back up data, and a discussion on the potential advantages of using GTL powered fuel cells over conventional power sources and of the problems that still must be overcome to bring fuel cells into the market place in this application.
- If requested, Syntroleum will provide supporting documentation for the cost of the fuels.

Final Report

At a minimum, the following shall be included in the Final Report:

All of the documentation deliverables listed above, unless waived by DOE.

An executive summary of the overall results and findings of the project.

The economic and market analysis

Discussion of the discrepancies, if any, between different sets of fuel tests

Discussion of unexpected project results, positive or negative.

Briefings

The Recipient shall prepare detailed briefings for presentation to the Contracting Officer's Representative (COR) at Pittsburgh, West Virginia or possibly at a different location designation by the COR. The briefings shall be given by the Recipient to explain the plans, progress, and results of the project effort. Briefings shall be presented at least 45 days before completion of the balance work for the particular continuation application event. The final briefing shall be presented at least 45 days before the award is due to expire.

Syntroleum®

Small Footprint Plant (SFP) Study

for

DOE Cooperative Agreement

DE-FC-01NT41009

Document No. GN-DC-0100

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1. INTRODUCTION

1.1 Purpose

This document provides information required by Section 2.1 of the DOE contract. Information provided in this document is based on four different plant configurations of varying capacities. Data for each plant differs based on the level of design information available, and the design objectives of the facility. Data for the 100 barrels per day (BPD) Small Footprint Plant is based on an existing plant which is part of the DOE Ultra-Clean Fuels Program. Conceptual design for the 1,700 BPD FlareBuster™ plant was developed as a flare gas mitigation option. Data for the GTL Barge is based on current work to develop the first commercial barge-mounted GTL plant. Data is also provided based on a high level review of a coal-based Small Footprint Plant.

1.2 General Overview Process

Although a Gas to Liquids (GTL) plant will contain more than one hundred pieces of process equipment, the conceptual chemistry involved in understanding the conversion of natural gas to synthetic hydrocarbon distillates can be summarized by two general chemical reactions.

The first general reaction is the partial combustion of natural gas to form a mixture of hydrogen and carbon monoxide, commonly known as syngas. A general reaction for the formation of syngas from methane is shown in Equation 1.

Equation 1 – Syngas Reaction

$$\overset{\text{Methane}}{CH_4} + \overset{\text{Air}}{O_2 + N_2} + \overset{\text{Steam}}{H_2O} \xrightarrow{\text{Catalyst}} \overset{\text{Syngas}}{CO + H_2} + N_2 + \overset{\text{Water}}{H_2O}$$

The second general reaction is known as the Fischer-Tropsch (FT) reaction and is shown as Equation 2. The Fischer-Tropsch reaction recombines the carbon monoxide and hydrogen in syngas to form a variety of hydrocarbons of varying molecular weight and hydrocarbon chain length.

Equation 2 – Fischer-Tropsch Reaction

$$\overset{\text{Syngas}}{H_2 + CO} + N_2 \xrightarrow{\text{Catalyst}} \overset{\text{Hydrocarbons}}{C_nH_{(2n+2)}} + \overset{\text{Nitrogen}}{N_2} + \overset{\text{Water}}{H_2O}$$

Hydrocarbons formed can range from ethane to heavy waxes. The raw Fischer-Tropsch product from the reactor contains what is typically described as a light Fischer-Tropsch syncrude (liquid at room temperature) and a heavy Fischer-Tropsch syncrude (solid at room temperature). Additional process equipment converts raw FT material / product to synthetic versions of traditional hydrocarbon products such as naphtha, diesel, and jet fuel. Carbon distribution of the raw Fischer-Tropsch product and the final products are represented by the following charts, Figures 1 and 2.

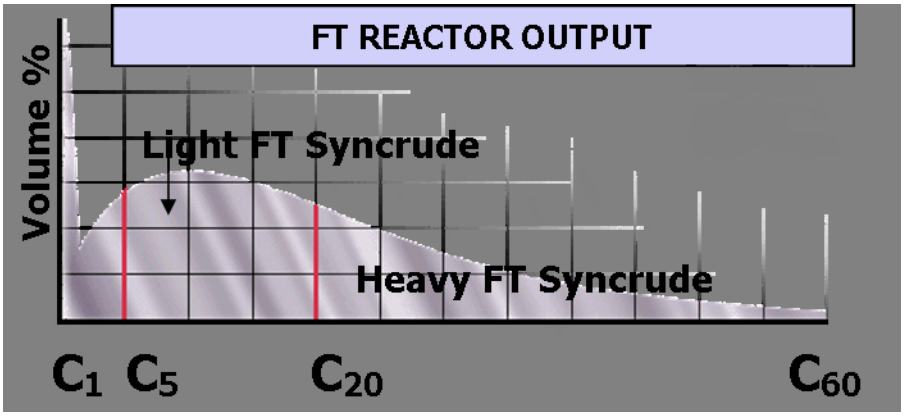


Figure 1 – Raw Fischer-Tropsch Product Carbon Distribution

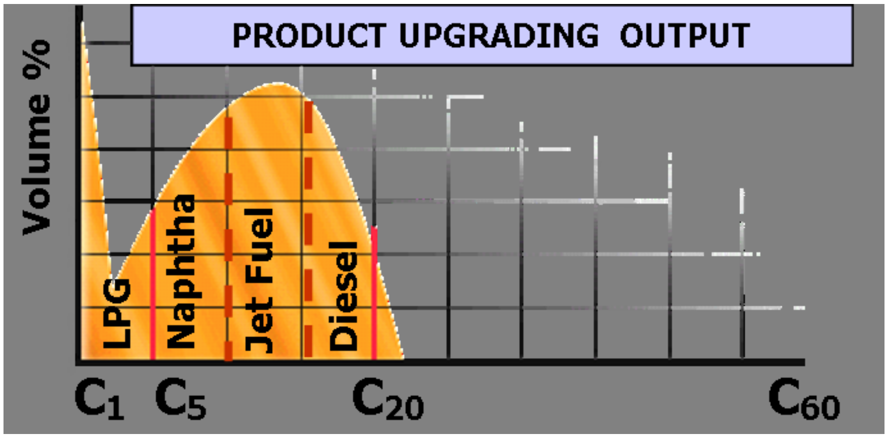


Figure 2 – Refined Fischer-Tropsch Product Carbon Distribution

2. SMALL FOOTPRINT PLANT (SFP) – 100 BPD FT LIQUIDS

2.1 Process Description

The Syntroleum® Process uses proprietary technology to convert natural gas into synthetic oil which can then be further processed into fuels and other hydrocarbon-based products. The Syntroleum Process can be optimized for location requirements. Overall material balances for the Syntroleum SFP GTL process producing conventional and arctic diesel are shown in Figures 3 and 4. A block flow diagram for the SFP plant is provided at the end of this section.

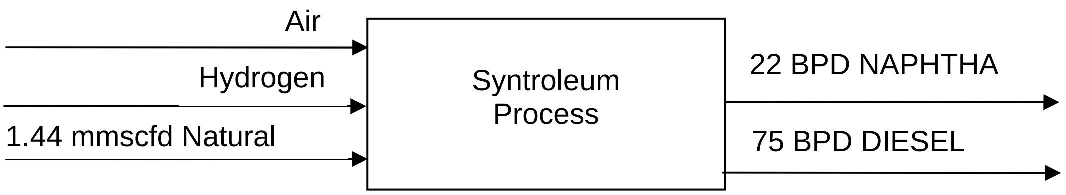


Figure 3 – SFP Mass Balance for Conventional Diesel

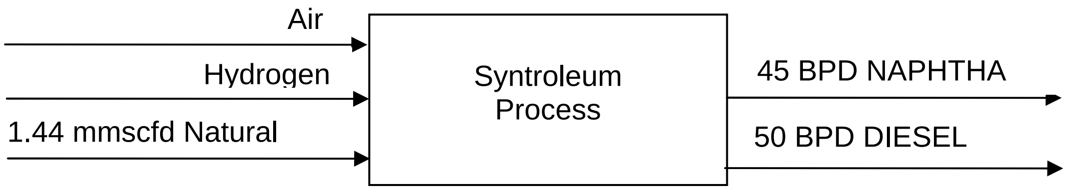


Figure 4 – SFP Mass Balance for Arctic Diesel

The SFP plant can be divided into four sections by process function using the existing demonstration plant as a basis for discussion. The syngas generation section reacts natural gas with compressed air to produce syngas. The Fischer-Tropsch synthesis section recombines the syngas to varying chain length paraffinic hydrocarbons. The product upgrade section refines the raw FT material / product into the required finished products to specification as naphtha or diesel. Hydrogen and typical process utilities provide support to the other four sections. The picture (Figure 5) highlights the individual areas of Syntroleum's 100 BPD demonstration plant located near Tulsa, Oklahoma at the Port of Catoosa.

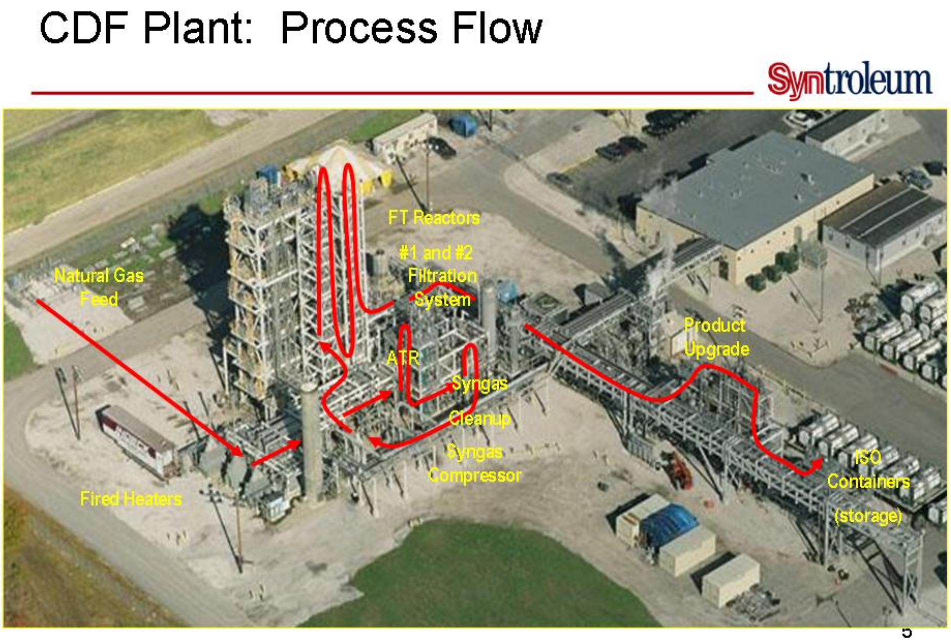

CDF Plant: Process Flow

Figure 5 – Syntroleum Catoosa Demonstration Facility

2.1.1 Syngas Generation

Pipeline quality natural gas is combined with hydrogen and heated prior to treatment for removal of sulfur compounds such as mercaptans or carbonyl sulfide. After sulfur removal, the residue gas is combined with high pressure steam, heated and fed to the autothermal reformer along with additional steam and compressed air. In the autothermal reformer, the mixed feeds pass over a catalyst where partial oxidation, steam reforming, and shift conversion reactions occur simultaneously. The overall reaction for the formation of syngas is represented by Equation 1 in Section 1.2 Syngas leaving the autothermal reformer is cooled by the generation of high pressure steam, scrubbed for impurities, and compressed prior to entering Fischer Tropsch synthesis.

2.1.2 Fischer-Tropsch Synthesis

The Fischer-Tropsch (FT) section has two reactors in series containing proprietary catalyst to convert syngas to Fischer-Tropsch products. Overhead vapors from the first FT reactor are cooled, condensed and separated into light Fischer-Tropsch liquids (LFTL), water, and tail gas. Tail gas from the first FT reactor feeds the second FT reactor. Overhead vapors from the second reactor are again cooled, condensed and separated into LFTL, water and tail gas. Nitrogen associated with the syngas passes through the reactors and is removed as tail gas. The overall reaction for the formation of hydrocarbons via the Fischer-Tropsch process is represented by Equation 2 in Section 1.2. Large amounts of medium pressure steam are generated in this section which can be used in the plant or for export.

Each FT reactor utilizes a Heavy Fischer-Tropsch Liquids (HFTL) withdrawal system that allows catalyst free product to be withdrawn from the reactor. Fischer-Tropsch liquids represent a variety of hydrocarbon products with varying molecular weights. Fischer-Tropsch liquids are primarily paraffinic hydrocarbons, with minor olefin content. Light Fischer-Tropsch liquid is most similar to naphtha while heavy Fischer-Tropsch is a high purity wax. Both LFTL and HFTL require additional processing for use as fuels. The FT liquids are sent to the product upgrading unit for processing into naphtha and diesel. The tail gas is burned in an incinerator.

2.1.3 Product Upgrading

The product upgrading section of the plant refines the FT liquids into the diesel and naphtha, each according to required specification. The operation is analogous to refining of crude oil, but is conducted under much less severe operating conditions than conventional crude oil refining. This is due to the high quantities of paraffin and the absence of sulfur and other contaminants in the FT liquids. The product upgrade unit includes several sections to process the FT liquid. The primary sections are Feed Fractionation, Hydroprocessing (Hydrotreater and Hydrocracker), and Product Fractionation. The product upgrading process has a flexible design that enables production of a wide range of distillate products and product adjustment to meet seasonal requirements.

2.1.4 Utilities

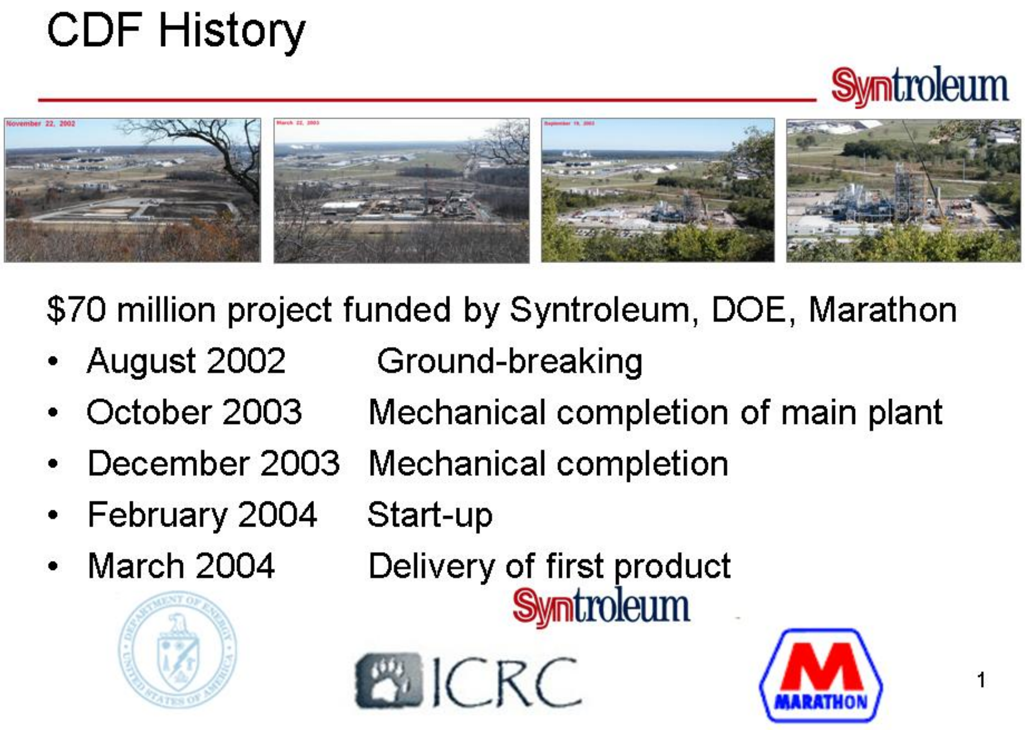
Process utilities for the SFP plant are shown below:

- Instrument and utility air
- Fuel gas
- Purchased Hydrogen
- Raw Water
- Cooling water
- Imported Electricity
- Startup steam and condensate
- Potable water and sewage

2.2 Improvements of SFP from Cherry Point Plant

Several improvements have been made to the Cherry Point Plant. The addition of a second Fischer-Tropsch Reactor and reducing the operating pressure of the autothermal reformer has improved conversion and overall carbon efficiency. The addition of the 2nd stage Fischer-Tropsch reactor increased the overall conversion of natural gas to a “raw” Fischer-Tropsch product (feed to the product upgrading) by approximately 30% based on the process simulations utilized for the plant design. At the Catoosa demonstration facility with an inlet natural gas flow of 1.334 million standard cubic feet per day, a single stage reactor produced approximately 70 barrels per day of Fischer-Tropsch product for a conversion of 19,040 standard cubic feet (scf) per barrel of product. The 2nd stage reactor increased the production of “raw” product to approximately 100 barrels per day resulting in a conversion of 13,313 scf per barrel of product.

The addition of a product upgrade unit allows production of finished ultra-clean products such as naphtha, diesel, and jet fuels. Syntroleum Fischer-Tropsch diesel (S-2) produced with the product upgrade unit has been provided for fleet testing. Product specification sheets are located in Appendix A. A timeline summary for the SFP (Catoosa Demonstration Facility) is highlighted below:



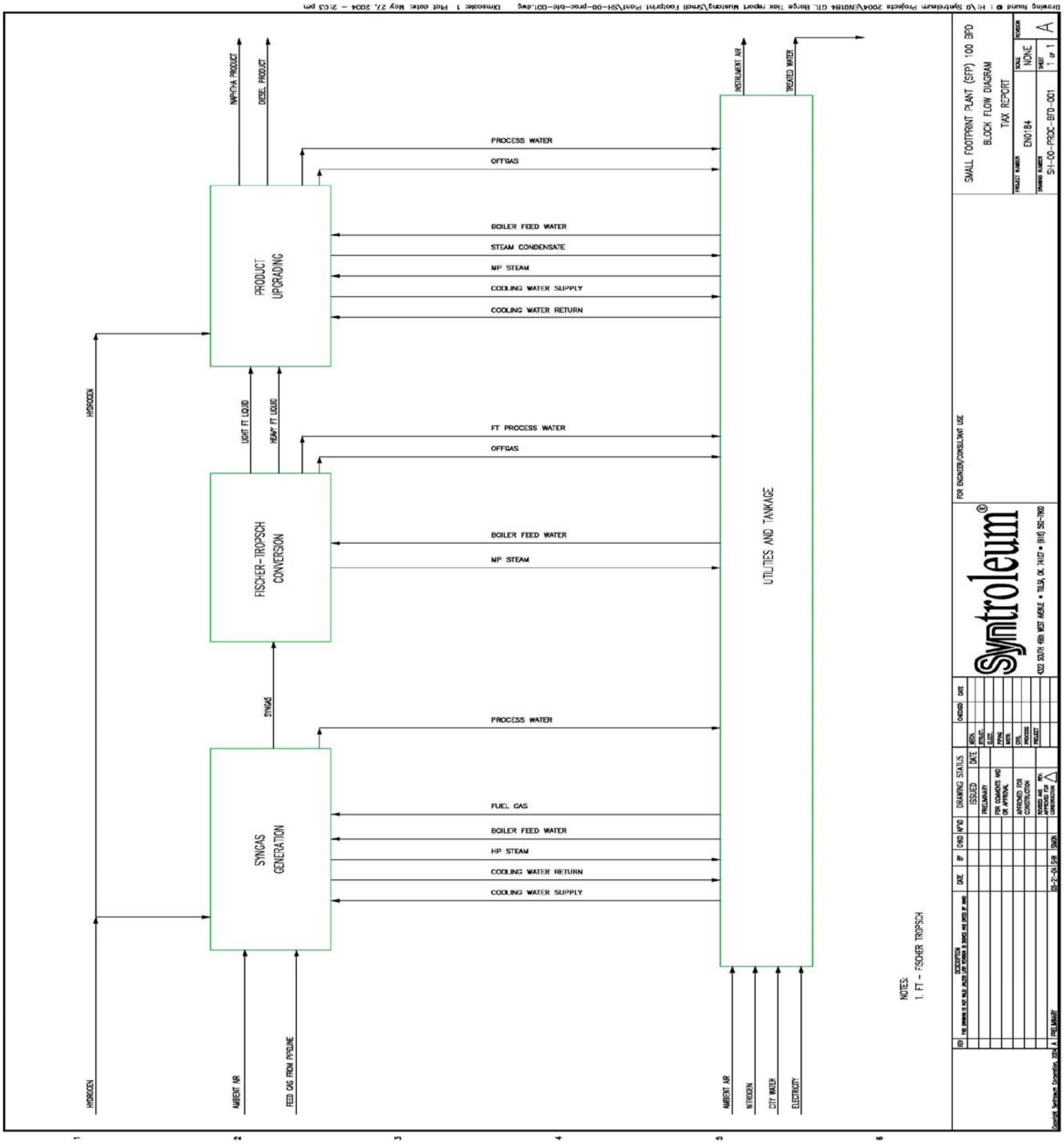
CDF History

Syntroleum

$70 million project funded by Syntroleum, DOE, Marathon

- August 2002 Ground-breaking
- October 2003 Mechanical completion of main plant
- December 2003 Mechanical completion
- February 2004 Start-up
- March 2004 Delivery of first product

Figure 6 – Catoosa Demonstration Facility History


Drawing found @ : H:\0 Syntroleum Projects 2004\EN0184 GTL Barge Tiax report Mustang\Small Footprint Plant\SH-00-proc-bfd-001.dwg Dimscale: 1 Plot date: May 27, 2004 - 2:03 pm
NAPHTHA PRODUCT
DIESEL PRODUCT
INSTRUMENT AIR
TREATED WATER
PROCESS WATER
OFFGAS
PRODUCT UPGRADING
BOILER FEED WATER
STEAM CONDENSATE
MP STEAM
COOLING WATER SUPPLY
COOLING WATER RETURN
HYDROGEN
LIGHT FT LIQUID
HEAVY FT LIQUID
FT PROCESS WATER
OFFGAS
FISCHER-TROPSCH CONVERSION
BOILER FEED WATER
MP STEAM
UTILITIES AND TANKAGE
SYNGAS
PROCESS WATER
SYNGAS GENERATION
FUEL GAS
BOILER FEED WATER
HP STEAM
COOLING WATER RETURN
COOLING WATER SUPPLY
NOTES:
1. FT - FISCHER TROPSCH
HYDROGEN
AMBIENT AIR
FEED GAS FROM PIPELINE
AMBIENT AIR
NITROGEN
CITY WATER
ELECTRICITY
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6
SMALL FOOTPRINT PLANT (SFP) 100 BPD
BLOCK FLOW DIAGRAM
TIAX REPORT
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EN0184
DRAWING NUMBER
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2.3 Construction Cost

Table 1 – SFP 100 BPD Construction Cost

SFP 100 BPD Construction Cost	
Total Installed Cost	
Syngas Generation	$6,800,000
FT Conversion	$15,000,000
Product Upgrading	$11,500,000
Utilities	$5,900,000
Total	$39,200,000
Cost Estimate Assumptions	
Book value for Cherry Point facilities $8,000,000	
Cost of buildings, roads, and infrastructure is distributed between the plant sections	

2.4 Module Size and Weights

Table 2 – SFP 100 BPD Size and Weight

100 BPD SFP GTL Plant		
	Area / Size	Weight
Overall	320,000 ft^2	1,280,000 lbs
Syngas Generation		
30-C-301 Air Compressor	6.5 ft x 14 ft	26,600 lbs
30-C-302 Syngas Compressor	10 ft x 15 ft	47,430 lbs
IM-1 Interface Module	10 ft x 10 ft	51,000 lbs
Mod-001 Autothermal Reformer	13.5 ft x 55 ft	80,000 lbs
30-F-310 Air Preheater	6.5 ft x 10 ft	15,000 lbs
30-F-311 Gas Preheater #1	6 ft x 7 ft	13,000 lbs
30-F-312 Gas Preheater #2	6.5 ft x 10 ft	9,000 lbs
Total	1300 ft^2	241,030 lbs

100 BPD SFP GTL Plant (cont.)		
	Area / Size	Weight
FT Conversion		
First Stage FT Reactor	14 ft x 16 ft	115,000 lbs
IM-1A Interface Module	6 ft x 11 ft	11,000 lbs
IM-1B Interface Module	10 ft x 20 ft	18,000 lbs
IM-1C Interface Module	10 ft x 12 ft	22,000 lbs
Mod-003 Wax Tank	13.5 ft x 32.5 ft	70,000 lbs
Mod-005 Second Stage FT Reactor	11 ft x 15 ft	245,000 lbs
Total	1200 ft^2	481,000 lbs
Product Upgrading		
UM-1 Upgrader Module	10 ft x 48.5 ft	145,800 lbs
UM-2 Upgrader Module	10 ft x 10 ft	10,000 lbs
UM-3 Upgrader Module	4 ft x 24 ft	15,000 lbs
60-T-610 C_{10+} Storage Tank	30 ft x 33 ft	19,600 lbs
Total	1700 ft^2	190,400 lbs
Utilities		
Mod-002 600# Steam Drum	13.5 ft x 40 ft	70,000 lbs
Mod-004 140# Steam Drum	13.5 ft x 22 ft	55,000 lbs
70-E-701 Excess Steam Condenser	7.5 ft x 21 ft	10,000 lbs
30-F-313 Vapor Combustor	14 ft x 14 ft	36,000 lbs
70-F-701 Startup Boiler	5 ft x 9 ft	8,600 lbs
70-U-703 Cooling Tower Pkg.	11 ft x 18 ft	7,000 lbs
70-U-707 Cooling Water Treatment	5.5 ft x 13 ft	200 lbs
70-U-704 Instrument Air Comp.	9 ft x 20 ft	12.500 lbs
70-U-701 Demin Water Pkg.	10 ft x 10 ft	3,000 lbs
70-U-702 Chemical Dosing Pkg.	6 ft x 12.5 ft	300 lbs
70-V-701 Deaerator	7.5 ft x 22 ft	6,700 lbs
70-V-702 Condensate Drum	4 ft x 14 ft	6,200 lbs
70-U-708 Caustic Pump & Storage	8 ft x 18 ft	700 lbs
70-V-706 Process Water Separator	7.5 ft x 25 ft	21,200 lbs
70-U-705 Nitrogen Storage	8 ft x 8 ft	6,400 lbs
Hydrogen Storage	50 ft x 50 ft	124,000 lbs
Total	5,000 ft^2	367,800 lbs

2.5 Operating Costs

Table 3 – SFP Operating Cost

SFP Operating Cost	
Natural Gas (based on $6.00/mmBtu)	$2,700,000/yr
Electricity	$ 770,000/yr
Water	$ 26,000/yr
Hydrogen	$ 640,000/yr
Nitrogen	$ 170,000/yr
Catalyst	$ 1,600,000/yr
Staffing, including operations, maintenance, and overhead. Based on actual costs from DoE plant and therefore includes additional costs as compared to a commercial facility due primarily to additional technical support (For example Engineering & Analytical support) typically seen with a new facility.	$ 4,900,000/yr
Note: Above annual costs based on 93% onstream factor	

3. FLAREBUSTER – 1,700 BPD

3.1 Differences from SFP

- Inlet gas treating
- Two trains of syngas generation and compression
- Three FT reactors including two trains of first stage Fischer-Tropsch Reactors
- Hydrogen PSA unit
- Power generation
- Tail gas burned for power generation
- Catalyst regeneration included
- Purpose built utilities such as instrument air compression and nitrogen generation

3.2 Process Description

The Syntroleum Process uses proprietary technology to convert natural gas into synthetic oil which can then be further processed into fuels and other hydrocarbon-based products. The Syntroleum Process can be optimized to provide different fuels based on location requirements. Overall material balances for the Syntroleum FlareBuster GTL process producing conventional diesel is shown in Figure 7.

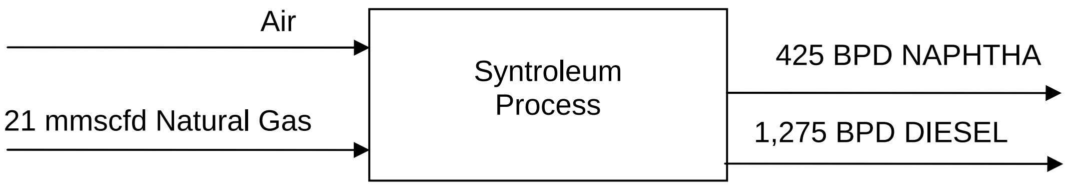


Figure 7 – FlareBuster Mass Balance for Conventional Diesel

The FlareBuster plant can be divided into four sections by process function similar to the SFP plant. The Syngas generation section reacts compressed flare or vent gas with compressed air to produce syngas. The Fischer-Tropsch synthesis section recombines the syngas to form long chain hydrocarbon products. The product upgrading section refines the Fischer-Tropsch liquids into the required finished products to specification as naphtha or diesel. Typical process utilities provide support to the other four sections. A block flow diagram for the FlareBuster plant is provided at the end of section 3.

3.2.1 Syngas Generation

Associated natural gas is delivered to FlareBuster plant from upstream facilities. The saturated natural gas is passed through a filter separator to remove entrained liquids, combined with hydrogen, and treated to remove impurities such as mercaptans (R-SH) ,carbonyl sulfide (COS) and hydrogen sulfide (H_2S). After the impurities are removed, the residue gas is heated before being combined with steam and pre-heated air in one of two autothermal reformers. In each of the autothermal reformers, the mixed feeds pass over a catalyst where partial oxidation, steam reforming, and shift conversion reactions occur simultaneously. The overall reaction for the formation of syngas is represented by Equation 1 in Section 1.2. Syngas is compressed, cooled, scrubbed, and treated in one of two trains to remove trace contaminates of hydrogen sulfide H_2S before entering Fischer-Tropsch Synthesis. High pressure steam is produced cooling the syngas.

3.2.2 Fischer-Tropsch Synthesis

The FlareBuster Fischer-Tropsch configuration consists of three FT reactors, two parallel first stage reactors supplied by individual syngas trains, and a combined second stage FT reactor. The overall reaction for the formation of hydrocarbons via the Fischer-Tropsch process is represented by Equation 2 in Section 1.2.

Tailgas from each of the first stage FT reactors is cooled, dewatered and routed to the second stage FT reactor. Fluids exiting the second stage FT reactor are separated into light Fischer-Tropsch liquids (LFTL), heavy Fischer-Tropsch liquids (HFTL), and tailgas. Nitrogen associated with the syngas passes through the reactors and is removed as tail gas. Remaining tail gas is consumed by turbine generators for plant power supply or burned in a vapor combustor.

Each FT reactor utilizes an HFTL withdrawal system that allows catalyst-free product to be withdrawn from the reactor. Large amounts of medium pressure steam are generated in this section which can be used in the plant or for export.

Fischer-Tropsch liquids represent a variety of hydrocarbon products with varying molecular weights. Fischer-Tropsch liquids are primarily paraffinic hydrocarbons, with minor olefin content. Light Fischer-Tropsch liquid is most similar to naphtha while heavy Fischer-Tropsch is a high purity wax. Both LFTL and HFTL require additional processing for use as fuels. The FT liquids are sent to the product upgrading unit for processing into naphtha and diesel.

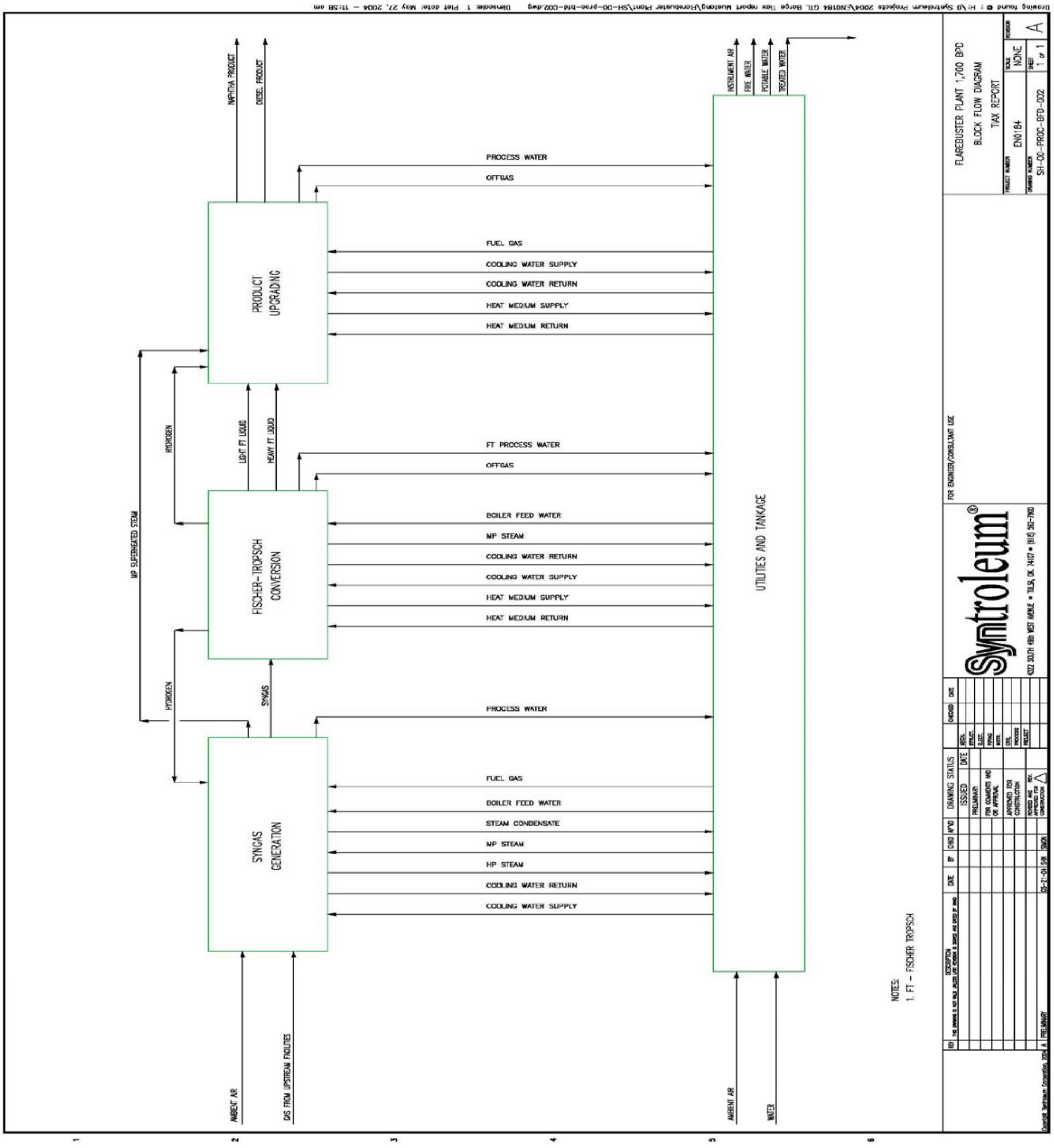
3.2.3 Product Upgrading

The product upgrading section of the plant refines the FT liquids into naphtha and diesel. The operation is analogous to refining of crude oil, but is conducted under much less severe operating conditions than conventional crude oil refining. This is due to the high quantities of paraffin and the absence of sulfur and other contaminants in the FT liquids. The product upgrade unit includes several sections to process the FT liquid. The primary sections are Naphtha Stabilization, Hydrocracking, and Product Fractionation. The product upgrading process has a flexible design that enables production of a wide range of distillate products and product adjustment to meet seasonal requirements.

3.2.4 Utilities

Process utilities for the FlareBuster plant are shown below:

- Power generation, startup, main and emergency
- Instrument and utility air
- Fuel gas
- Cooling water
- Startup steam and condensate
- Potable water and firewater


Drawing found @ : H:\0 Syntroleum Projects 2004\EN0184 GTL Barge Tax report Mustang\Flarebuster Plant\SH-00-proc-bfd-002.dwg Dimscale: 1 Plot date: May 27, 2004 - 11:58 am
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DIESEL PRODUCT
PRODUCT UPGRADING
PROCESS WATER
OFFGAS
FUEL GAS
COOLING WATER SUPPLY
COOLING WATER RETURN
HEAT MEDIUM SUPPLY
HEAT MEDIUM RETURN
HYDROGEN
LIGHT FT LIQUID
HEAVY FT LIQUID
MP SUPERHEATED STEAM
FISCHER-TROPSCH CONVERSION
FT PROCESS WATER
OFFGAS
BOILER FEED WATER
MP STEAM
COOLING WATER RETURN
COOLING WATER SUPPLY
HEAT MEDIUM SUPPLY
HEAT MEDIUM RETURN
HYDROGEN
SYNGAS
SYNGAS GENERATION
PROCESS WATER
FUEL GAS
BOILER FEED WATER
STEAM CONDENSATE
MP STEAM
HP STEAM
COOLING WATER RETURN
COOLING WATER SUPPLY
AMBIENT AIR
GAS FROM UPSTREAM FACILITIES
UTILITIES AND TANKAGE
INSTRUMENT AIR
FIRE WATER
POTABLE WATER
TREATED WATER
AMBIENT AIR
WATER
NOTES:
1. FT - FISCHER TROPSCH
FLAREBUSTER PLANT 1,700 BPD
BLOCK FLOW DIAGRAM
TAX REPORT
PROJECT NUMBER EN0184
DRAWING NUMBER SH-00-PROC-BFD-002
SCALE NONE
SHEET 1 of 1
REVISION A
FOR ENGINEER/CONSULTANT USE
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Construction Cost

Table 4 – FlareBuster 1,700 BPD Construction Cost

FlareBuster 1,700 BPD Construction Cost	
Total Installed Cost (2004 US$)	
Syngas Generation	$40,600,000
FT Conversion	$25,400,000
Product Upgrading	$19,100,000
Utilities	$61,200,000
Total	$146,300,000
Cost Estimate Assumptions	
Estimated accuracy +/- 50%	
Cost of buildings, roads, and infrastructure is distributed between the plant sections	
Cost Estimate Exclusions	
Spare parts	
Contingency	

3.3 Module Size and Weights

Table 5 – FlareBuster 1,700 BPD Size and Weight

FlareBuster 1,700 BPD Size and Weight		
	Area	Weight
Overall (Excludes Buildings and Roads)	159,600 ft^2	4,600 tons
Syngas Generation		
Feed Gas Filter Separator	21 ft x 66 ft	20 tons
Feed Gas Treating	14 ft x 53 ft	41 tons
Air Preheater	13 ft x 80 ft	124 tons
Autothermal Reformer	14 ft x 40 ft	15 tons
ATR Steam Drum A	14 ft x 40 ft	25 tons
ATR Steam Drum B	14 ft x 40 ft	25 tons
BFW Preheater	14 ft x 40 ft	8 tons
Syngas Air Cooler #1	10 ft x 20 ft	59 tons
Syngas Air Cooler #2	10 ft x 20 ft	59 tons
ATR Process Condensate Separator #1	9 ft x 9 ft	6 tons
ATR Process Condensate Separator #2	9 ft x 9 ft	6 tons
Syngas Compressor Suction Drum #1	9 ft x 9 ft	18 tons
Syngas Compressor Suction Drum #2	9 ft x 9 ft	18 tons
Syngas Compressor #1	16 ft x 32 ft	40 tons
Syngas Compressor #2	16 ft x 32 ft	40 tons
Lube Oil, 4 Modules	500 ft^2	10-20 tons typ.
Total	7,700 ft^2	585 tons

FlareBuster 1,700 BPD Size and Weight (cont.)		
	Area	Weight
FT Conversion		
FT Feed Effluent Exchanger	14 ft x 40 ft	141 tons
FT Reactor First Stage A	21 ft x 21 ft	300 tons
FT Reactor First Stage B	21 ft x 21 ft	300 tons
FT Reactor Second Stage	21 ft x 21 ft	131 tons
FT Product Cooler	14 ft x 40 ft	52 tons
FT Cold Separator (2nd Stage)	8 ft x 16 ft	26 tons
Hydrogen PSA	24 ft x 48 ft	47 tons
PSA Tail Gas Compressor	14 ft x 53 ft	5 tons
Hydrogen Coolers	20 ft x 30 ft	3 tons
19 Additional Modules		795 tons
Total	13,400 ft^2	1,800 tons
Product Upgrading		
17 Modules	4,000 ft^2	20 tons (typ.)
Total Weight		340 tons
Utilities		
30 Modules	52,000 ft^2	20 tons (typ.)
Total Weight		1,800 tons

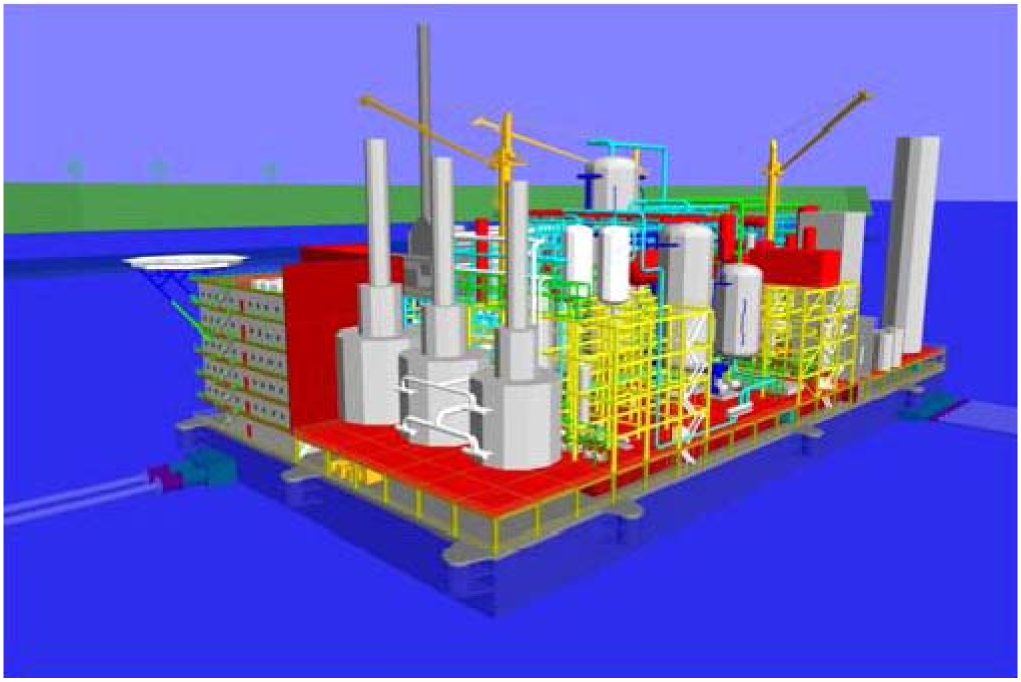
3.4 Operating Costs

Table 6 – FlareBuster Operating Cost

FlareBuster Operating Cost	
Natural Gas, assumes $0.50/mmBtu	$ 3,600,000/yr
Electricity	$ 0/yr (self generated)
Water	$ 2,500/yr
Catalyst	$ 800,000/yr
Staffing	$ 2,200,000/yr
Water Treating Chemicals	$ 36,000/yr
Notes	1. Electricity will be generated on-site using tail gas to drive a gas turbine generator.

4. GTL BARGE – 12,000 BPD FT LIQUIDS, 19,300 BPD TOTAL

The GTL Barge is designed to develop near shore natural gas assets. A conceptual drawing is shown in Figure 8.



Courtesy of Waller Marine Inc.

Figure 8 – GTL Barge Concept Drawing

4.1 Differences from SFP

- Inlet gas treating
- Natural gas liquids (NGL) recovery
- Steam turbine for syngas compression
- Three FT reactors in series
- Hydrogen PSA
- Purpose built utilities such as instrument air compression and nitrogen generation
- Seawater cooled

4.2 Process Description

The Syntroleum Process uses proprietary technology to convert natural gas into a synthetic mix (light and heavy Fischer-Tropsch syncrude) which can then be further processed into fuels and other hydrocarbon-based products. The Syntroleum Process can be optimized to provide different fuels based on location requirements. Overall material balance for the Syntroleum GTL barge producing conventional diesel is shown in Figure 9.

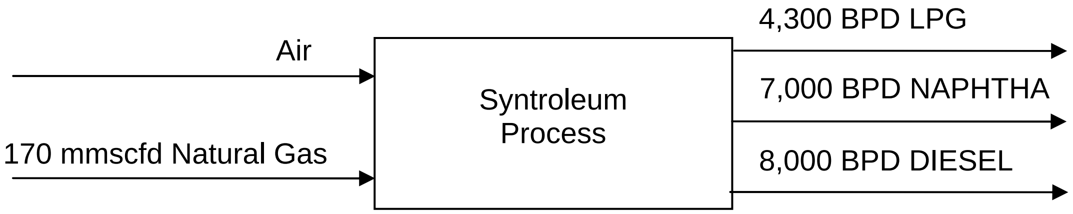


Figure 9 – GTL Barge Mass Balance for Conventional Diesel

The GTL Barge can be divided into five sections by process function. The NGL recovery section separates condensate associated with the incoming natural gas. The Syngas generation section reacts incoming natural gas to produce syngas. The Fischer-Tropsch synthesis section recombines the syngas to form long chain hydrocarbon products. The product upgrading section refines raw FT product / material into the required finished products such as LPG, naphtha, and diesel. A block flow diagram for the GTL barge plant is provided at the end of this section.

4.2.1 NGL Recovery

Low sulfur natural gas is delivered to the GTL Barge from upstream facilities. The saturated natural gas is dehydrated, chilled, and fractionated to residue gas and natural gas liquids. The residue gas is fed to the front of the GTL plant and the natural gas liquids are fed to the product upgrading section for further refining.

4.2.2 Syngas Generation

Residue gas is treated in the syngas generation section to remove mercaptans (R-SH) and carbonyl sulfide (COS). After the mercaptans and carbonyl sulfide are removed, the residue gas is heated before being combined with steam and pre-heated air in the autothermal reformer. In the autothermal reformer, the mixed feeds pass over a catalyst where partial oxidation, steam reforming, and shift conversion reactions occur simultaneously. The overall reaction for the formation of syngas is represented by Equation 1 in Section 1.2. Syngas is compressed, cooled, scrubbed, and treated to remove trace contaminates of H_2S before entering Fischer-Tropsch Synthesis. High pressure steam is produced cooling the syngas.

4.2.3 Fischer-Tropsch Synthesis

The Fischer-Tropsch (FT) section has three reactors containing proprietary catalyst to achieve high conversion of syngas to Fischer-Tropsch products. The tail gas from each of the first two reactors, feeds subsequent reactors to convert remaining syngas into FT product. Each reactor produces light Fischer-Tropsch liquid (LFTL), heavy Fischer-Tropsch liquid (HFTL), and water as a byproduct. After the final FT reactor stage, the remaining tail gas is cooled to maximize recovery of FT condensate. Nitrogen associated with the syngas passes through the reactors and is removed as tail gas. The overall reaction for the formation of hydrocarbons via the Fischer-Tropsch process is represented by Equation 2 in Section 1.2. Large amounts of medium pressure steam are generated in this section which can be used in the plant or for export.

Fischer-Tropsch liquids represent a variety of hydrocarbon products with varying molecular weights. Fischer-Tropsch liquids are primarily paraffinic hydrocarbons, with minor olefin content. Light Fischer-Tropsch liquid is most similar to naphtha while heavy Fischer-Tropsch material / product is a high purity wax. Both LFTL and HFTL require additional processing for use as fuels. The FT liquids are sent to the product upgrading unit for processing into naphtha and diesel. The tail gas is burned in an incinerator.

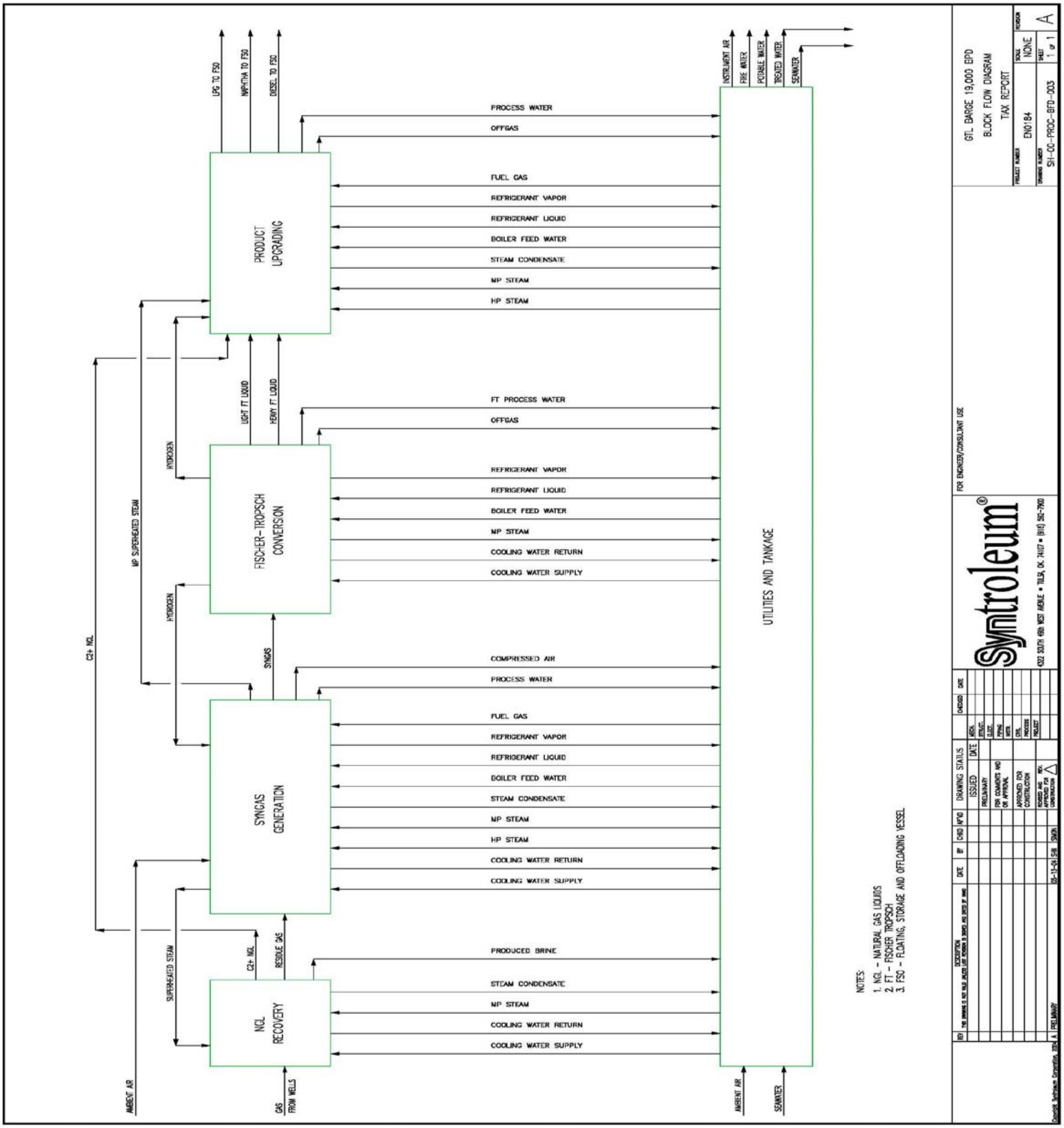
4.2.4 Product Upgrading

The product upgrading section of the plant refines the FT liquids into diesel, naphtha, and liquefied petroleum gas (LPG). The operation is analogous to refining of crude oil, but is conducted under much less severe operating conditions than conventional crude oil refining. This is due to the high quantities of paraffin and the absence of sulfur and other contaminants in the FT liquids. The product upgrade unit includes several sections to process the FT liquid. The primary sections are FT Fractionation, Hydroprocessing (Hydrotreater and Hydrocracker), Product Fractionation, and LPG and Naphtha Recovery and Stabilization. The product upgrading process has a flexible design that enables production of a wide range of distillate products and product adjustment to meet seasonal requirements.

4.2.5 Utilities

Process utilities for the GTL barge are shown below:

- Power generation, startup, main and emergency
- Instrument and utility air
- Fuel gas
- Diesel supply and storage
- Propane refrigeration
- Cooling water
- Startup steam and condensate
- Raw water, seawater, potable water, and firewater


LPG TO FSO
NAPHTHA TO FSO
DIESEL TO FSO
PROCESS WATER
OFFGAS
FUEL GAS
REFRIGERANT VAPOR
REFRIGERANT LIQUID
BOILER FEED WATER
STEAM CONDENSATE
MP STEAM
HP STEAM
PRODUCT UPGRADING
LIGHT FT LIQUID
HEAVY FT LIQUID
HYDROGEN
FT PROCESS WATER
OFFGAS
REFRIGERANT VAPOR
REFRIGERANT LIQUID
BOILER FEED WATER
MP STEAM
COOLING WATER RETURN
COOLING WATER SUPPLY
FISCHER-TROPSCH CONVERSION
MP SUPERHEATED STEAM
HYDROGEN
C2+ NGL
SYNGAS
COMPRESSED AIR
PROCESS WATER
FUEL GAS
REFRIGERANT VAPOR
REFRIGERANT LIQUID
BOILER FEED WATER
STEAM CONDENSATE
MP STEAM
HP STEAM
COOLING WATER RETURN
COOLING WATER SUPPLY
SYNGAS GENERATION
SUPERHEATED STEAM
C2+ NGL
RESIDUE GAS
PRODUCED BRINE
STEAM CONDENSATE
MP STEAM
COOLING WATER RETURN
COOLING WATER SUPPLY
NGL RECOVERY
AMBIENT AIR
GAS FROM WELLS
UTILITIES AND TANKAGE
INSTRUMENT AIR
FIRE WATER
POTABLE WATER
TREATED WATER
SEAWATER
AMBIENT AIR
SEAWATER
NOTES:
1. NGL - NATURAL GAS LIQUIDS
2. FT - FISCHER TROPSCH
3. FSO - FLOATING, STORAGE AND OFFLOADING VESSEL
GTL BARGE 19,000 BPD
BLOCK FLOW DIAGRAM
TAX REPORT
PROJECT NUMBER
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DRAWING NUMBER
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4.3 Construction Cost

Table 7 – GTL Barge Construction Cost

GTL Barge Construction Cost	
Total Installed Cost (2004 US$)	
Process	$601,984,777
GTL Barge Hull	$46,601,050
Living Quarters	$10,536,402
Construction Management	$16,286,762
Insurance and Legal	$10,223,741
Total	$685,642,732
GTL Barge FT Cost	
General Plant	$2,287,446
Feed Gas Pretreating	$23,643,774
Syngas Production	$215,695,058
Fischer-Tropsch	$179,092,894
Hydrogen Management	$4,764,767
Hydroprocessing	$43,490,007
Utilities	$133,010,832
Total	$601,984,777
Cost Estimate Assumptions	
Estimated accuracy +/- 30%	
Cost Estimate Exclusions	
Gas field development	
Gas risers and production equipment	
Spare parts including catalyst	
Environmental permitting / impact studies	
Contingency	

4.4 Module Size and Weights

Table 8 – GTL Barge Size and Weight

GTL Barge Size and Weight		
	Area	Weight
Overall GTL Barge	250 ft x 450 ft	25,000 DWT
NGL Recovery		
2 Modules	10,000 ft^2	530 - 560 DWT
Total Weight		1,090 DWT
Syngas Generation		
7 Modules	53,000 ft^2	350 - 2,600 DWT
Total Weight		6,450 DWT
FT Conversion		
6 Modules	17,000 ft^2	50 - 8,900 DWT
Total Weight		11,500 DWT
Product Upgrading		
1 Module	56,000 ft^2	1,300 DWT
Utilities		
16 Modules	37,000 ft^2	7 - 900 DWT
Total Weight		3,000 DWT
Notes	1. One deadweight ton (DWT) equals 1,000 kg or 2,205 lbs.	

4.5 Operating Costs

Table 9 – GTL Barge Operating Cost

GTL Barge Operating Cost	
Natural Gas, assumes $0.50/mmBtu	$ 30,000,000 / yr
Electricity	$ 0 / yr (self generated)
Water	$ 18,000/yr
Catalyst	$ 5,600,000 / yr
Staffing	$ 4,680,000 / yr
Water Treating Chemicals	$ 260,000 / yr
Notes 1. Electricity will be generated on-barge using stranded gas to drive a gas turbine generator.	

5. COAL BASED SYNGAS FOR SFP 100 BPD FT LIQUIDS

5.1 Differences from SFP

- Solids (coal) handling facilities including mills and driers
- Air Separation Unit (ASU)
- Replacement of Autothermal reformer with coal gasification equipment for preparation of raw syngas
- Additional gas treating facilities to purify syngas
- Additional water treating equipment
- LPG

5.2 Process Description

Mined coal entering the facility is finely milled and dried. The milled and dried coal is mixed with oxygen from an air separation unit before flowing to the gasifier. In the gasifier, the milled coal is converted to a mixture of syngas and carbon dioxide, along with the many contaminates naturally present in coal.

Once the syngas generated from coal has been cleaned, it is compressed, heated and sent to Fischer-Tropsch and product upgrading units. A typical mass balance for converting coal to hydrocarbon fuels for a nominal 100 bpd of FT liquid plant is shown below:

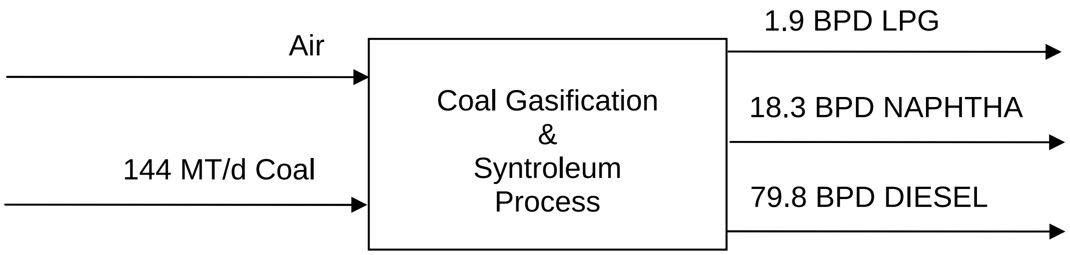
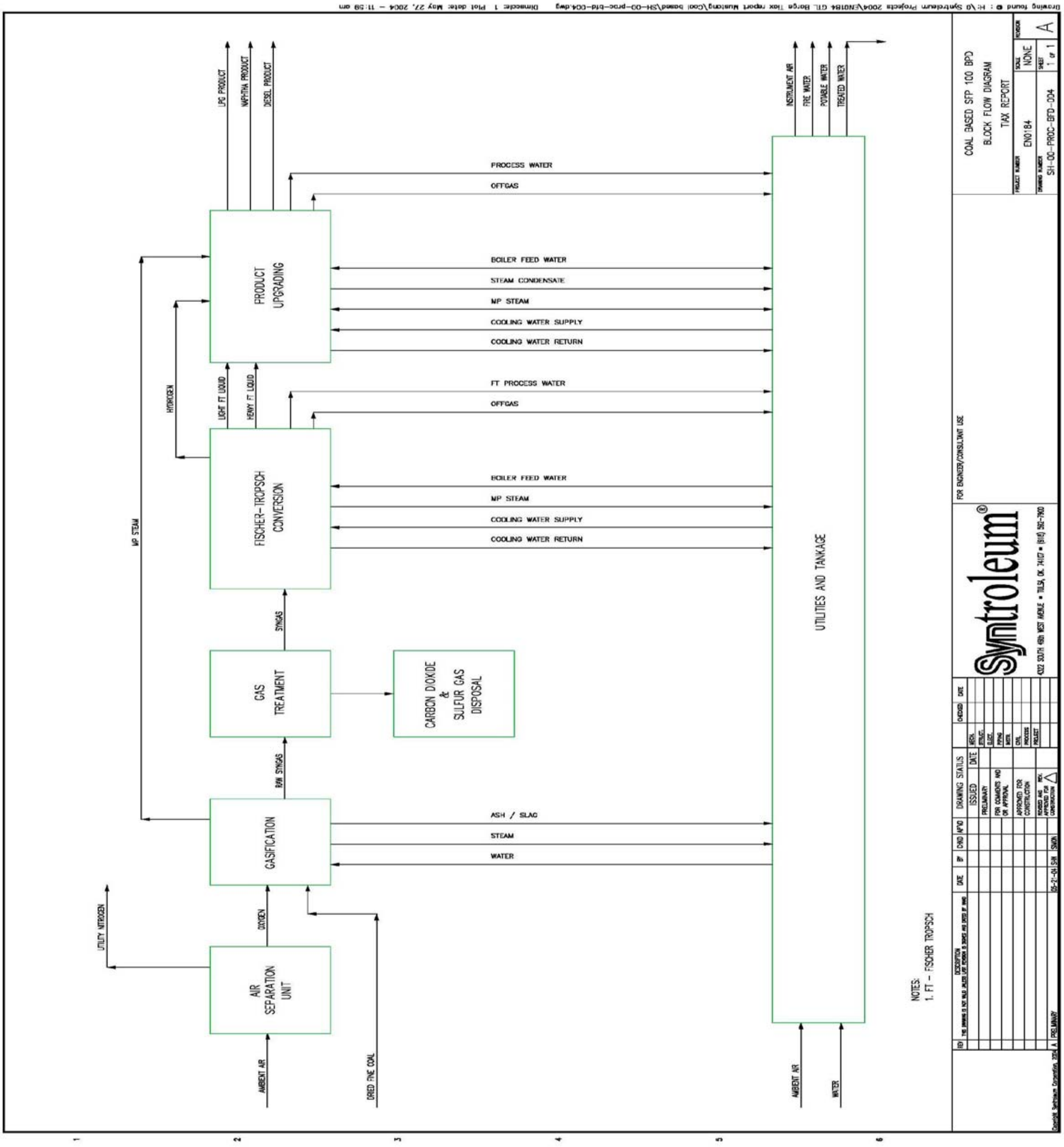


Figure 10 – Coal Based Syngas GTL Mass Balance

Contaminants from coal and coal gasification include carbon dioxide and sulfur compounds which must be removed by a series of gas treating stages to prevent poisoning of the Fischer-Tropsch catalyst. A block flow diagram for the coal based SFP plant is provided at the end of this section.


COAL BASED SFP 100 BPD
BLOCK FLOW DIAGRAM
TIAX REPORT
PROJECT NUMBER EN0184
DRAWING NUMBER SH-OO-PROC-BFD-004
SCALE NONE
SHEET 1 of 1
REVISION A
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NOTES:
1. FT - FISCHER TROPSCH
AIR SEPARATION UNIT
GASIFICATION
GAS TREATMENT
CARBON DIOXIDE & SULFUR GAS DISPOSAL
FISCHER-TROPSCH CONVERSION
PRODUCT UPGRADING
UTILITIES AND TANKAGE
AMBIENT AIR
DRIED FINE COAL
OXYGEN
UTILITY NITROGEN
RAW SYNGAS
SYNGAS
MP STEAM
HYDROGEN
LIGHT FT LIQUID
HEAVY FT LIQUID
LPG PRODUCT
NAPHTHA PRODUCT
DIESEL PRODUCT
PROCESS WATER
OFFGAS
BOILER FEED WATER
STEAM CONDENSATE
MP STEAM
COOLING WATER SUPPLY
COOLING WATER RETURN
FT PROCESS WATER
OFFGAS
BOILER FEED WATER
MP STEAM
COOLING WATER SUPPLY
COOLING WATER RETURN
ASH / SLAG
STEAM
WATER
INSTRUMENT AIR
FIRE WATER
POTABLE WATER
TREATED WATER
AMBIENT AIR
WATER
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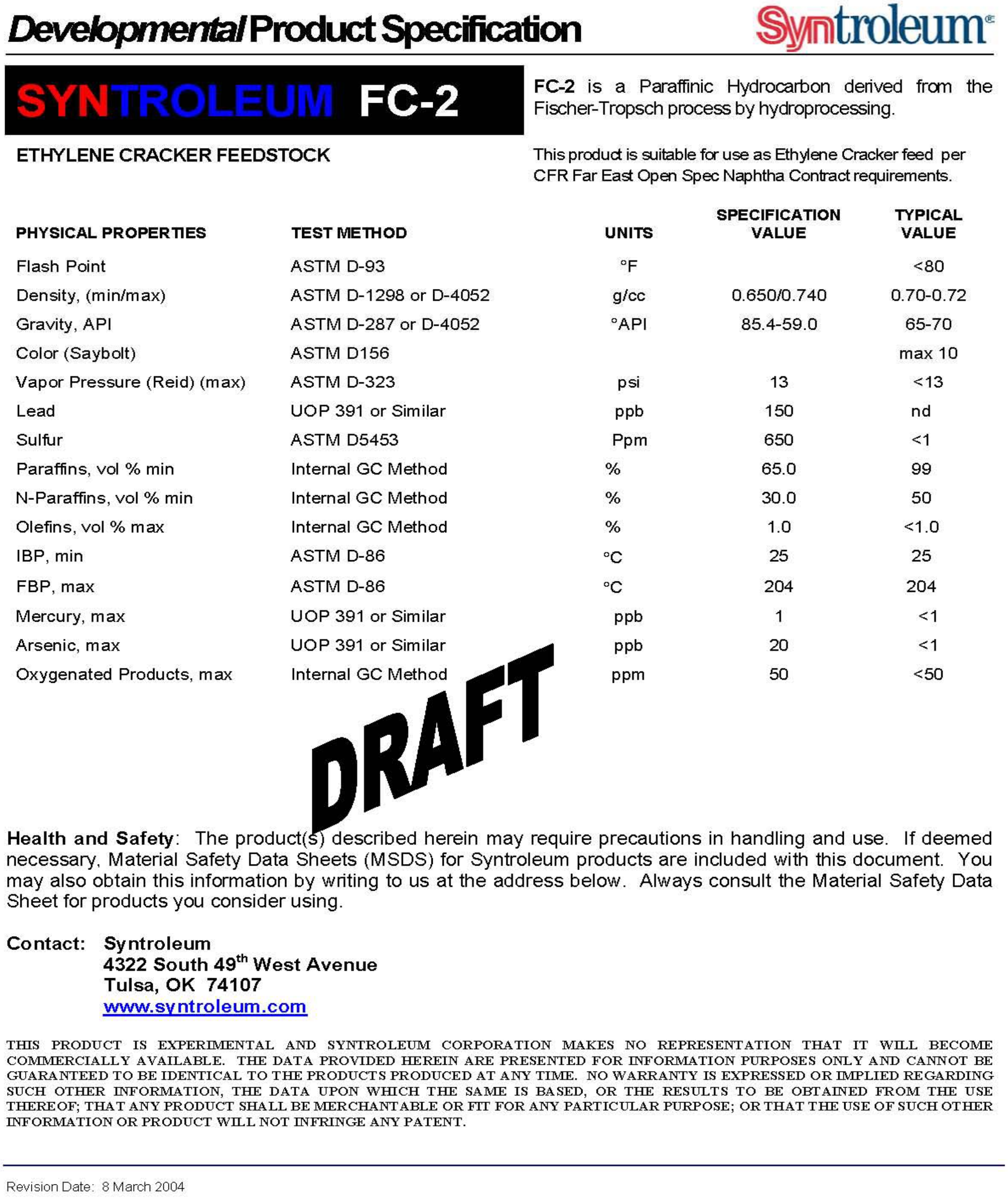
5.3 Construction Cost

Table 10 – Coal Based GTL SFP Construction Cost

Coal Based GTL SFP Construction Cost	
Total Installed Cost	
Air Separation Unit	$21,000,000
Syngas Generation	$40,000,000
FT Conversion	$21,500,000
Product Upgrading	$11,500,000
Utilities	$15,000,000
Total	$109,000,000
Cost Estimate Assumptions	
Coal syngas generation has no impact on Fischer-Tropsch or Product Upgrade Units	
Estimated accuracy +/- 50%	
Cost Estimate Exclusions	
Power generation	
Mining and coal production	
Spare parts	
Contingency	

6. APPENDIX A - SYNTROLEUM PRODUCT SPECIFICATIONS



Developmental Product Specification

Syntroleum®

SYNTROLEUM FC-2

FC-2 is a Paraffinic Hydrocarbon derived from the Fischer-Tropsch process by hydroprocessing.

ETHYLENE CRACKER FEEDSTOCK

This product is suitable for use as Ethylene Cracker feed per CFR Far East Open Spec Naphtha Contract requirements.

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	TYPICAL VALUE
Flash Point	ASTM D-93	°F		<80
Density, (min/max)	ASTM D-1298 or D-4052	g/cc	0.650/0.740	0.70-0.72
Gravity, API	ASTM D-287 or D-4052	°API	85.4-59.0	65-70
Color (Saybolt)	ASTM D156			max 10
Vapor Pressure (Reid) (max)	ASTM D-323	psi	13	<13
Lead	UOP 391 or Similar	ppb	150	nd
Sulfur	ASTM D5453	Ppm	650	<1
Paraffins, vol % min	Internal GC Method	%	65.0	99
N-Paraffins, vol % min	Internal GC Method	%	30.0	50
Olefins, vol % max	Internal GC Method	%	1.0	<1.0
IBP, min	ASTM D-86	°C	25	25
FBP, max	ASTM D-86	°C	204	204
Mercury, max	UOP 391 or Similar	ppb	1	<1
Arsenic, max	UOP 391 or Similar	ppb	20	<1
Oxygenated Products, max	Internal GC Method	ppm	50	<50

Health and Safety: The product(s) described herein may require precautions in handling and use. If deemed necessary, Material Safety Data Sheets (MSDS) for Syntroleum products are included with this document. You may also obtain this information by writing to us at the address below. Always consult the Material Safety Data Sheet for products you consider using.

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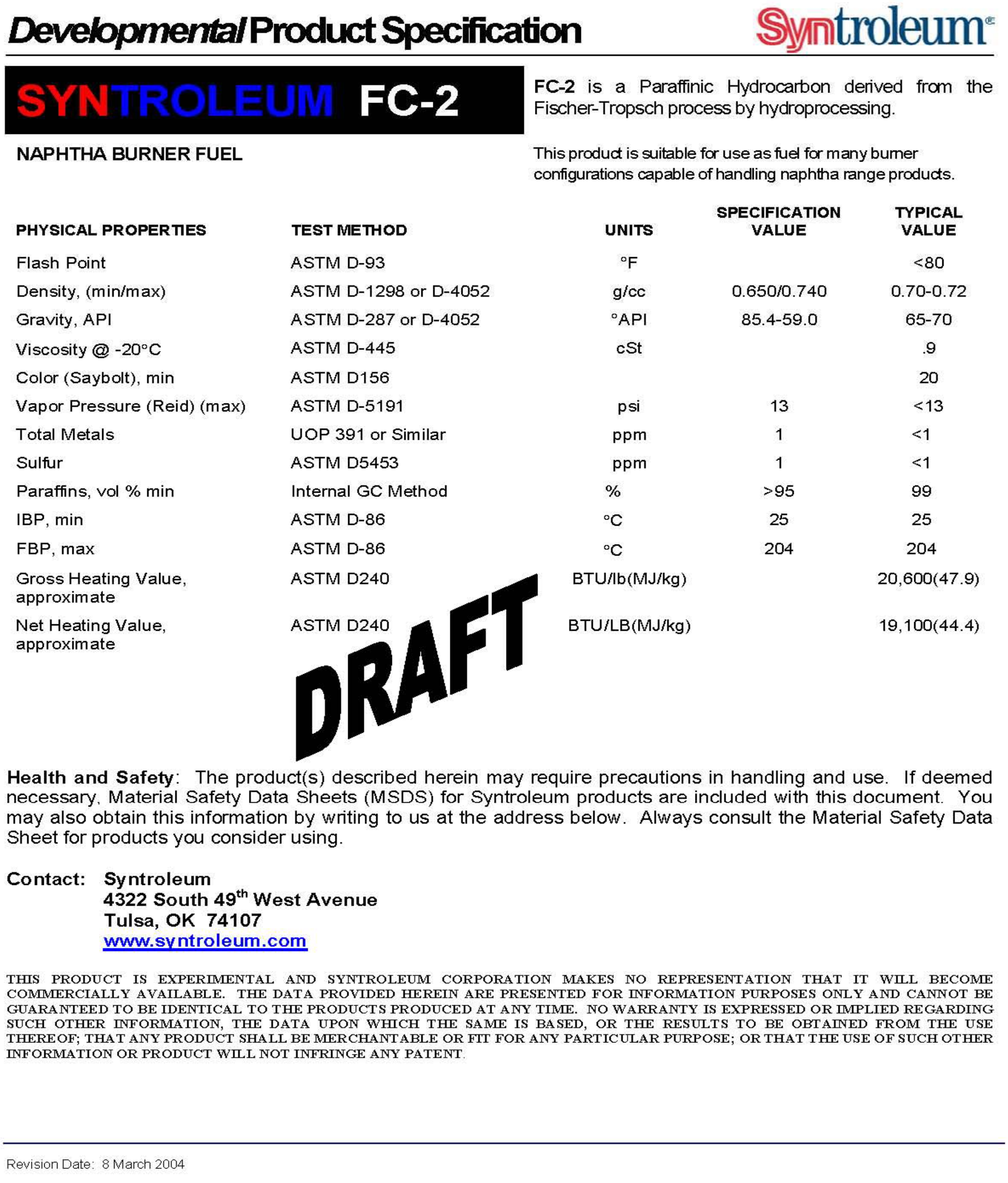
Revision Date: 8 March 2004

Appendix A-1 – Synthetic Naphtha (FC-2) for Ethylene Cracker Feedstock



Developmental Product Specification

Syntroleum®

SYNTROLEUM FC-2

NAPHTHA BURNER FUEL

FC-2 is a Paraffinic Hydrocarbon derived from the Fischer-Tropsch process by hydroprocessing.

This product is suitable for use as fuel for many burner configurations capable of handling naphtha range products.

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	TYPICAL VALUE
Flash Point	ASTM D-93	°F		<80
Density, (min/max)	ASTM D-1298 or D-4052	g/cc	0.650/0.740	0.70-0.72
Gravity, API	ASTM D-287 or D-4052	°API	85.4-59.0	65-70
Viscosity @ -20°C	ASTM D-445	cSt		.9
Color (Saybolt), min	ASTM D156			20
Vapor Pressure (Reid) (max)	ASTM D-5191	psi	13	<13
Total Metals	UOP 391 or Similar	ppm	1	<1
Sulfur	ASTM D5453	ppm	1	<1
Paraffins, vol % min	Internal GC Method	%	>95	99
IBP, min	ASTM D-86	°C	25	25
FBP, max	ASTM D-86	°C	204	204
Gross Heating Value, approximate	ASTM D240	BTU/lb(MJ/kg)		20,600(47.9)
Net Heating Value, approximate	ASTM D240	BTU/LB(MJ/kg)		19,100(44.4)

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Tulsa, OK 74107
www.syntroleum.com

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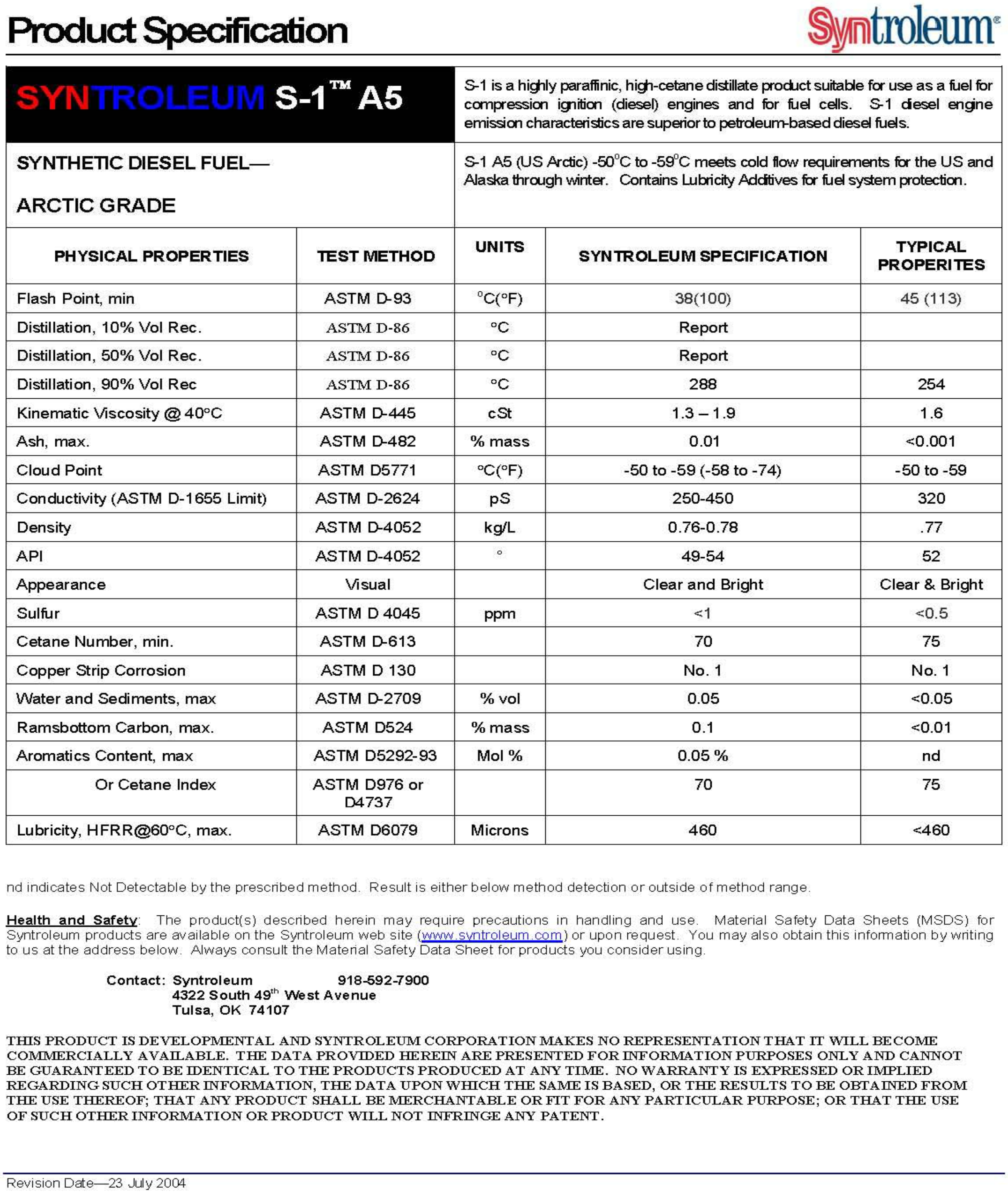
Revision Date: 8 March 2004

Appendix A-2 – Synthetic Naphtha (FC-2) for Naphtha Burner Fuel



Product Specification

Syntroleum®

SYNTROLEUM S-1™ A5	S-1 is a highly paraffinic, high-cetane distillate product suitable for use as a fuel for compression ignition (diesel) engines and for fuel cells. S-1 diesel engine emission characteristics are superior to petroleum-based diesel fuels.
SYNTHETIC DIESEL FUEL— **ARCTIC GRADE**	S-1 A5 (US Arctic) -50°C to -59°C meets cold flow requirements for the US and Alaska through winter. Contains Lubricity Additives for fuel system protection.

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SYNTROLEUM SPECIFICATION	TYPICAL PROPERITES
Flash Point, min	ASTM D-93	°C(°F)	38(100)	45 (113)
Distillation, 10% Vol Rec.	ASTM D-86	°C	Report	
Distillation, 50% Vol Rec.	ASTM D-86	°C	Report	
Distillation, 90% Vol Rec	ASTM D-86	°C	288	254
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.3 – 1.9	1.6
Ash, max.	ASTM D-482	% mass	0.01	<0.001
Cloud Point	ASTM D5771	°C(°F)	-50 to -59 (-58 to -74)	-50 to -59
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	320
Density	ASTM D-4052	kg/L	0.76-0.78	.77
API	ASTM D-4052	°	49-54	52
Appearance	Visual		Clear and Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	<0.5
Cetane Number, min.	ASTM D-613		70	75
Copper Strip Corrosion	ASTM D 130		No. 1	No. 1
Water and Sediments, max	ASTM D-2709	% vol	0.05	<0.05
Ramsbottom Carbon, max.	ASTM D524	% mass	0.1	<0.01
Aromatics Content, max	ASTM D5292-93	Mol %	0.05 %	nd
Or Cetane Index	ASTM D976 or D4737		70	75
Lubricity, HFRR@60°C, max.	ASTM D6079	Microns	460	<460

nd indicates Not Detectable by the prescribed method. Result is either below method detection or outside of method range.

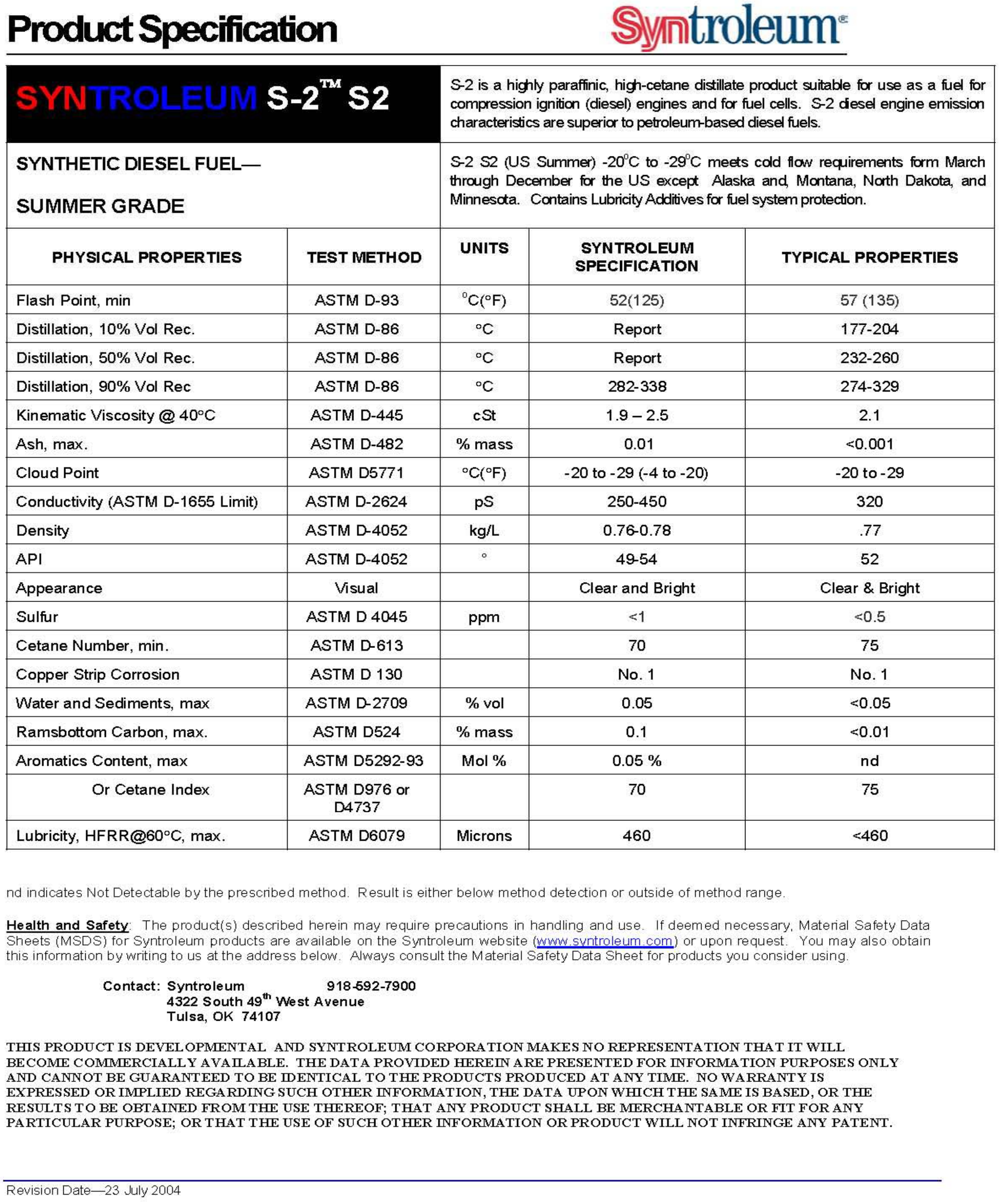
Health and Safety: The product(s) described herein may require precautions in handling and use. Material Safety Data Sheets (MSDS) for Syntroleum products are available on the Syntroleum web site (www.syntroleum.com) or upon request. You may also obtain this information by writing to us at the address below. Always consult the Material Safety Data Sheet for products you consider using.

Contact: Syntroleum 918-592-7900
4322 South 49th West Avenue
Tulsa, OK 74107

THIS PRODUCT IS DEVELOPMENTAL AND SYNTROLEUM CORPORATION MAKES NO REPRESENTATION THAT IT WILL BECOME COMMERCIALLY AVAILABLE. THE DATA PROVIDED HEREIN ARE PRESENTED FOR INFORMATION PURPOSES ONLY AND CANNOT BE GUARANTEED TO BE IDENTICAL TO THE PRODUCTS PRODUCED AT ANY TIME. NO WARRANTY IS EXPRESSED OR IMPLIED REGARDING SUCH OTHER INFORMATION, THE DATA UPON WHICH THE SAME IS BASED, OR THE RESULTS TO BE OBTAINED FROM THE USE THEREOF; THAT ANY PRODUCT SHALL BE MERCHANTABLE OR FIT FOR ANY PARTICULAR PURPOSE; OR THAT THE USE OF SUCH OTHER INFORMATION OR PRODUCT WILL NOT INFRINGE ANY PATENT.

Revision Date—23 July 2004

Appendix A-3 – Synthetic Arctic Grade #1 Diesel (S-1)



Product Specification

Syntroleum®

SYNTROLEUM S-2™ S2	S-2 is a highly paraffinic, high-cetane distillate product suitable for use as a fuel for compression ignition (diesel) engines and for fuel cells. S-2 diesel engine emission characteristics are superior to petroleum-based diesel fuels.
SYNTHETIC DIESEL FUEL— **SUMMER GRADE**	S-2 S2 (US Summer) -20^{0}C to -29^{0}C meets cold flow requirements form March through December for the US except Alaska and, Montana, North Dakota, and Minnesota. Contains Lubricity Additives for fuel system protection.

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SYNTROLEUM SPECIFICATION	TYPICAL PROPERTIES
Flash Point, min	ASTM D-93	^{o}C(°F)	52(125)	57 (135)
Distillation, 10% Vol Rec.	ASTM D-86	°C	Report	177-204
Distillation, 50% Vol Rec.	ASTM D-86	°C	Report	232-260
Distillation, 90% Vol Rec	ASTM D-86	°C	282-338	274-329
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9 – 2.5	2.1
Ash, max.	ASTM D-482	% mass	0.01	<0.001
Cloud Point	ASTM D5771	°C(°F)	-20 to -29 (-4 to -20)	-20 to -29
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	320
Density	ASTM D-4052	kg/L	0.76-0.78	.77
API	ASTM D-4052	°	49-54	52
Appearance	Visual		Clear and Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	<0.5
Cetane Number, min.	ASTM D-613		70	75
Copper Strip Corrosion	ASTM D 130		No. 1	No. 1
Water and Sediments, max	ASTM D-2709	% vol	0.05	<0.05
Ramsbottom Carbon, max.	ASTM D524	% mass	0.1	<0.01
Aromatics Content, max	ASTM D5292-93	Mol %	0.05 %	nd
Or Cetane Index	ASTM D976 or D4737		70	75
Lubricity, HFRR@60°C, max.	ASTM D6079	Microns	460	<460

nd indicates Not Detectable by the prescribed method. Result is either below method detection or outside of method range.

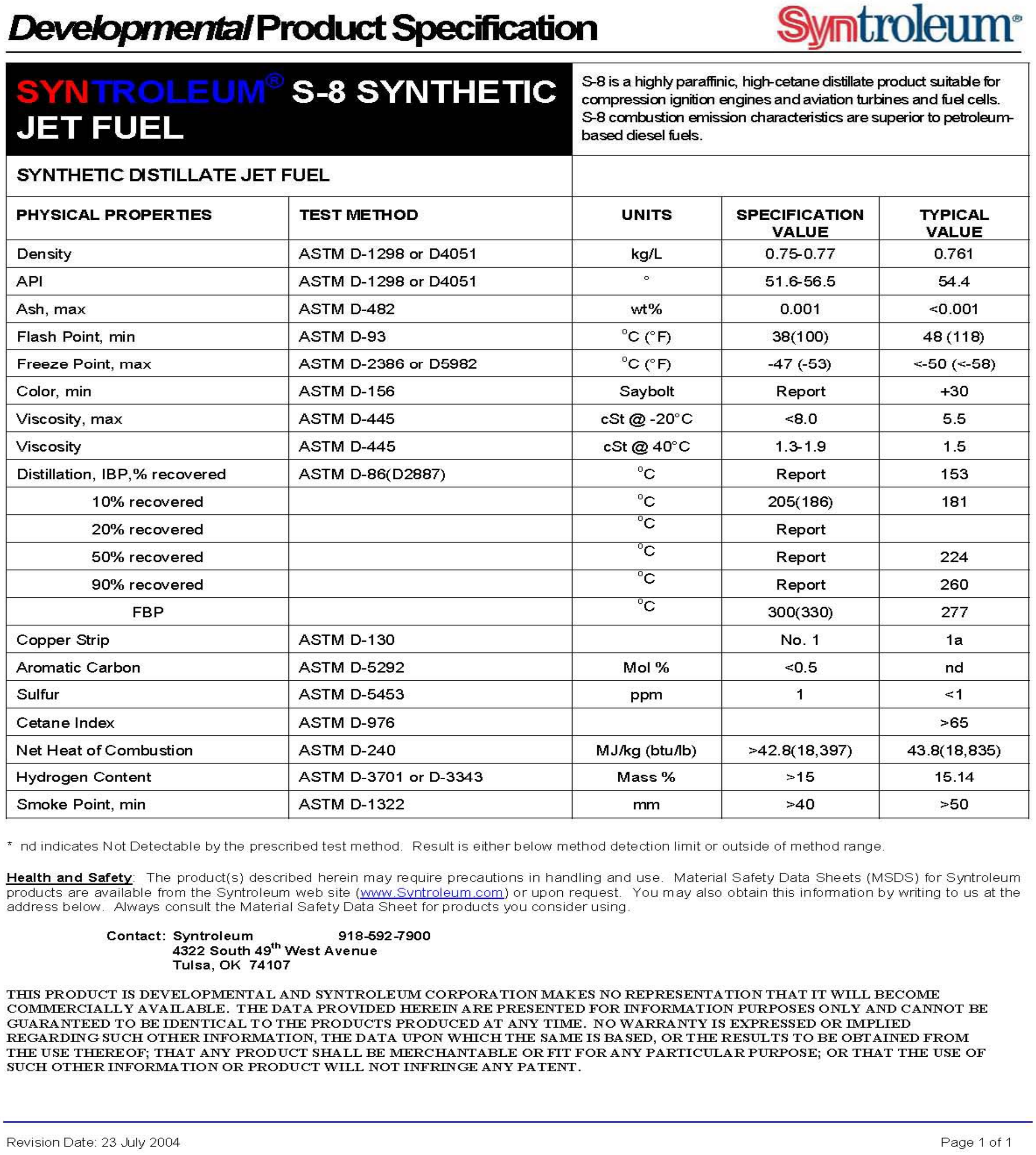
Health and Safety: The product(s) described herein may require precautions in handling and use. If deemed necessary, Material Safety Data Sheets (MSDS) for Syntroleum products are available on the Syntroleum website (www.syntroleum.com) or upon request. You may also obtain this information by writing to us at the address below. Always consult the Material Safety Data Sheet for products you consider using.

Contact: Syntroleum 918-592-7900
4322 South 49th West Avenue
Tulsa, OK 74107

THIS PRODUCT IS DEVELOPMENTAL AND SYNTROLEUM CORPORATION MAKES NO REPRESENTATION THAT IT WILL BECOME COMMERCIALLY AVAILABLE. THE DATA PROVIDED HEREIN ARE PRESENTED FOR INFORMATION PURPOSES ONLY AND CANNOT BE GUARANTEED TO BE IDENTICAL TO THE PRODUCTS PRODUCED AT ANY TIME. NO WARRANTY IS EXPRESSED OR IMPLIED REGARDING SUCH OTHER INFORMATION, THE DATA UPON WHICH THE SAME IS BASED, OR THE RESULTS TO BE OBTAINED FROM THE USE THEREOF; THAT ANY PRODUCT SHALL BE MERCHANTABLE OR FIT FOR ANY PARTICULAR PURPOSE; OR THAT THE USE OF SUCH OTHER INFORMATION OR PRODUCT WILL NOT INFRINGE ANY PATENT.

Revision Date—23 July 2004

Appendix A-4 – Synthetic Summer Grade #2 Diesel (S-2)



Developmental Product Specification

Syntroleum®

SYNTROLEUM® S-8 SYNTHETIC JET FUEL

S-8 is a highly paraffinic, high-cetane distillate product suitable for compression ignition engines and aviation turbines and fuel cells. S-8 combustion emission characteristics are superior to petroleum-based diesel fuels.

SYNTHETIC DISTILLATE JET FUEL

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	TYPICAL VALUE
Density	ASTM D-1298 or D4051	kg/L	0.75-0.77	0.761
API	ASTM D-1298 or D4051	°	51.6-56.5	54.4
Ash, max	ASTM D-482	wt%	0.001	<0.001
Flash Point, min	ASTM D-93	°C (°F)	38(100)	48 (118)
Freeze Point, max	ASTM D-2386 or D5982	°C (°F)	-47 (-53)	<-50 (<-58)
Color, min	ASTM D-156	Saybolt	Report	+30
Viscosity, max	ASTM D-445	cSt @ -20°C	<8.0	5.5
Viscosity	ASTM D-445	cSt @ 40°C	1.3-1.9	1.5
Distillation, IBP,% recovered	ASTM D-86(D2887)	°C	Report	153
10% recovered		°C	205(186)	181
20% recovered		°C	Report	
50% recovered		°C	Report	224
90% recovered		°C	Report	260
FBP		°C	300(330)	277
Copper Strip	ASTM D-130		No. 1	1a
Aromatic Carbon	ASTM D-5292	Mol %	<0.5	nd
Sulfur	ASTM D-5453	ppm	1	<1
Cetane Index	ASTM D-976			>65
Net Heat of Combustion	ASTM D-240	MJ/kg (btu/lb)	>42.8(18,397)	43.8(18,835)
Hydrogen Content	ASTM D-3701 or D-3343	Mass %	>15	15.14
Smoke Point, min	ASTM D-1322	mm	>40	>50

* nd indicates Not Detectable by the prescribed test method. Result is either below method detection limit or outside of method range.

Health and Safety: The product(s) described herein may require precautions in handling and use. Material Safety Data Sheets (MSDS) for Syntroleum products are available from the Syntroleum web site (www.Syntroleum.com) or upon request. You may also obtain this information by writing to us at the address below. Always consult the Material Safety Data Sheet for products you consider using.

Contact: Syntroleum 918-592-7900
4322 South 49th West Avenue
Tulsa, OK 74107

THIS PRODUCT IS DEVELOPMENTAL AND SYNTROLEUM CORPORATION MAKES NO REPRESENTATION THAT IT WILL BECOME COMMERCIALLY AVAILABLE. THE DATA PROVIDED HEREIN ARE PRESENTED FOR INFORMATION PURPOSES ONLY AND CANNOT BE GUARANTEED TO BE IDENTICAL TO THE PRODUCTS PRODUCED AT ANY TIME. NO WARRANTY IS EXPRESSED OR IMPLIED REGARDING SUCH OTHER INFORMATION, THE DATA UPON WHICH THE SAME IS BASED, OR THE RESULTS TO BE OBTAINED FROM THE USE THEREOF; THAT ANY PRODUCT SHALL BE MERCHANTABLE OR FIT FOR ANY PARTICULAR PURPOSE; OR THAT THE USE OF SUCH OTHER INFORMATION OR PRODUCT WILL NOT INFRINGE ANY PATENT.

Revision Date: 23 July 2004 Page 1 of 1

Appendix A-5 – Synthetic JP-8 Jet Fuel (S-8)

Copies of Required Construction and Environmental Permits for Small Footprint Plant

DOE award DE-FC26-01NT41099

January 12, 2006

Prepared by

Syntroleum Corporation
4322 South 49th West Avenue
Tulsa, Oklahoma 74107
Ph. (918) 592-7900
Fax (918) 592-7979

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DOE CDF Building Permit……………………………………………………...25
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NORTHSTAR
ENVIRONMENTAL RESOURCES, INC.

February 28, 2005

<u>FedEx Airbill# 847933742035</u>

Mr. Raymond Bishop
Air Quality Division
Oklahoma Department of Environmental Quality
707 N. Robinson
Oklahoma City, OK 73102

Re: Syntroleum Corporation 2004 Annual Air Emissions Inventories

Dear Mr. Bishop:

Please find enclosed the 2004 Air Emissions Inventory- Turn-Around Documents for the Syntroleum Corporation Pilot Plant located at 1900 N. 161st East Avenue in Tulsa and the Syntroleum Corporation Catoosa Demonstration Facility located at 880 West Tenkiller Road at the Port of Catoosa. I would like to point out that the Pilot Plant did not operated in the 2004 calendar year as designated by the "Idle" status on the report and therefore had no emissions.

If you have any questions concerning this submittal or need any additional information, please feel free to contact me at telephone number 918.695.2368 or Mr. Sid Schmoker of Syntroleum Corporation at telephone number 918.764.4384.

Sincerely,

Robert K Kennedy

Robert K. Kennedy, CHMM
Northstar Environmental Resources, Inc.

Enclosures

Cc: Mr. Sid Schmoker, Syntroleum Corporation- Catoosa, OK
Mr. Paul Kennedy, Syntroleum Corporation- Tulsa, OK

OKLAHOMA DEPARTMENT OF ENVIRONMENTAL QUALITY

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

Air Quality Division, Dept. of Environmental Quality, PO Box 1677, OKC, OK 73101-1677, (405) 702-4100

SYNTROLEUM CORP

GTL FUELS

TEAM ID
4952

Company Mailing Address	4322 S 49TH WEST AVE		
	TULSA	OK	741076100
Facility Physical Address	880 W TENKILLER RD		
	CATOOSA	OK	74015
Driving Directions	880 W TENKILLER, ROGERS CO, CATOOSA 74015. Facility is located at the Tulsa Port-of-Catoosa, a 2,000 acre industrial park.		

Ownership

Select one event:

- No Change ☒
- Sold ☐
- Dismantled ☐
- Acquired ☐
- New ☐

Start Date:

Stop Date:

Comments:

Status:	Active	
NAICS:	211112	
EPA:		
SIC:	1321	
Dunn and Brad:		
TRI:		
ORIS:		
Issued Permits:	2001-006-O 2001-006-C	9/16/2004 7/2/2001

Comments from this facility:

Inventory Format for Next Year:

● Hard Copy ○ Snapshot ○ AEI ○ DNI

Responsible Official

Name: ~~SID SCHMOKER~~ Jeffery M. Bigger

Phone: ~~(918) 764-4384~~ (918) 592-7900

Fax: ~~(918) 266-7376~~ (918) 592-7979

E-mail:

Location

County: ROGERS

Sec Loc:

Section: 6

Town: 20N

Range: 15E

UTM

Horz:

Vert:

Zone:

Latitude:

Longitude:

OKLAHOMA DEPARTMENT OF ENVIRONMENTAL QUALITY

20__ AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

FACILITY NAME: Syntroleum Corporation-Catoosa Demonstration Facility

Sequence [redacted] **Point Name:** Vapor Combustor

Notes	Status	UTM Horz	UTM Vert	Latitude	Longitude
	Active				

Stack Name	Gas Exit (ft/s)	Stack Height(ft)	Stack Dia. (1/10 ft)	Stack Temp(F)	FlowRate(acfm)	Fugitive Ht. (ft)
Vappr Combustor	1.18	50	8.0	1650	14,246	0

SCC	Process Description	Units	Confidential	Sulfur %	Ash %	MMBTU
31000205	Oil & Gas Production	Vapor Combustor	No	0	0	150

Seasonal Operation: (Decimal Percents) Spring 0.35 Summer 0.27 Fall 0.30 Winter 0.08

Rates: Hourly 0.39 Daily 4.03 Annual 684.8

Capacities: Design 9.36 Max 9.36

MACT: Code 0501 Compliance

Temporal: (24hr Clock) Start 12:00:00 am Stop 12:00:00 am Hours/Day 24 Days/Week 57 Weeks/Year 52 Hours/Year 5,581

POLLUTANT NAME: Carbon Monoxide
CAS#630-08-0

Allowed:	Excess %:	Amount (tons):
63.20		40.5

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Produced	AP-42 Factors	lbs	0.37

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
Flaring	98.0	None	

POLLUTANT NAME: Nitrogen Oxides (NOx)

Allowed:	Excess %:	Amount (tons):
11.62		7.4

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Produced	AP-42 Factors	lbs	0.068

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
Flaring	98.0	None	

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

FACILITY NAME: Syntroleum Corporation-Catoosa Demonstration Facility

Sequence	**Point Name:**
[redacted]	Vapor Combustor (Continued)

Notes	**Status**	**UTM Horz**	**UTM Vert**	**Latitude**	**Longitude**

Stack Name	**Gas Exit (ft/s)**	**Stack Height(ft)**	**Stack Dia. (1/10 ft)**	**Stack Temp(F)**	**FlowRate(acfm)**	**Fugitive Ht. (ft)**

SCC	**Process Description**	**Units**	**Confidential**	**Sulfur %**	**Ash %**	**MMBTU**

Seasonal Operation: (Decimal Percents) Spring ☐ Summer ☐ Fall ☐ Winter ☐

Rates: Hourly ☐ Daily ☐ Annual ☐

Capacities: Design ☐ Max ☐

MACT: Code ☐ Compliance ☐

Temporal: (24hr Clock) Start ☐ Stop ☐ Hours/Day ☐ Days/Week ☐ Weeks/Year ☐ Hours/Year ☐

POLLUTANT NAME: Total Hydrocarbon (THC)

Allowed:	**Excess %:**	**Amount (tons):**
23.92		15.3

Material:	**Material I/O:**	**Calculation Method:**	**Units:**	**Factor:**
Natural Gas	Produced	AP-42 Factors	lbs	0.14

Primary Control:	**Efficiency %:**	**Secondary Control:**	**Efficiency %:**
Flaring	98.0	None	

POLLUTANT NAME:

Allowed:	**Excess %:**	**Amount (tons):**

Material:	**Material I/O:**	**Calculation Method:**	**Units:**	**Factor:**

Primary Control:	**Efficiency %:**	**Secondary Control:**	**Efficiency %:**

20<u>04</u> AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

FACILITY NAME: Syntroleum Corporation- Catoosa Demonstration Facility

Sequence [redacted] **Point Name:** Fugative Emissions

Notes	Status	UTM Horz	UTM Vert	Latitude	Longitude
	Active	0	0	0	0

Stack Name	Gas Exit (ft/s)	Stack Height(ft)	Stack Dia. (1/10 ft)	Stack Temp(F)	FlowRate(acfm)	Fugitive Ht. (ft)

SCC	Process Description	Units	Confidential	Sulfur %	Ash %	MMBTU
31000207	Oil & Gas Production	Valves, connectors, flanges compressors, pump seals	No	0	0	0

Seasonal Operation: (Decimal Percents)	Spring	0.35	Summer	0.27	Fall	0.30	Winter	0.08	*Rates:*	Hourly	0.39	Daily	4.03	Annual	684.8
Capacities:	Design	9.36	Max	9.36					*MACT:*	Code	0501	Compliance			
Temporal: (24hr Clock)	Start	12:00:00 am	Stop	12:00:00 am	Hours/Day	24	Days/Week	7	Weeks/Year	52	Hours/Year	5,581			

POLLUTANT NAME: Total Hydrocarbons (THC)

Allowed:	Excess %:	Amount (tons):
30.63		19.11

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Produced	AP-42 Factors	lbs	0.14

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
None		None	

POLLUTANT NAME:

Allowed:	Excess %:	Amount (tons):

Material:	Material I/O:	Calculation Method:	Units:	Factor:

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:

DEQ
OKLAHOMA DEPARTMENT OF ENVIRONMENTAL QUALITY

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

FACILITY NAME: Syntroleum Corporation-Catoosa Demonstration Facility

Sequence [redacted]

Point Name: Deminimus Combustion Sources

Notes	Status	UTM Horz	UTM Vert	Latitude	Longitude
	Active				

Stack Name	Gas Exit (ft/s)	Stack Height(ft)	Stack Dia. (1/10 ft)	Stack Temp(F)	FlowRate(acfm)	Fugitive Ht. (ft)
Fugitive						

SCC	Process Description	Units	Confidential	Sulfur %	Ash %	MMBTU
31000207	Oil & Gas Production	Heater 1,2,3, Startup and Auxillary boilers				

Seasonal Operation: (Decimal Percents) Spring 0.35 Summer 0.27 Fall 0.30 Winter 0.08

Rates: Hourly Daily Annual

Capacities: Design Max

MACT: Code Compliance

Temporal: (24hr Clock) Start 12:00:00 am Stop 12:00:00 am Hours/Day Days/Week Weeks/Year Hours/Year

POLLUTANT NAME: Particulate Matter (PM$_{10}$)

Allowed:	Excess %:	Amount (tons):
0.88		0.49

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Consumed	AP-42 Factors	lbs	7.6/MMCF

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
None		None	

POLLUTANT NAME: Sulfur Dioxide

Allowed:	Excess %:	Amount (tons):
0.07		0.04

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Consumed	AP-42 Factors	lbs	0.6/MMCF

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
None			

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

FACILITY NAME: Syntroleum Corporation-Catoosa Demonstration Facility

Sequence [redacted] **Point Name:** Deminimus Combustion Sources (Continued)

Notes	Status	UTM Horz	UTM Vert	Latitude	Longitude

Stack Name	Gas Exit (ft/s)	Stack Height(ft)	Stack Dia. (1/10 ft)	Stack Temp(F)	FlowRate(acfm)	Fugitive Ht. (ft)

SCC	Process Description	Units	Confidential	Sulfur %	Ash %	MMBTU

Seasonal Operation: (Decimal Percents) Spring ☐ Summer ☐ Fall ☐ Winter ☐

Rates: Hourly ☐ Daily ☐ Annual ☐

Capacities: Design ☐ Max ☐

MACT: Code ☐ Compliance ☐

Temporal: (24hr Clock) Start ☐ Stop ☐ Hours/Day ☐ Days/Week ☐ Weeks/Year ☐ Hours/Year ☐

POLLUTANT NAME: Nitrous Oxides (NOx)

Allowed:	Excess %:	Amount (tons):
11.5		6.43

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Consumed	AP-42 Factors	lbs	100/MMCF

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
None			

POLLUTANT NAME: Carbon Monoxide

Allowed:	Excess %:	Amount (tons):
9.7		5.4

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Consumed	AP-42 Factors	lbs	84/MMCF

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
None			

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

FACILITY NAME: Syntroleum Corporation-Catoosa Demonstration Facility

Sequence [redacted] **Point Name:** Deminimus Combustion Sources (Continued)

Notes	Status	UTM Horz	UTM Vert	Latitude	Longitude

Stack Name	Gas Exit (ft/s)	Stack Height(ft)	Stack Dia. (1/10 ft)	Stack Temp(F)	FlowRate(acfm)	Fugitive Ht. (ft)

SCC	Process Description	Units	Confidential	Sulfur %	Ash %	MMBTU

Seasonal Operation: (Decimal Percents) Spring: Summer: Fall: Winter:

Rates: Hourly: Daily: Annual:

Capacities: Design: Max:

MACT: Code: Compliance:

Temporal: (24hr Clock) Start: Stop: Hours/Day: Days/Week: Weeks/Year: Hours/Year:

POLLUTANT NAME: Volatile Organic Compounds (VOC)

Allowed:	Excess %:	Amount (tons):
0.63		0.35

Material:	Material I/O:	Calculation Method:	Units:	Factor:
Natural Gas	Consumed	AP-42 Factors	lbs	5.5 MMCF

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:
None			

POLLUTANT NAME:

Allowed:	Excess %:	Amount (tons):

Material:	Material I/O:	Calculation Method:	Units:	Factor:

Primary Control:	Efficiency %:	Secondary Control:	Efficiency %:

DEQ
OKLAHOMA
DEPARTMENT OF ENVIRONMENTAL QUALITY

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

(Please Update with 2004 Totals)

GTL FUELS

4952

"I certify, based on information and belief formed after reasonable inquiry, the statements and information in the document are true, accurate, and complete."

Printed Name: Jeffery M. Bigger

Signature:

Date: 2/28/05

Title: Sr.VP-Engineering Chief Technology Officer

DEQ
OKLAHOMA DEPARTMENT OF ENVIRONMENTAL QUALITY

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

Air Quality Division, Dept. of Environmental Quality, PO Box 1677, OKC, OK 73101-1677, (405) 702-4100

COMPANY NAME: Syntroleum Corporation-Pilot Plant
FACILITY NAME:

Company Mailing Address
STREET: 4322 S. 49th West Avenue
CITY: Tulsa STATE: OK ZIP: 74116

Facility Physical Address
STREET: 1900 North 161st East Avenue
CITY: Tulsa STATE: OK ZIP: 74116

Driving Directions
I-44 East to 161st E. Ave. exit. Go north on 161st E. Ave. approximately 1 mile. Enter West through Cust-O-Fab facility gate.

Status: Idle
NAICS: 211112
EPA: 14500200
SIC: 1321
Dunn and Brad:
TRI:
ORIS:
Issued Permits:

Ownership

Select one event:
No Change ☒
Sold ☐
Dismantled ☐
Acquired ☐
New ☐
Start Date:
Stop Date:
Comments:

Comments from this facility:

This facility was idle for the full 2004 calendar year. There were no emissions from this facility during the reporting period of 1/1/04 through 12/31/04.

Inventory Format for Next Year:

● Hard Copy ○ Snapshot ○ AEI ○ DNI

Responsible Official

Name: Jeffery M. Bigger
Phone: (918) 592-7900
Fax: (918) 592-7979
E-mail:

Location

County: Rogers
Sec Loc:
Section: 17
Town: 18N
Range: 17E

UTM

Horz:
Vert:
Zone:
Latitude:
Longitude:

DEQ FORM # 100-730 TEAM GENERATED 12/15/2003 2:30:49 PM REV. 12/15/03

2004 AIR EMISSIONS INVENTORY TURN-AROUND DOCUMENT

(Please Update with 2004 Totals)

GTL FUELS

4952

"I certify, based on information and belief formed after reasonable inquiry, the statements and information in the document are true, accurate, and complete."

Printed Name: Jeffery M. Bigger

Signature:

Date: 2/28/05

Title: Sr.VP-Engineering Chief Technology Officer

NORTHSTAR
ENVIRONMENTAL RESOURCES, INC.

February 27, 2004

Mr. Jim Parker
City of Tulsa
Industrial Pretreatment Office
4818 South Elwood Avenue
Tulsa, OK 74107-8129

Re: Annual Permit Renewal for Syntroleum Corporation- Permit #6185

Dear Mr. Parker:

Please find enclosed the following items with regard to the annual permit renewal for the Syntroleum Corporation Pilot Plant facility, Permit # 6185.

Permit Application
Methods of Disposal Form
Attestation Statement
Check # 5905 in the amount of $375.00

If you should have any questions concerning this submittal or need additional information, please feel free to contact me at telephone number 918.695.2368.

Sincerely,

Robert K Kennedy
Robert K. Kennedy, CHMM
President

Enclosure

Cc: Mr. Steve LeViness, Syntroleum Corporation- Tulsa, OK

CITY OF TULSA
PUBLIC WORKS DEPARTMENT

Industrial Pretreatment
4818 South Elwood Avenue
Tulsa, OK 74107-8129
(918) 591-4378

Application For Permit For Industries To Discharge Wastewater To The Sanitary Sewer

Name of Industry Syntroleum Corp.- Pilot Plant		Standard Industrial Classification (SIC) Code(s) (if known) 1321			Date 2/25/04
Person to Contact If More Information Required Steve LeViness	Title Technical Director-Pilot Plant				Phone 918-764-3512
Mailing Address 4322 S. 49th W. Ave.	City Tulsa	State OK		Zip Code 74107	Phone 918-592-7900
Facility Address 1900 N. 161st E. Ave.	City Tulsa	State OK		Zip Code 74116	Phone 918-592-7900
Is Industry Inside Tulsa City Limits? ☒ Yes ☐ No	Average Number of Employees 5	Office 5	Production -0-	Total 5	
Days of Operation per Month 30	Days of Operation per Week 7		Hours of Operation per Day 11		

What is the nature of industries business? Give a brief description of products used. Type process used and/or service provided.

The Syntroleum Pilot Plant is a gas to liquids (GTL) processing facility. The facility takes natural gas and converts it to liquid hydrocarbons or syncrude. It is a two step process where the methane is reformulated into syngas. Once the syngas is produced it goes to the Fischer-Tropsch reactor where the syngas is converted to liquid aliphatic hydrocarbons. This produces both a light and heavy syncrude.

List water account number(s) for applicant facility

None (facility leases property from Cust-O-Fab, Inc. which provides the facility with water from their account)

Remarks:

For the 2003 calander year facility operated it's process from January 1 through August 23rd. It currently is in an "in-active" status other than office personnel with domestic water usage.

I certify that I am familiar with the information contained in the application and that to the best of my knowledge and belief such information is true, complete and accurate. I also certify that my company will take immediate steps to achieve compliance with the ordinance of the City of Tulsa if we are not in compliance at this time.

Typed or Printed Name of Person Signing Jeffrey M. Bigger	Title Sr. Vice President-Chief Technology Officer
Date Application Signed 27 Feb 04	Signature of Applicant or Representative

Return To:
Industrial Pretreatment
4818 South Elwood Avenue
Tulsa, OK 74107-8129

ATTESTATION STATEMENT

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

By: ____________________
Signature

27 Feb 04
Date

Jeffrey M. Bigger
Print Name

Sr. VP- Chief Technology Officer
Title

METHODS OF DISPOSAL

FACILITY NAME: Syntroleum Corp.- Pilot Plant

COMPLETED BY: Bob Kennedy (Northstar Environmental)

DATE: 2/25/04

WATER USE DISPOSAL: Please make entry in appropriate box

Water Use: Average and Maximum (1,000 gallons per day)

	SANITARY SEWER		STORM SEWER (NPDES)		EVAPORATION		HAULED		LAND APPLICATION		TOTAL RETENTION		OTHER (State Methods)		TOTAL	
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
ler																
Cooling																
Domestic Use	0.075	0.075													0.075	0.075
Food Processing																
Hydro-test																
Industrial Process																
Laundry																
Photo Rinses																
Plating Solutions																
Plating se																
Used in Product																
Vehicle Wash																
Other (State Use)																
TOTAL	0.075	0.075													0.075	0.075

NORTHSTAR ENVIRONMENTAL
RESOURCES, INC.
4626 W 86TH ST. PH. 918-447-9672
TULSA, OK 74132

86-1297/1031
900250666

5905

DATE February 26, 2004

PAY TO THE ORDER OF City of Tulsa ************************** $ 375.00****

Three Hundred Seventy Five and 00/100******** DOLLARS

ARVEST® BANK
(918) 631-1000
Tulsa, OK

146

MEMO Syn. Permit # 6185

Robert K Kennedy

⑆103112976⑆ 5905 900250666⑈

ONEOK GAS
TRANSPORTATION, L.L.C.

ONEOK GAS TRANSPORTATION

Measurement Department
P.O. BOX 871
Tulsa OK. 74102-0871

Orifice Meter Station Inspection Report

Date 3/15/2005

Station Number 2029001 Station Name Syntroleum

Legals ______ County Rogers State OK

Measuring Gas From A-1170 To Plant

Type Connection Flange Taps ☐ Pipe Taps ☐ Tube I.D. Size ______ Orifice Size ______ Orifice Changed? Yes ☐ No ☐

ORIFICE METER

Type Clock ______

Make ______ **Type** ______ **Rotation** ______

Manufacturer's Serial No. ______

Diff. Range ______ **Static Range** ______

Pen arc ______ **Time Lag** ______

Zero @ W.P. ______ **Zero @ Atmos.** ______

Friction Test ______

Before ______ **After** ______

Leaks Found ______ **Repaired** ______

THERMOMETER TEST

Make ______

Serial No. ______

Indicating ☐ Recording ☒

Range 0-150 Scale Test ☐

TEST	FOUND	LEFT
43.3	44.3	44.3

PRODUCER INFORMATION

	YES	NO
Producr Compressor	☐	☐
Pulastion Test	☐	☐
Pulastion Plate Size ______		
Producrer Dehy.	☐	☐
Producer Treating	☐	☐
Split-Connect	☐	☐

1. ______
2. ______
3. ______

DIFFERENTIAL TEST

INITIAL UP		INITIAL DOWN	
W.C.	METER	W.C.	METER
0	0	150	150.1
50	50.1	100	100.1
100	100	50	50.1
150	150.1	0	0.1
250	250		
FINAL UP		**FINAL DOWN**	
same		same	

OTHER TEST

H2O Vapor ______ LBS/MMCF

Meeco ☐ Other ☐

H2S Test 0 GR/100 ft3

Sample Taken Yes ☐ No ☐

Spot ☐ Composit ☐

Cylinder No. ______

Effective Date ______

Pressure ______ PSIG

Rate ______ MCF/D

Report of Changes

INSTALLED		REMOVED
	Orifice Size	
	Static Range	
	Differential Range	
	Line Size I/D	
	Chart Rotation Hours	
	Type Meter	

Time

Remarks ______

STATIC TEST

INITIAL TEST / SCALE TEST				FINAL TEST			
TEST INSTRUMENT		METER		TEST INSTRUMENT		METER	
260	PSIG	262.2	PSIG	0	PSIG	0	PSIG
0	PSIG	2.69	PSIG	260	PSIG	260	PSIG
	PSIG		PSIA		PSIG		PSIA
	PSIG		PSIA		PSIG		PSIA
	PSIG		PSIA		PSIG		PSIA

REMARKS / CHANGES Check static, diff and temp all OK

ORIFICE FITTING AND PLATE INSPECTION

Type Fitting Senior ☒ Simplex ☐ Flange ☐

Manufacture's Serial No. na

Condition of Fitting Operates Properly ☒ Need Attn. ☐

Condition of Plate Sharp ☒ Nicked ☐ Other ☐

Clean ☐ Dirty ☒

Plate Miked Yes ☐ No ☒

DIFFERENTAL FOUND ______

DIFFERENTIAL LEFT ______

WITNESS'S SIGNATURE None

INSPECTOR'S SIGNATURE Carnahan 109

NORTHSTAR
ENVIRONMENTAL RESOURCES, INC.

March 30, 2005

Mr. Jim Parker
City of Tulsa
Industrial Pretreatment Office
4818 South Elwood Avenue
Tulsa, OK 74107

Re: Syntroleum Clean Fuels Demonstration Facility, Permit # 6186

Dear Mr. Parker:

Please find enclosed the Semi-Annual Compliance Monitoring report for the above referenced facility located at 880 West Tenkiller Road in Catoosa, Oklahoma. This report covers the period of October 1, 2004 through March 31, 2005 and includes required analytical testing of their discharge, a completed Methods of Disposal form and an executed Attestation Statement by Syntroleum's company official.

If you have any questions concerning this submittal or if you need any additional information, please give me a call at telephone number 918.695.2368

Sincerely,

Robert K Kennedy

Robert K. Kennedy, CHMM
President

Enclosures

Cc: Mr. Jeffrey Bigger, Syntroleum Corporation- Tulsa, OK
Mr. Paul Kennedy, Syntroelum Corporation- Catoosa, OK
Mr. Sid Schmoker, Syntroleum Corporation- Catoosa, OK

ATTESTATION STATEMENT

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

By: Paul Kennedy
Signature

March 30, 2005
Date

Paul E. Kennedy
Print Name

Special Projects Manager
Title

NORTHSTAR
ENVIRONMENTAL RESOURCES, INC.

POTW Sampling and Analysis Form

Sampling Description

Date/Time of Sampling: 03/02/05 @ 1631 hr.

Location of Sampling: Designated sample chamber

Sampling Equipment Used: MasterFlex Composite Sampler
500ml glass sample container

Name of Sampler: Bob Kennedy

Analytical Results

Date/Time of Analysis: 03/02/05 @ 1632 hr.

Name of Analyst: Bob Kennedy

pH Results: 6.6 corrected to 25 C.

I certify that the sample obtained described above was representative of a normal discharge from the facility.

Paul Kennedy
Authorized Representative

3/30/05
Date

METHODS OF DISPOSAL

SySyntroleum Clean Fuels Demonstration Facility

JasJason DeVore

3/23/21/05

WATER USE DISPOSAL: Please make entry in appropriate box

Water Use: Average and Maximum (1,000 gallons per day)

RY RY R	STORM SEWER (NPDES)		EVAPORATION		HAULED		LAND APPLICATION		TOTAL RETENTION		OTHER (State Methods)		TOTAL	
MaxMax.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
			0.57	2.06							0.42	4.32	0.99	6.38
1.41.45			7.60	19.06									12.00	70.51
0.980.98													0.69	0.98
5.945.94													1.35	5.94
8.38.37			8.17	21.12							0.42	4.32	15.03	83.81

CERTIFICATE OF OPERATION

THIS CERTIFICATE SHOULD BE POSTED UNDER GLASS IN THE SAME ROOM AS THE VESSEL DESCRIBED.

THIS IS TO CERTIFY THAT THE VESSEL DESCRIBED BELOW MAY BE OPERATED AT A PRESSURE NOT TO EXCEED THAT SHOWN BELOW AND ONLY AT THE LOCATION SPECIFIED HEREIN.

OK NO. **46511**	LOCATION OF VESSEL Start Up Boiler				DATE OF INSPECTION 04/04/2005
NB/OTHER NO. 295	MANUFACTURER Universal	YEAR 2003	MAWP 700	HS 2760 VOL	EXTERNAL No INTERNAL Yes
MAXIMUM ALLOWED PRESSURE 700	INSPECTION AGENCY State		INSPECTED BY T Granneman		THIS CERTIFICATION EXPIRES **11/30/2005**

Syntroleum Corp
880 W Tenkiller Rd
Catoosa, OK 74015

NAME OF OWNER OR USER

STATE OF OKLAHOMA
DEPARTMENT OF LABOR
4001 North Lincoln Boulevard
Oklahoma City, Oklahoma 73105-5212
(405) 528-1500

THIS CERTIFICATION MAY BE REVOKED FOR FAILURE TO KEEP VESSEL IN SAFE CONDITION. WELDED REPAIRS SHOULD NOT BE ATTEMPTED WITHOUT FIRST CONSULTING THE

ROGERS COUNTY BUILDING PERMIT

Rogers County Metropolitan Area Planning Commission
212 South Missouri - Claremore, Oklahoma 74017
(918) 341-3486

Address 880 West Tenkiller Road Catoosa, ok

Subdivision Port of Catoosa Lot ______ Block ______ S 6 T 20 N R 15 E

Complete legal/finding property info: ______

Zoning I-3 Flood Zone ______ Corner ______ Back to back corner ______

Setbacks: Front ______ Side ______ Side ______ Rear ______ roadway centerline ______

Note: Restrictive covenants compliance is Owners responsibility & must abide by whichever restrictions are greater.

Description of Construction: Office

Outside dimensions = 76 x 106 Inside Sq. Ft. 7504 Floors ______

Garage: ______ Detached ______ x ______ Lot Size ______ x ______ Acres ______

A/C ______ Full Baths ______ Partial Baths ______

CONSTRUCTION COST $ 729,000.00 FOOT/FRAME FEES $ 80.00

FEES: BUILDING $ 1825.00 ELECTRICAL $ 270.00 PLUMBING $ 195.00 MECHANICAL $ 185.00

TOTAL FEES: $ 2,655.00 Approved by: Gary Orr Date Dec 18, 2002

OWNER: NAME Fleming Building Co, Inc PHONE ______

ADDRESS ______

BUILDER: NAME Syntroluem PHONE ______

ADDRESS ______

The owner and the undersigned agree to conform to requirements of Oklahoma Health Department and other pertinent codes. Described work is to begin within 90 days. **PERMIT EXPIRES ONE YEAR FROM ISSUE DATE.** Subcontractors to call for rough and top-out inspections; builder or owner to call for finals before move-in.

Signature of Applicant ______ Date 12-18-02

SUBCONTRACTORS: **

ELECT. Alpha Electric PLUMB. Davco Mech MECH. Davco Mech

Elec. phone # 610-9917 Plb. phone # 439-0540 Mech. phone # 439-0540

INSPECTIONS: **

Building Inspect:	Date/Inspector	Other Inspect.	Date / Inspector's Initials Rough	Top Out	Final
Foundations		Plumbing			
Framing					
Electric, Temporary Pole		Electrical		Temp. Final	
FOR INSPECTIONS, CALL 341-3486		Mechanical			
ROGERS COUNTY BUILDING PERMIT					

ROGERS COUNTY BUILDING PERMIT 7789

UNITED STATES OF AMERICA
DEPARTMENT OF TRANSPORTATION
PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION

HAZARDOUS MATERIALS CERTIFICATE OF REGISTRATION FOR REGISTRATION YEAR(S) 2004-2006

Registrant: SYNTROLEUM CORP

880 TENKILLER ROAD
CATOOSA, OK 74015

This certifies that the registrant is registered with the U.S. Department of Transportation as required by 49 CFR Part 107, Subpart G.

This certificate is issued under the authority of 49 U.S. C. 5108. It is unlawful to alter or falsify this document.

Reg. No: 033005 700 001MN **Issued: 03/30/05** **Expires: 06/30/06**

Record Keeping Requirements for the Registration Program

The following must be maintained at the principal place of business for a period of three years from the date of issuance of this Certificate of Registration:

(1) A copy of the registration statement filed with PHMSA; and
(2) This Certificate of Registration

Each person subject to the registration requirement must furnish that person's Certificate of Registration (or a copy) and all other records and information pertaining to the information contained in the registration statement to an authorized representative or special agent of the U. S. Department of Transportation upon request.

Each motor carrier (private or for-hire) and each vessel operator subject to the registration requirement must keep a copy of the current Certificate of Registration or another document bearing the registration number identified as the "U.S. DOT Hazmat Reg. No." in each truck and truck tractor or vessel (trailers and semi-trailers not included) used to transport hazardous materials subject to the registration requirement. The Certificate of Registration or document bearing the registration number must be made available, upon request, to enforcement personnel.

For information, contact the Hazardous Materials Registration Manager, DHM-60 Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, 400 Seventh Street, SW, Washington, DC 20590, telephone (202) 366-4109.

Syntroleum

July 31, 2006

Mr. Steve Bergin
Project Manager
Integrated Concepts Research Corporation
41150 Technology Park Drive, Suite 103
Sterling Heights, MI 48314

Subject: DOE Cooperative Agreement DE-FC26-01NT41099
Final Cost Summary – Subcontract No. 3044-SUB-01

Dear Steve,

As requested, in conjunction with the DOE Cooperative Agreement DE-FC26-01NT41009, the cost breakdown of the project is:

Syntroleum Corporation
DOE Cooperative Agreement DE-FC-01NT41099
Total Expense by Cost and Phase

AFE #2001118	WBS Code	DESCRIPTION	Third Party Expenditures	Synm Internal Labor	Marathon Internal Labor	Total Cost
	A	**Program Management**	$ 76,291	$ 139,393	$ 1,766,455	$ 1,982,139
BD0024	*B*	**Early Fuels Production**	$ 3,611	$ 36,175	$ -	$ 39,786
	C	**Process Design**	$ 600,856	$ 417,324	$ 590,943	$ 1,609,123
GTL Fuel Production and Demonstration Plant	*D*	**Engr. Procure & Const....Total**	$ 25,206,057	$ 3,957,647	$ 1,635,154	$ 30,798,858
	E	**Cherry Point Facilities**	$ 7,948,921	$ 1,100	$ -	$ 7,950,021
	F	**Start-Up**	$ 3,353,642	$ 512,652	$ 288,309	$ 4,154,602
	G	**Fuel Production**	$ 8,223,302	$ 11,116,767	$ 649,151	$ 19,989,219
	H	**Fuel Delivery**	$ 223,767	$ -	$ -	$ 223,767
	J	**Decommissioning**	$ -	$ -	$ -	$ -
	I	**Contingency**	$ -	$ -	$ -	$ -
TOTAL			**$ 45,636,447**	**$ 16,181,058**	**$ 4,930,012**	**$ 66,747,516**

BD0062 Cat Regen	WBS Code	DESCRIPTION	Third Party Expenditures	Synm Internal Labor	Marathon Internal Labor	Total Cost
	A	Program Management	$ 1,138	$ -	$ 74,618	$ 75,756
BD0062	C	Process Design	$ 612,751	$ 261,288	$ -	$ 874,039
CAT Regen	D	Engr. Procure & Const....Total	$ 5,836,249	$ 333,169	$ 67,010	$ 6,236,428
	F	Start-Up	$ 381,352	$ 308,405	$ -	$ 689,757
	G	Fuel Production	$ 89,202	$ 6,008	$ 105,064	$ 200,274
	I	Contingency	$ -	$ -	$ -	$ -
TOTAL			**$ 6,920,693**	**$ 908,870**	**$ 246,692**	**$ 8,076,255**

Catoosa Projects	WBS Code	DESCRIPTION	Third Party Expenditures	Synm Internal Labor	Marathon Internal Labor	Total Cost
	A	Program Management	$ -	$ -	$ -	$ -
Filter System Operability	C	Process Design	$ -	$ -	$ -	$ -
	D	Engr. Procure & Const....Total	$ 4,129,591	$ 516,808	$ -	$ 4,646,399
	F	Start-Up	$ -	$ -	$ -	$ -
	G	Fuel Production	$ -	$ -	$ -	$ -
	I	Contingency	$ -	$ -	$ -	$ -
TOTAL			**$ 4,129,591**	**$ 516,808**	**$ -**	**$ 4,646,399**

Regards,

Jon A. Warzel
Vice President – Business Development and Government Programs

Syntroleum Corporation • 4322 South 49th West Avenue • Tulsa, Oklahoma 74107 USA
(918) 592-7900 • FAX (918) 592-7979

Summary of the Production and Delivery of Syntroleum S-2 to Testing Laboratories and Field Demonstration Locations Participating in the DOE Ultra Clean Transportation Fuels

DOE award DE-FC26-01NT41099

August 31, 2005

Prepared by

Syntroleum Corporation
4322 South 49th West Avenue
Tulsa, Oklahoma 74107
Ph. (918) 592-7900
Fax (918) 592-7979

Robert L. Freerks: Director Product Development
Peter Havlik, Paul Ahner, Nathan Jannasch: Engineering Staff—Catoosa Demonstration Facility

Abstract:

Syntroleum Corporation has been tasked with production of synthetic diesel fuel from natural gas utilizing the Fischer-Tropsch process and conventional hydroprocessing technology for the DOE Ultra Clean Transportation Fuels Initiative—Topic 1, Production and Verification of Ultra-Clean Fuels. The scope of this task is to “produce ultra-clean fuels from a variety of energy resources - conventional crude oil, petroleum coke, refinery wastes, natural gas or coal - and verify the performance of these fuels by testing in engines” Syntroleum produced and delivered 110,800 gallons of fuel under this program. Recipients of the Syntroleum S-2 and S-2 Synthetic diesel fuels were the Washington Metropolitan Area Transportation Authority, ARAMARK/Denali National Park, Massachusetts Institute of Technology—Sloan Automotive Laboratory, the University of Alaska-Fairbanks Cold Test Facility. Also produced was synthetic jet fuel for evaluation by the DOD at various locations for use in turbine engine and transportation vehicle applications

EXECUTIVE SUMMARY

GTL Technology along with conventional upgrading technology offers an opportunity to convert hitherto unutilized or under-utilized resources into Ultra-Clean transportation fuels. Natural gas located throughout the world falls into this category in many instances as there is either no local market for the gas or conversion into other useful products is hindered by the location, abundance or cost of the natural gas resource. Additional gas resources are available as co-production with conventional crude oil resources. In many instances this gas is flared as it is inconvenient or expensive to reinject into the reserve it was taken from. In this instance, conversion of this gas into Ultra-Clean transportation fuel will either eliminate a significant Greenhouse Gas emissions source or allow production of crude oil that otherwise may not be produced due to lack of methods for handling the associated natural gas production.

Syntroleum Corporation is developing technology to convert natural gas and other carbon-bearing resources into Ultra-Clean transportation fuels via initial conversion to synthesis gas (CO and H_2), production of paraffinic hydrocarbons via the Fischer-Tropsch synthesis reaction, and finally conversion of the F-T products into transportation fuels utilizing conventional hydrocarbon processing technologies. Demonstration of the utility and benefits to the environment and society of these Gas-To-Liquids Ultra-Clean transportation fuels is critical to moving forward with development of commercial production facilities.

Under DOE contract DE-FC26-01NT41099, ICRC Corporation has contracted with Syntroleum Corporation to produce synthetic Ultra-Clean Transportation Fuel meeting ASTM D975 requirements. This fuel will be used in field and laboratory evaluations which will lead to better understanding of the utility and benefits of GTL Ultra-Clean fuels to the United States and society in general. Under the contract, Syntroleum Corp. produced 110,800 gallons of fuel. This fuel was made up of S-2 synthetic No. 2D diesel, S-1 synthetic No. 1D diesel, and S-8 synthetic JP-8 fuel. The diesel fuels were produced to meet ASTM D975 requirements and additional engine manufacturer and customer requirements typical for conventionally sourced diesel fuels. An additive package provided by Lubrizol Corporation was blended with the synthetic diesel fuel to allow the fuel to meet critical lubricity requirements as well as corrosion inhibition, foam control, water dispersion, oxidation stability and conductivity requirements. The synthetic jet fuel was treated with an approved antioxidant additive only to assure that reaction with atmospheric oxygen was minimized during transportation and storage of the jet fuel before delivery to the DOD for evaluation as a replacement fuel for conventionally produced JP-8 turbine engine fuel.

Fuels Production and Delivery from the Syntroleum Catoosa Demonstration Facility

Fuel Production and Formulation

Syntroleum Corporation has constructed a demonstration facility to produce 70 bbl/day of GTL products. This facility utilizes pipeline natural gas as feed to an autothermal reactor which produces synthesis gas of an appropriate ratio of hydrogen to carbon monoxide for use in the Fischer-Tropsch reaction. The Fischer-Tropsch reactor utilizes a proprietary catalyst technology for conversion of synthesis gas into paraffinic hydrocarbons. The FT reaction products follow the Anderson-Shultz-Flory distribution equation yielding a mixture of hydrocarbons ranging from C1 to above C60. A general representation of this distribution is shown in Figure 1.

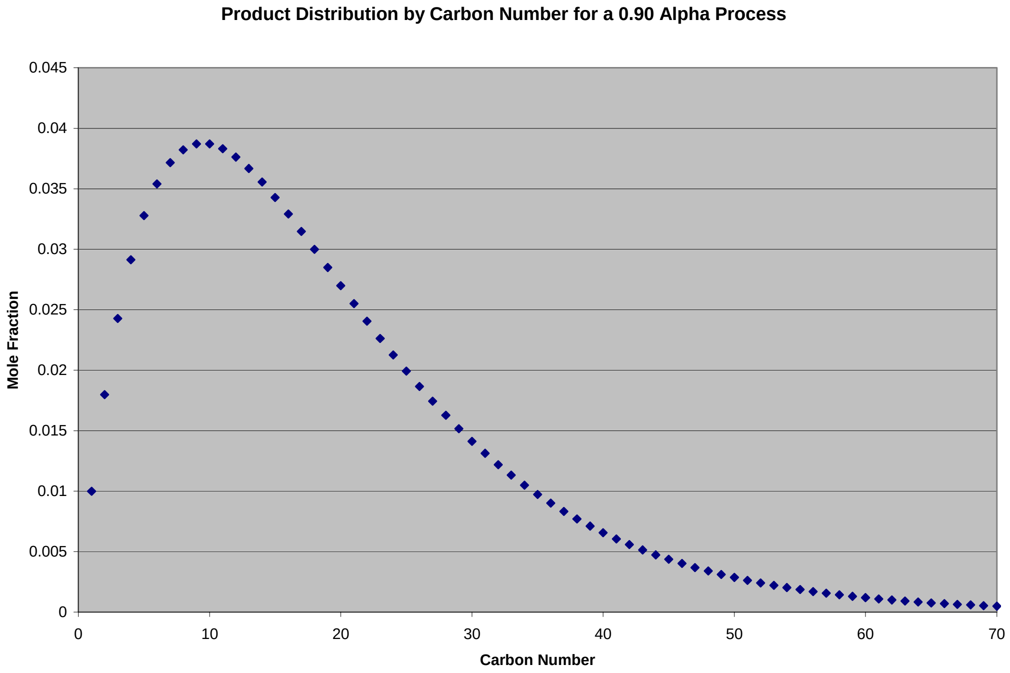


Figure 1. Product Distribution by Carbon Number for a 0.90 Alpha F-T Process

Diesel fuel and jet fuel must meet requirements specified in several documents such as ASTM D975 Standard Specification for Diesel Fuel Oils or ASTM D1655 Standard Specification for Aviation Turbine Fuels. These specifications set the distillation ranges appropriate for each fuel as well as numerous other requirements critical to the successful use of a fuel in an application. These specifications are not exhaustive, however, and they do not cover all issues that make a fuel “Fit For Purpose.” In the case of diesel fuel, it is often left to the fuel supplier to determine what additional performance requirements are necessary to make the fuel fit for use in customer's engines.

Syntroleum Corporation has developed technology for converting raw F-T reaction products into commercially viable products utilizing conventionally available hydroprocessing techniques. Although these techniques are well known in the industry, adaptation of these techniques to paraffinic feedstocks is not as well known. In order to make Ultra Clean Transportation Fuel using F-T feedstocks, several physical and chemical processes must take place. The broad carbon distribution of the FT reaction must be distilled into appropriate feeds for hydroprocessing equipment. The proper feed is then subjected to hydrocracking catalysts and conditions sufficient to convert all of the FT feedstock into material boiling in the diesel of jet fuel range along with some material boiling below that range which has use in other chemical processes.

Syntroleum was requested to provide fuels meeting several different diesel product requirements spanning the ASTM D975 No. 2D and No. 1D ranges. Fuel meeting D975 No. 2D specifications are known as Syntroleum S-2 and fuels meeting No. 1D specifications are know as S-1. Within D975, there are various climatic requirements outlined. Syntroleum provided S-2 meeting relatively severe low temperature requirements so that no problems with filter plugging would occur during any of the testing programs. This "summer diesel" fuel met a maximum Cloud Point of -20°C which is well below the minimum temperature that would be seen during the two field demonstration programs. To demonstrate utilization of the fuel in arctic climates, Syntroleum provided No. 1D fuel meeting the most stringent climatic requirements specified in D975. Syntroleum S-1 met a Cloud Point of -50ºC maximum, below the Tenth Percentile Minimum Ambient Air Temperature for Northern Alaska in winter as shown in ASTM D975 Appendix X.4.

Diesel fuels that are highly hydroprocessed to meet ultra low sulfur requirements established by the EPA will not provide sufficient lubricity to fuel handling components of a diesel engine. These fuels will require a lubricity additive that will replace the naturally occurring lubricity components of diesel fuel which are removed by hydroprocessing. Ultra Clean Transportation Fuels will also need lubricity additives and can utilize the same technology developed for ULSD fuels. These additives are commercially available. Syntroleum has partnered with Lubrizol Corporation to develop an additive system that will meet lubricity requirements of all world diesel fuels and engine manufacturers. At the time this program was initiated, ASTM did not include lubricity as a part of D975 specifications. However, the European specification EN590 did have a requirement and this was set as the target for Syntroleum S-2 and S-1 fuels. Subsequently, ASTM has adopted lubricity requirements into D975 which are not as stringent as those in EN590, so the development work is still valid. The additive system developed by Lubrizol also addresses other aspects of fuel performance which are not included in specifications such as EN590 and D975. These include oxidative stability (prevention of peroxide accumulation), foam stability (prevention of aeration of the fuel), demulsibility (prevention of emulsion formation with water), and corrosion prevention. Also included was an additive that improves the electrical conductivity of the fuel. This is considered a safety issue as accumulation of static charge in fuel has been associated with electrical discharge in some situations. The conductivity of the fuel is used as a quality assurance measurement to ascertain the presence and amount of the additive package in the fuel.

Fuel Specifications

Syntroleum bases its specifications for fuel on ASTM D975 as several other fuel specifications have density minimums which are above the typical density for highly paraffinic fuels such as GTL Ultra Clean fuel. D975 does not specifically set winter properties for diesel fuel but does address Cloud Point requirements with this comment and in Appendix X4:

> **It is unrealistic to specify low temperature properties that will ensure satisfactory operation at all ambient conditions. In general, cloud point (or wax appearance point) may be used as an estimate of operating temperature limits for Grades Low Sulfur No. 1; Low Sulfur No. 2; and No. 1 and No. 2 diesel fuel oils. However, satisfactory operation below the cloud point (or wax appearance point) may be achieved depending on equipment design, operating conditions, and the use of flow-improver additives as described in X4.1.2. Tenth percentile minimum air temperatures for U.S. locations are provided in Appendix X4 as a means of estimating expected regional temperatures. This guidance is general. Some equipment designs or operation may allow higher or require lower cloud point fuels. Appropriate low temperature operability properties should be agreed upon between the fuel supplier and purchaser for the intended use and expected ambient temperatures.**

Syntroleum has designated several quality grades of diesel fuels to address low temperature performance of the fuel. Using D975 Appendix X4 as a guide, Summer fuel should meet climatic minimum temperatures for the lower 48 states through the Fall months. The November 10th Percentile Minimum Ambient Air Temperature for the Lower 48 states is -20ºC (North Dakota). Syntroleum has therefore defined three grades of Summer Diesel Fuel with average cloud point requirements of -5ºC, -15ºC, and -25ºC. Winter diesel fuels should satisfy customer performance requirements under all winter conditions except Arctic Climates. Two Winter Diesel Fuel grades have been defined with average cloud point requirements of -35ºC and -45ºC. To meet winter arctic conditions, a fuel must meet the 10th Percentile Minimum Ambient Air Temperature for Northern Alaska for all winter months which is -49ºC. Arctic Diesel Fuel is therefore defined as having a cloud point below -50ºC. Specific ranges for these grades of S-2 and S-1 are shown in the table below.

Product Name	Product Grade	Flash, °C	KV 40, cSt	Cloud, °C
		D 93	D 445	D 5771
S-2	S0	125 min.	1.9-2.5	0 to -9°C
S-2	S1	125 min.	1.9-2.5	-10 to -19°C
S-2	S2	125 min.	1.9-2.5	-20 to -29°C
S-2	W3	125 min.	1.9-2.5	-30 to -39°C
S-2	W4	125 min.	1.9-2.5	-40 to -49°C
S-2	A5	125 min.	1.9-2.5	-50 to -59°C
S-1	S0	100 min.	1.3-2.4	0 to -9°C
S-1	S1	100 min.	1.3-2.4	-10 to -19°C
S-1	S2	100 min.	1.3-2.4	-20 to -29°C
S-1	W3	100 min.	1.3-2.4	-30 to -39°C
S-1	W4	100 min.	1.3-2.4	-40 to -49°C
S-1	A5	100 min.	1.3-2.4	-50 to -59°C

Table 1. Flash Point, Kinematic Viscosity and Cloud Point ranges for Syntroleum Fuels.

Appendix 1 shows the specification sheet for Syntroleum S-2 S2 Summer Diesel fuel which is the fuel provided for the majority of the testing and demonstrations programs of this project. Appendix 2 shows the specification for S-1 S5 Arctic diesel fuel which was supplied to the University of Alaska Fairbanks for generator set testing.

Fuel Additization and Quality Control Testing

In order to simplify production, handling and delivery of fuel from the Catoosa Demonstration Facility, the output from the hydroprocessing unit was fed directly to ISO containers. These containers are suitable for international transportation of liquid products. They can contain 24,000 liters of liquid and were usually filled to 6000 gallons. During filling, additive concentrate was placed in the container so that mixing could occur. At the end of filling, a sample was taken for quality assurance testing.

Blending additives with fuels and lubricants is a well practiced art. Quality assurance of these blends involves testing those properties that can vary during the production and blending of the product and not testing those properties that are invariant. For Syntroleum S-2, production variables include distillation range, density, flash point, viscosity, ash, cloud point, specific gravity, appearance and conductivity. All the variables except for conductivity are related to production of the fuel. Conductivity is related to the presence of the additive package at the proper concentration. Since sufficient testing has been conducted to know that the additive system provides the required lubricity function in the fuel, simple tests to verify that the additive is present in the fuel will suffice for quality assurance. Syntroleum S-2 has essentially no conductivity as produced. Addition of the Lubrizol additive to the fuel increases the conductivity to 300-450 pS/m. Therefore conductivity is used as the measure of the presence of additive in the fuel prior to shipping. Appendixes 3 to 27 contains Certificate of Analysis sheets for all of the fuel shipments for this project.

Fuel Shipments

The majority of fuel shipped under this contract was done by ISO container. Both field test locations were able to receive bulk fuel and transfer the fuel to on-site fuel storage tanks. AVL Powertrain Engineering has an underground tank and also received bulk fuel. MIT Sloan Automotive Laboratory received drum quantities of fuel as they did not have bulk storage capabilities.

Table 2 summarizes the ISO container shipments from the Catoosa Demonstration Facility. Approximately 93,000 gallons of fuel were shipped by this method.

TABLE 2. Catoosa Demonstration Facility Fuels Shipping Details Through 8/05/05
ISO Container shipments

Production Period		**Production Volume (3)**	**Product**		**Iso-Container Serial No.**	**Ship Date**	**Location**
Start	**End**	**Gallons**	Type	Grade			
03-Mar-04	11-Mar-04	5,894	S-1	W3	124269-0	**30-Apr-04**	Univ. of Alaska - Fairbanks, AK
29-Mar-04	05-Apr-04	6,073	S-2	S2	124245-2	**07-Apr-04**	AVL - Ann Arbor, MI
06-Apr-04	14-Apr-04	5,332	S-2	S3	124015-1	**25-Jun-04**	WMATA - Landover, MD
15-Apr-04	27-Apr-04	5,950	S-2	S3	124039-9	**04-Jun-04**	Denali NP - Denali, AK
23-Apr-04	09-Jun-04	6,164	S-2	S2	124120-3	**16-Mar-05**	WMATA - Landover, MD
09-Jun-04	13-Jun-04	6,000	S-2	S2	635005-8	**01-Nov-04**	AVL - Ann Arbor, MI
01-Aug-04	08-Aug-04	4,600	S-1	W4	124159-0	**14-Sep-04**	Denali NP - Denali, AK
07-Aug-04	10-Aug-04	6,110	S-2	S2	125214-7	**01-Sep-04**	AVL - Ann Arbor, MI
10-Aug-04	13-Aug-04	6,010	S-2	S2	124056-8	**26-Oct-04**	WMATA - Landover, MD
13-Aug-04	15-Aug-04	6,008	S-2	S2	124194-4	**09-Feb-05**	WMATA - Landover, MD
15-Aug-04	18-Aug-04	6,058	S-2	S2	124180-0	**19-Aug-04**	Univ. of Alaska - Fairbanks, AK
24-Aug-04	03-Sep-04	6,014	S-2	S2	124260-0	**10-Sep-04**	WMATA - Landover, MD
03-Sep-04	06-Sep-04	6,039	S-2	S2	124265-8	**08-Oct-04**	AVL - Ann Arbor, MI
06-Sep-04	08-Sep-04	6,190	S-2	S2	124285-3	**20-Dec-04**	WMATA - Landover, MD
26-Sep-04	30-Sep-04	6,050	S-1	A5	125216-8	**19-Oct-04**	Univ. of Alaska - Fairbanks, AK
03-Dec-04	03-Dec-04	4,323	S-2	S2	124015-1	**04-Dec-04**	AVL - Ann Arbor, MI
Total gal from ISO shipments		92,815					

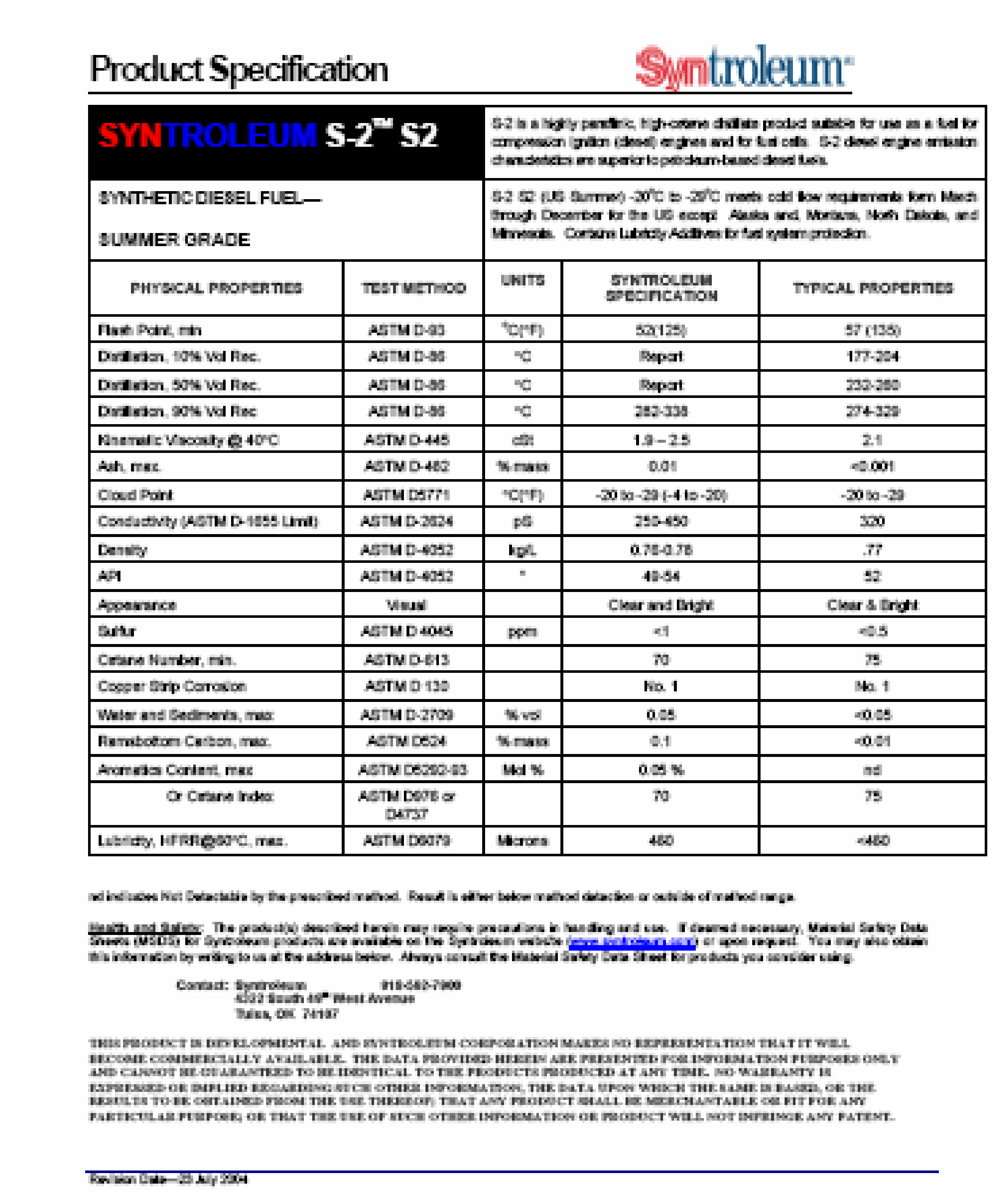
Syntroleum S-8 Synthetic Jet fuel produced under this program was drummed prior to shipment since many of the locations receiving this fuel did not have bulk fuel storage capabilities. In addition, this fuel will be stored for a substantial period of time in some cases, and sealed epoxy lined drums are preferable to bulk storage to reduce degradation of the fuel. To further improve storage of the fuel, drums were flushed with nitrogen prior to and during filling to reduce the amount of oxygen available in the drums. Two separate production runs of S-8 Jet Fuel were conducted. The first shipment volume was 10,000 gallons and the second was 4,600 gallons. Appendix 25 and 26 show the Certificates of Analysis for the two ISO containers of S-8 from the first production run, and Appendix 27 shows the Certificate of analysis for the second smaller batch of S-8.

Syntroleum S-2 and S-1 fuel was also shipped in epoxy lined drums, but these drums were not purged with nitrogen prior to filling as the fuel would be consumed within a short time period.

TABLE 3. Catoosa Demonstration Facility Fuels Shipping Details Through 8/05/05

	Shipment						
Client	**Drum Qty.**	**Gal.**	**Type**	**Grade**	**Source**	**Shipping Date**	**Shipping Location and/or notes**
US Army	25	1,375	S-8	na	ISO 124069-7	24-Sep-2004	Air Force, Wright Patterson AFB
	6	330	S-8	na	ISO 124069-7	27-Sep-2004	Army, Warren MI
	4	220	S-8	na	ISO 124069-7	27-Sep-2004	Naval Air Station, MD
	104	5,720	S-8	na	ISO 620001-6	12-Oct-2004	SWRI, TX
	48	2,640	S-8	na	ISO 620001-6	12-Oct-2004	SWRI, TX
WMATA	2	110	S-2	S3	Batch 2 Lot 1	29-Mar-2004	Preliminary testing.
MIT	2	110	S-2	S2	Batch 3 Lot 1	28-Apr-2004	Cambridge, Massachusetts
	4	220	S-1	W4	Batch 10 Lot 2	6-Aug-2004	Cambridge, Massachusetts
	33	1,815	S-2	S2	ISO 124015-1	14-Oct-2004	Cambridge, Massachusetts
	15	825	S-2	S2	Note 5	22-Jun-2005	Cambridge, Massachusetts
DoD	84	4,620	S-8	na	ISO 124154-3		Wright-Patterson AFB
STotal	352	17985					

Appendix 1. Example specification sheet for Syntroleum S-2 Synthetic Diesel Fuel



Product Specification

Syntroleum

SYNTROLEUM S-2™ S2	S-2 is a highly paraffinic, high-cetane distillate product suitable for use as a fuel for compression ignition (diesel) engines and for fuel cells. S-2 diesel engine emission characteristics are superior to petroleum-based diesel fuels.
SYNTHETIC DIESEL FUEL— SUMMER GRADE	S-2 S2 (US Summer) -20°C to -29°C meets cold flow requirements from March through December for the US except Alaska and, Montana, North Dakota, and Minnesota. Contains Lubricity Additives for fuel system protection.

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SYNTROLEUM SPECIFICATION	TYPICAL PROPERTIES
Flash Point, min	ASTM D-93	°C(°F)	52(125)	57 (135)
Distillation, 10% Vol Rec.	ASTM D-86	°C	Report	177-204
Distillation, 50% Vol Rec.	ASTM D-86	°C	Report	232-280
Distillation, 90% Vol Rec	ASTM D-86	°C	282-338	274-329
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9 – 2.5	2.1
Ash, max.	ASTM D-482	% mass	0.01	<0.001
Cloud Point	ASTM D5771	°C(°F)	-20 to -29 (-4 to -20)	-20 to -29
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	320
Density	ASTM D-4052	kg/L	0.76-0.78	.77
API	ASTM D-4052	°	49-54	52
Appearance	Visual		Clear and Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	<0.5
Cetane Number, min.	ASTM D-613		70	75
Copper Strip Corrosion	ASTM D 130		No. 1	No. 1
Water and Sediments, max	ASTM D-2709	% vol	0.05	<0.05
Ramsbottom Carbon, max.	ASTM D524	% mass	0.1	<0.01
Aromatics Content, max	ASTM D5292-93	Mol %	0.05 %	nd
Or Cetane Index	ASTM D976 or D4737		70	75
Lubricity, HFRR@60°C, max.	ASTM D6079	Microns	460	<460

nd indicates Not Detectable by the prescribed method. Result is either below method detection or outside of method range.

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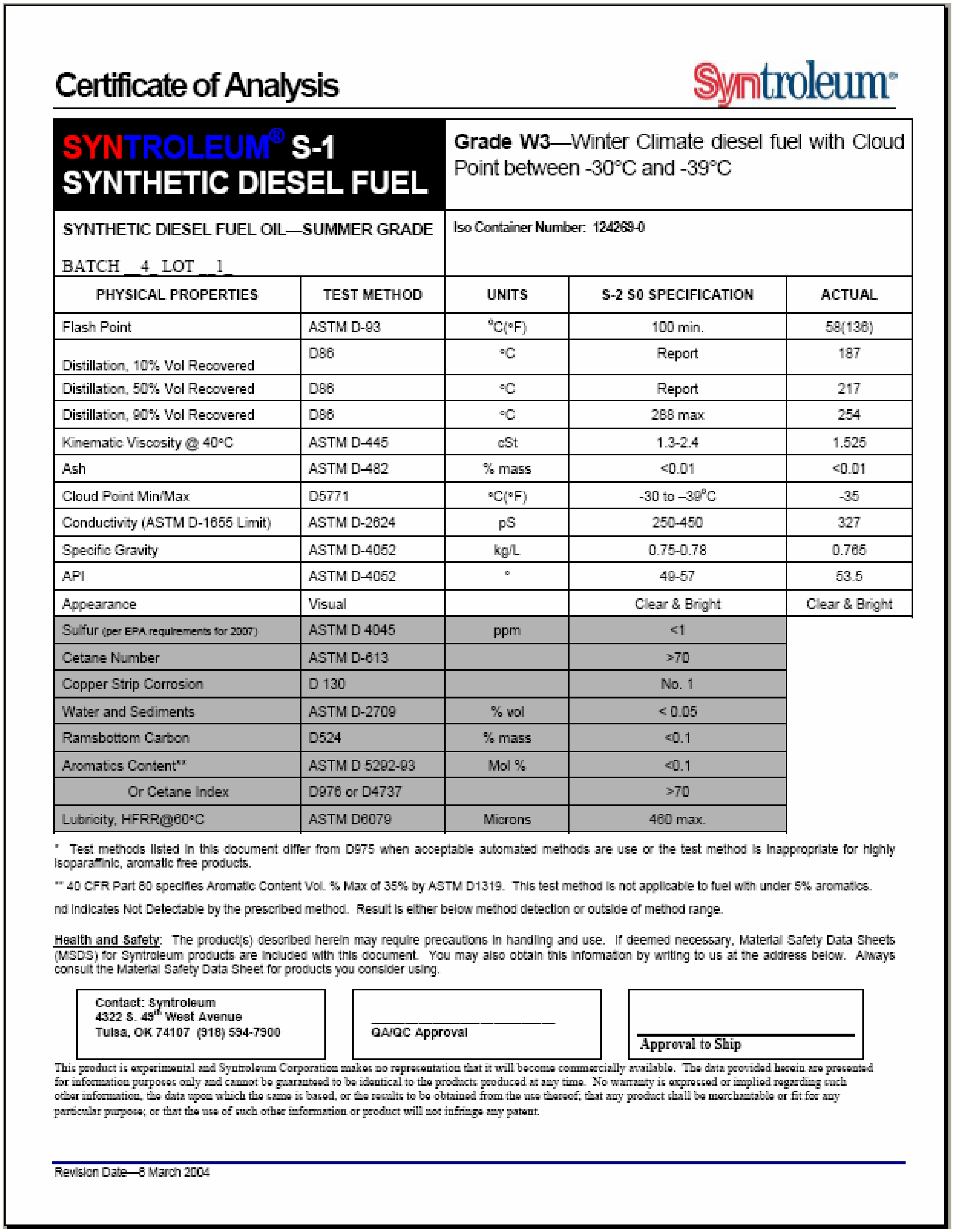
Revision Date—25 July 2004

Appendix 2.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-1 SYNTHETIC DIESEL FUEL

Grade W3—Winter Climate diesel fuel with Cloud Point between -30°C and -39°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

Iso Container Number: 124269-0

BATCH __4_ LOT __1_

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S0 SPECIFICATION	ACTUAL
Flash Point	ASTM D-93	°C(°F)	100 min.	58(136)
Distillation, 10% Vol Recovered	D86	°C	Report	187
Distillation, 50% Vol Recovered	D86	°C	Report	217
Distillation, 90% Vol Recovered	D86	°C	288 max	254
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.3-2.4	1.525
Ash	ASTM D-482	% mass	<0.01	<0.01
Cloud Point Min/Max	D5771	°C(°F)	-30 to –39°C	-35
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	327
Specific Gravity	ASTM D-4052	kg/L	0.75-0.78	0.765
API	ASTM D-4052	°	49-57	53.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur (per EPA requirements for 2007)	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	460 max.	

* Test methods listed in this document differ from D975 when acceptable automated methods are use or the test method is inappropriate for highly isoparaffinic, aromatic free products.

** 40 CFR Part 80 specifies Aromatic Content Vol. % Max of 35% by ASTM D1319. This test method is not applicable to fuel with under 5% aromatics.

nd indicates Not Detectable by the prescribed method. Result is either below method detection or outside of method range.

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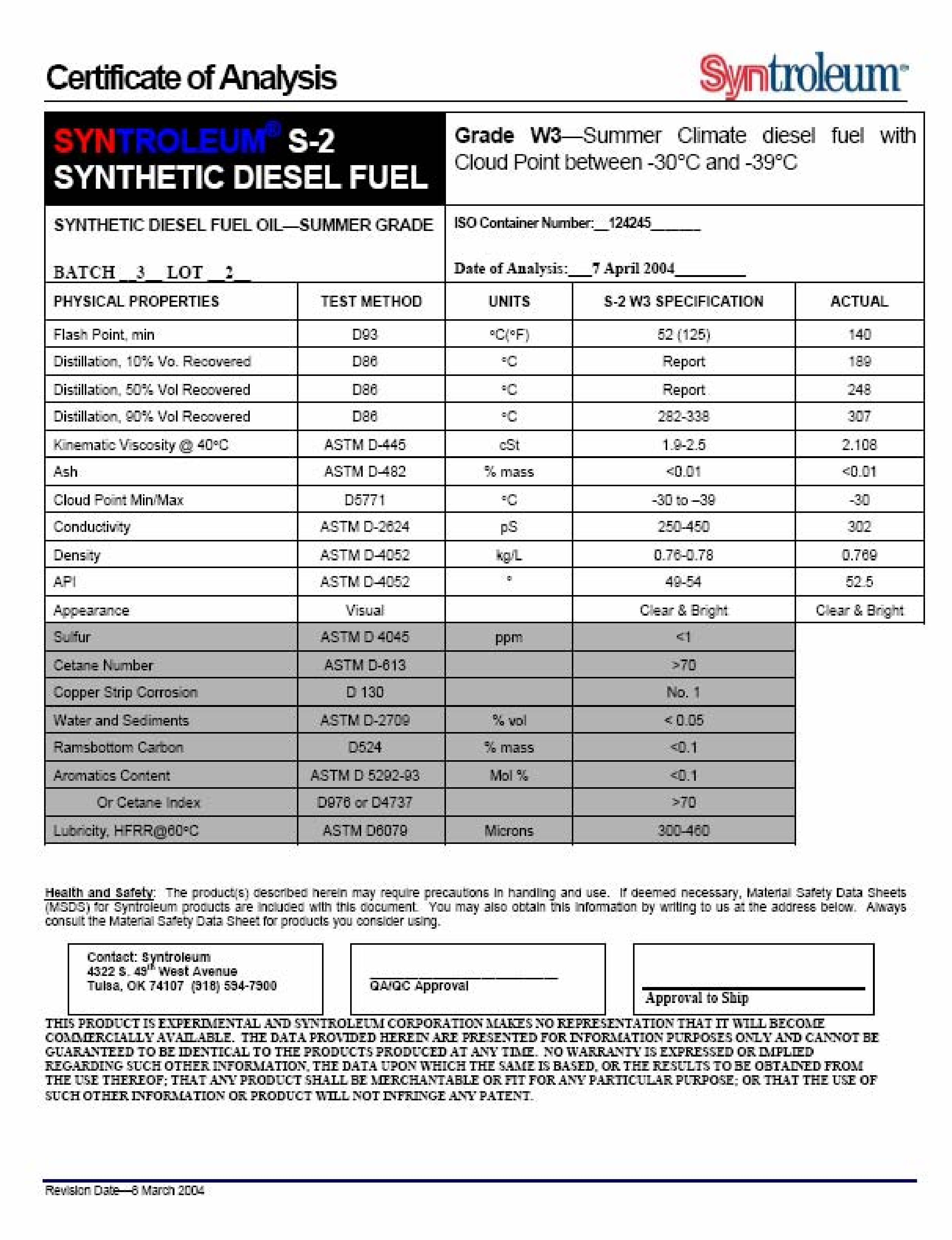
Revision Date—8 March 2004

Appendix 3.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade W3—Summer Climate diesel fuel with Cloud Point between -30°C and -39°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH __3__ LOT __2__

ISO Container Number:__124245______

Date of Analysis:___7 April 2004________

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 W3 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	140
Distillation, 10% Vo. Recovered	D86	°C	Report	189
Distillation, 50% Vol Recovered	D86	°C	Report	248
Distillation, 90% Vol Recovered	D86	°C	282-338	307
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.108
Ash	ASTM D-482	% mass	<0.01	<0.01
Cloud Point Min/Max	D5771	°C	-30 to –39	-30
Conductivity	ASTM D-2624	pS	250-450	302
Density	ASTM D-4052	kg/L	0.76-0.78	0.769
API	ASTM D-4052	°	49-54	52.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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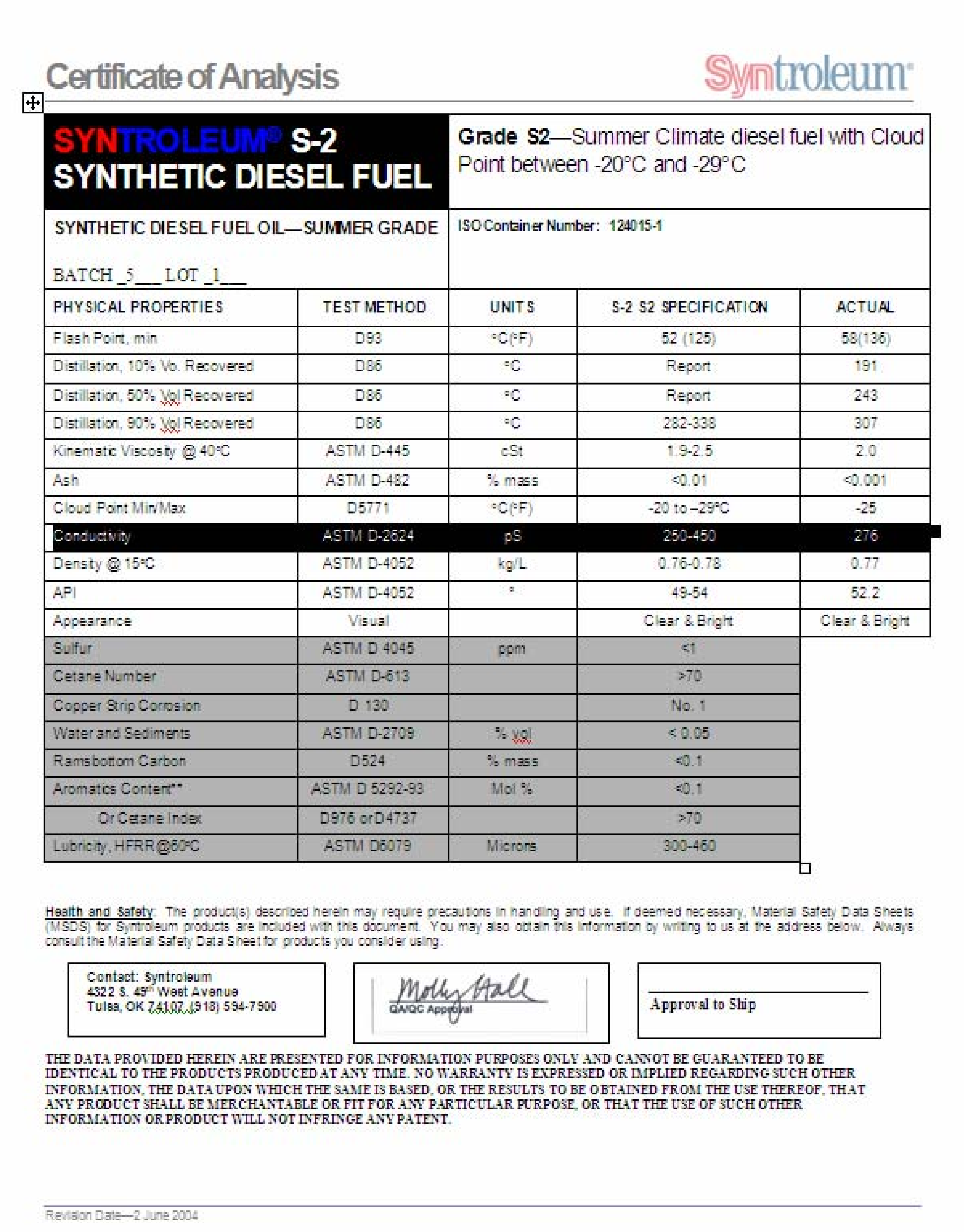
Revision Date—8 March 2004

Appendix 4.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL	**Grade S2**—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C
SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE BATCH _5___ LOT _1___	ISO Container Number: 124015-1

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	58(136)
Distillation, 10% Vo. Recovered	D86	°C	Report	191
Distillation, 50% Vol Recovered	D86	°C	Report	243
Distillation, 90% Vol Recovered	D86	°C	282-338	307
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.0
Ash	ASTM D-482	% mass	<0.01	<0.001
Cloud Point Min/Max	D5771	°C(°F)	-20 to –29°C	-25
Conductivity	ASTM D-2624	pS	250-450	276
Density @ 15°C	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	52.2
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Molly Hall
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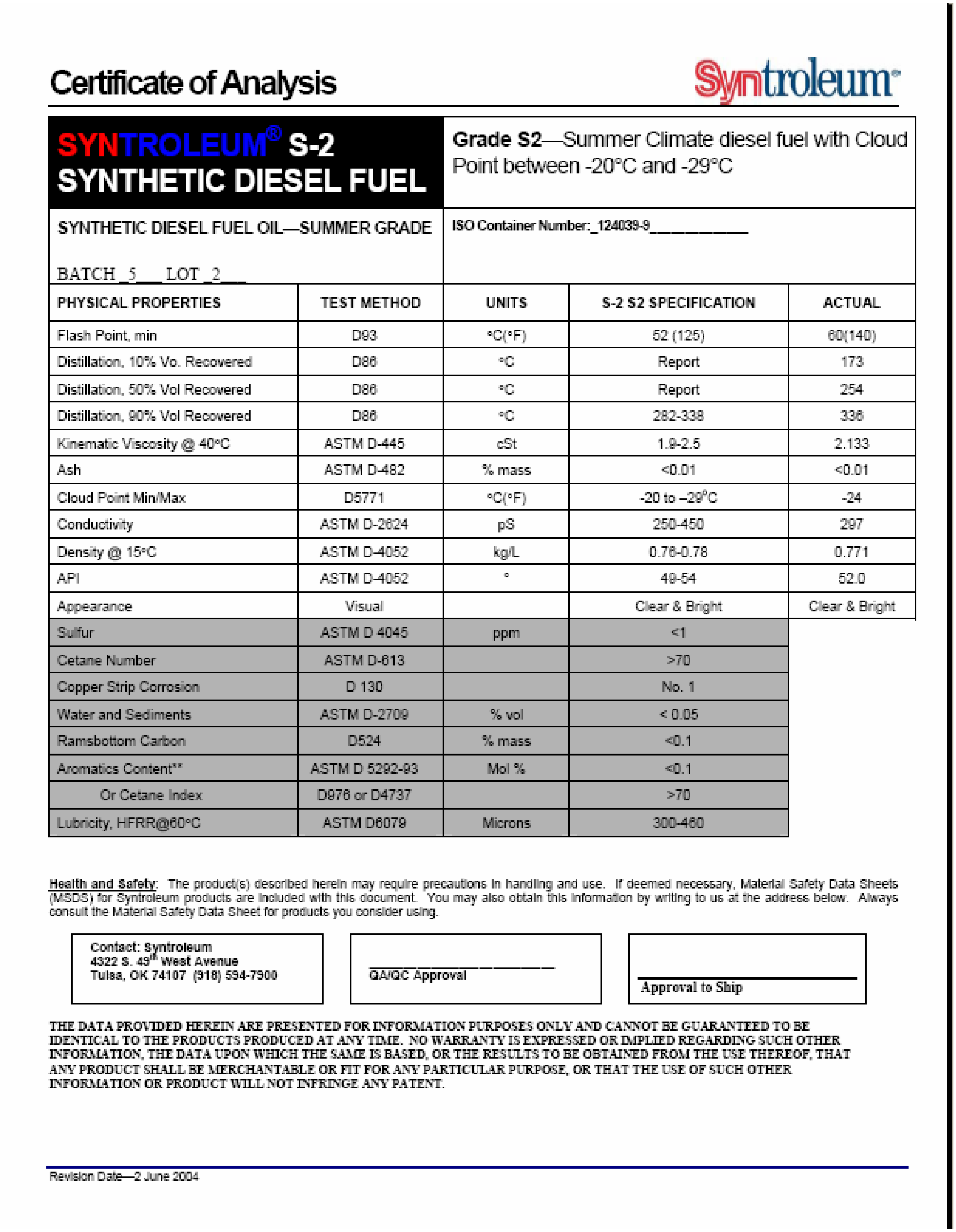
Revision Date—2 June 2004

Appendix 5.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2
SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH _5___ LOT _2___

ISO Container Number:_124039-9____________

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	60(140)
Distillation, 10% Vo. Recovered	D86	°C	Report	173
Distillation, 50% Vol Recovered	D86	°C	Report	254
Distillation, 90% Vol Recovered	D86	°C	282-338	336
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.133
Ash	ASTM D-482	% mass	<0.01	<0.01
Cloud Point Min/Max	D5771	°C(°F)	-20 to –29°C	-24
Conductivity	ASTM D-2624	pS	250-450	297
Density @ 15°C	ASTM D-4052	kg/L	0.76-0.78	0.771
API	ASTM D-4052	°	49-54	52.0
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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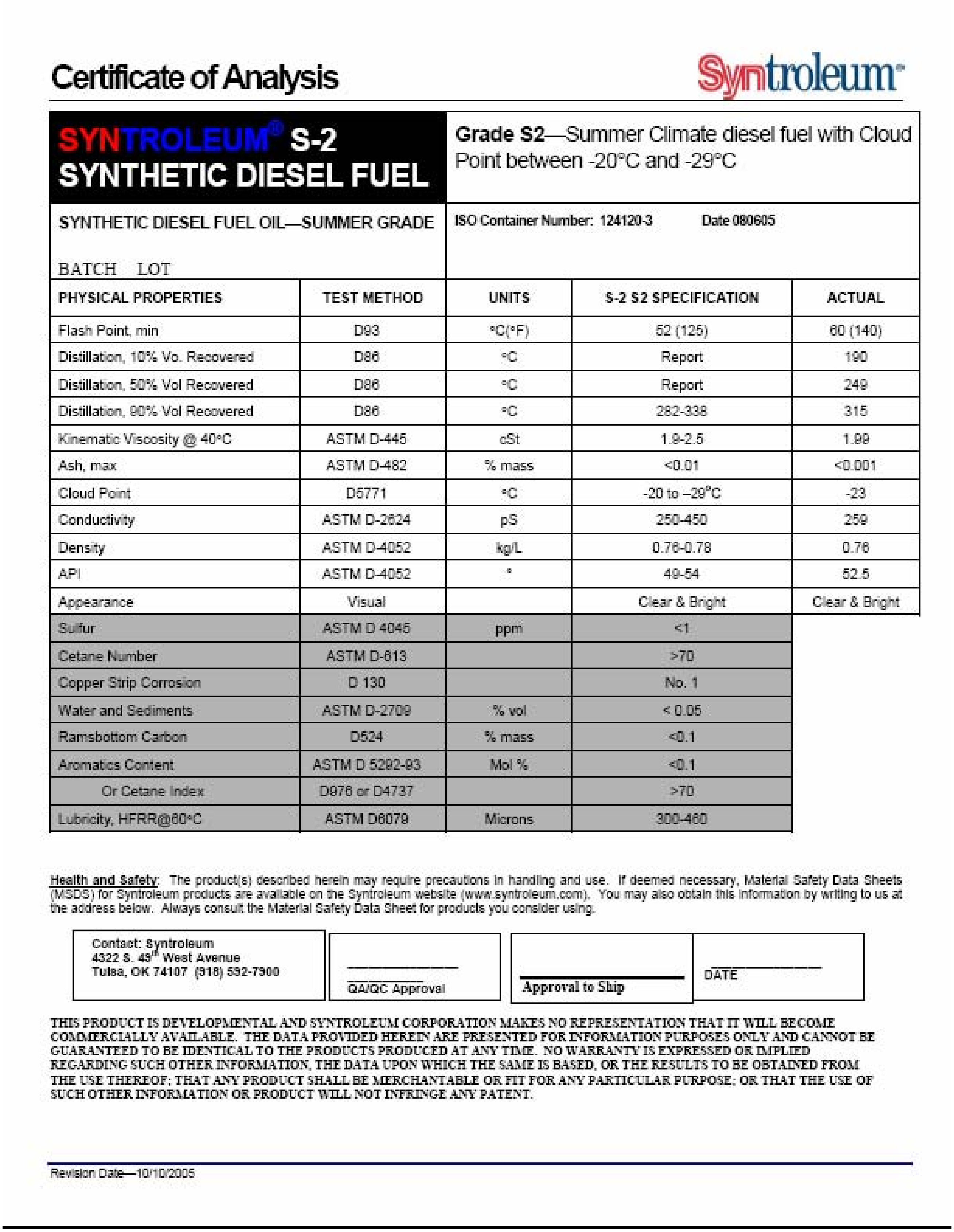
Revision Date—2 June 2004

Appendix 6.



Certificate of Analysis

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

ISO Container Number: 124120-3 Date 080605

BATCH LOT

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	60 (140)
Distillation, 10% Vo. Recovered	D86	°C	Report	190
Distillation, 50% Vol Recovered	D86	°C	Report	249
Distillation, 90% Vol Recovered	D86	°C	282-338	315
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	1.99
Ash, max	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C	-20 to –29°C	-23
Conductivity	ASTM D-2624	pS	250-450	259
Density	ASTM D-4052	kg/L	0.76-0.78	0.76
API	ASTM D-4052	°	49-54	52.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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QA/QC Approval

Approval to Ship

DATE

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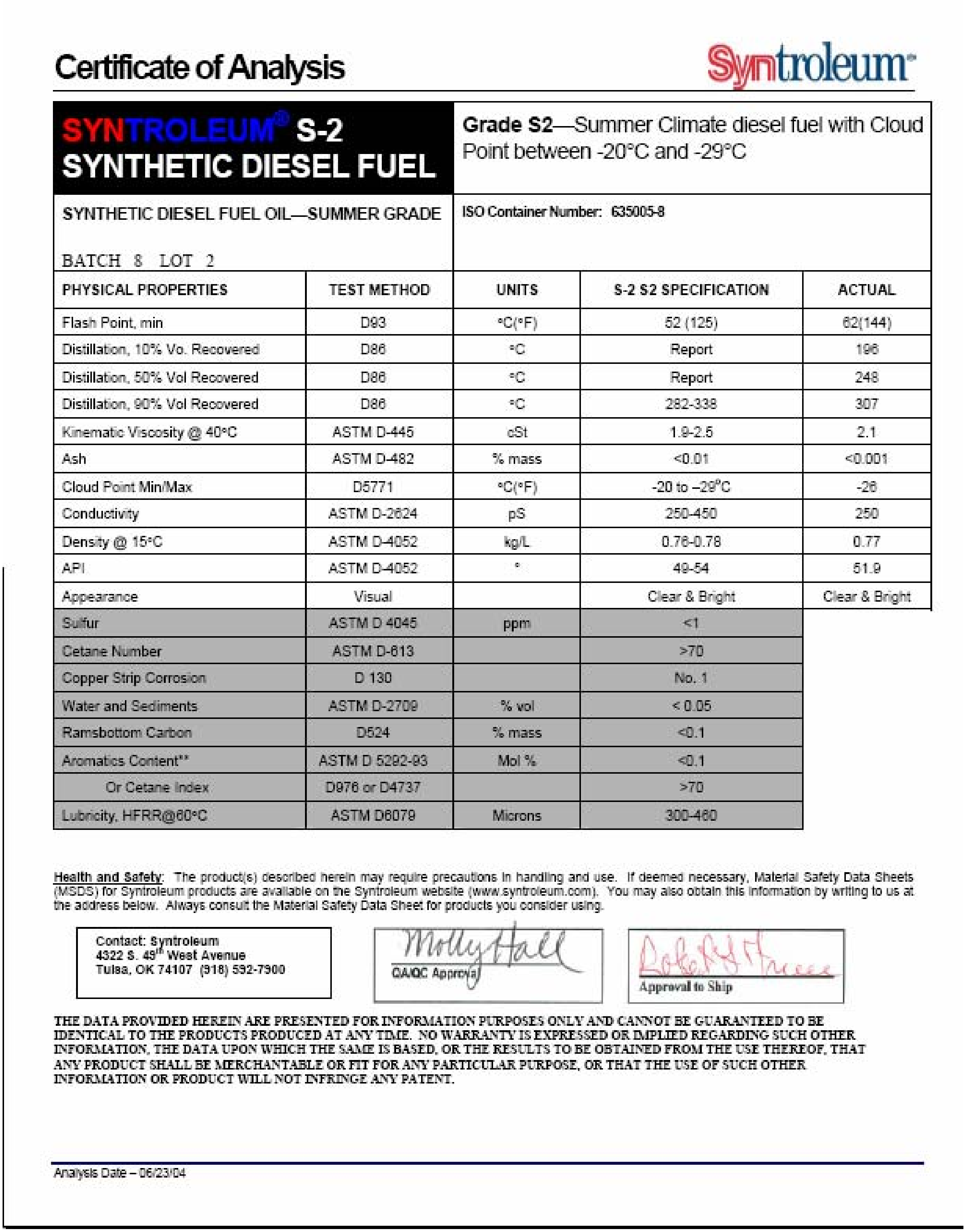
Revision Date—10/10/2005

Appendix 7.



Certificate of Analysis

Syntroleum

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 8 LOT 2

ISO Container Number: 635005-8

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	62(144)
Distillation, 10% Vo. Recovered	D86	°C	Report	196
Distillation, 50% Vol Recovered	D86	°C	Report	248
Distillation, 90% Vol Recovered	D86	°C	282-338	307
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.1
Ash	ASTM D-482	% mass	<0.01	<0.001
Cloud Point Min/Max	D5771	°C(°F)	-20 to –29°C	-26
Conductivity	ASTM D-2624	pS	250-450	250
Density @ 15°C	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.9
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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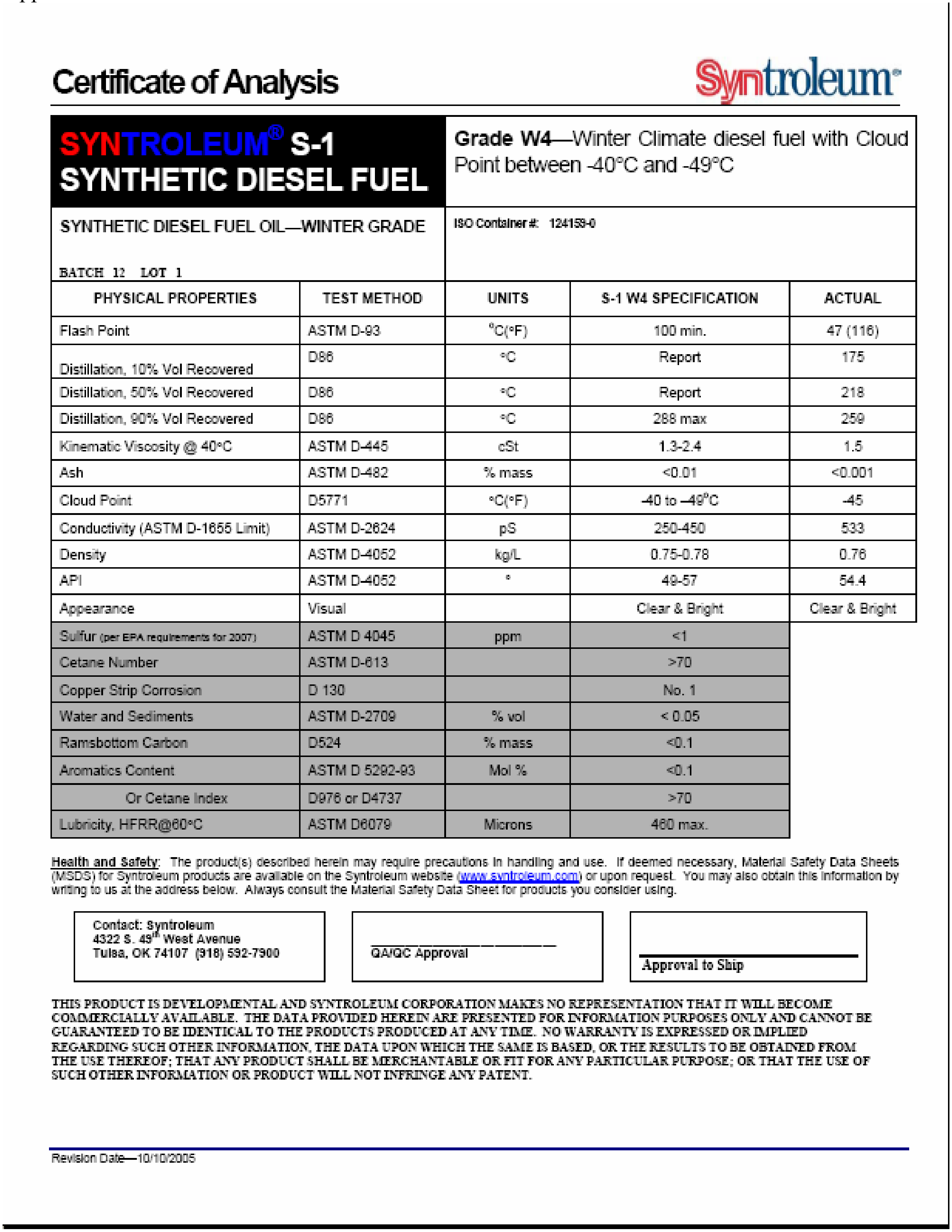
Contact: Syntroleum
4322 S. 49th West Avenue
Tulsa, OK 74107 (918) 592-7900

Molly Hall
QA/QC Approval

Approval to Ship

Analysis Date – 06/23/04

Appendix 8.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-1 SYNTHETIC DIESEL FUEL

Grade W4—Winter Climate diesel fuel with Cloud Point between -40°C and -49°C

SYNTHETIC DIESEL FUEL OIL—WINTER GRADE

ISO Container #: 124159-0

BATCH 12 LOT 1

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-1 W4 SPECIFICATION	ACTUAL
Flash Point	ASTM D-93	°C(°F)	100 min.	47 (116)
Distillation, 10% Vol Recovered	D86	°C	Report	175
Distillation, 50% Vol Recovered	D86	°C	Report	218
Distillation, 90% Vol Recovered	D86	°C	288 max	259
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.3-2.4	1.5
Ash	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C(°F)	-40 to –49°C	-45
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	533
Density	ASTM D-4052	kg/L	0.75-0.78	0.76
API	ASTM D-4052	°	49-57	54.4
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur (per EPA requirements for 2007)	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	460 max.	

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Tulsa, OK 74107 (918) 592-7900

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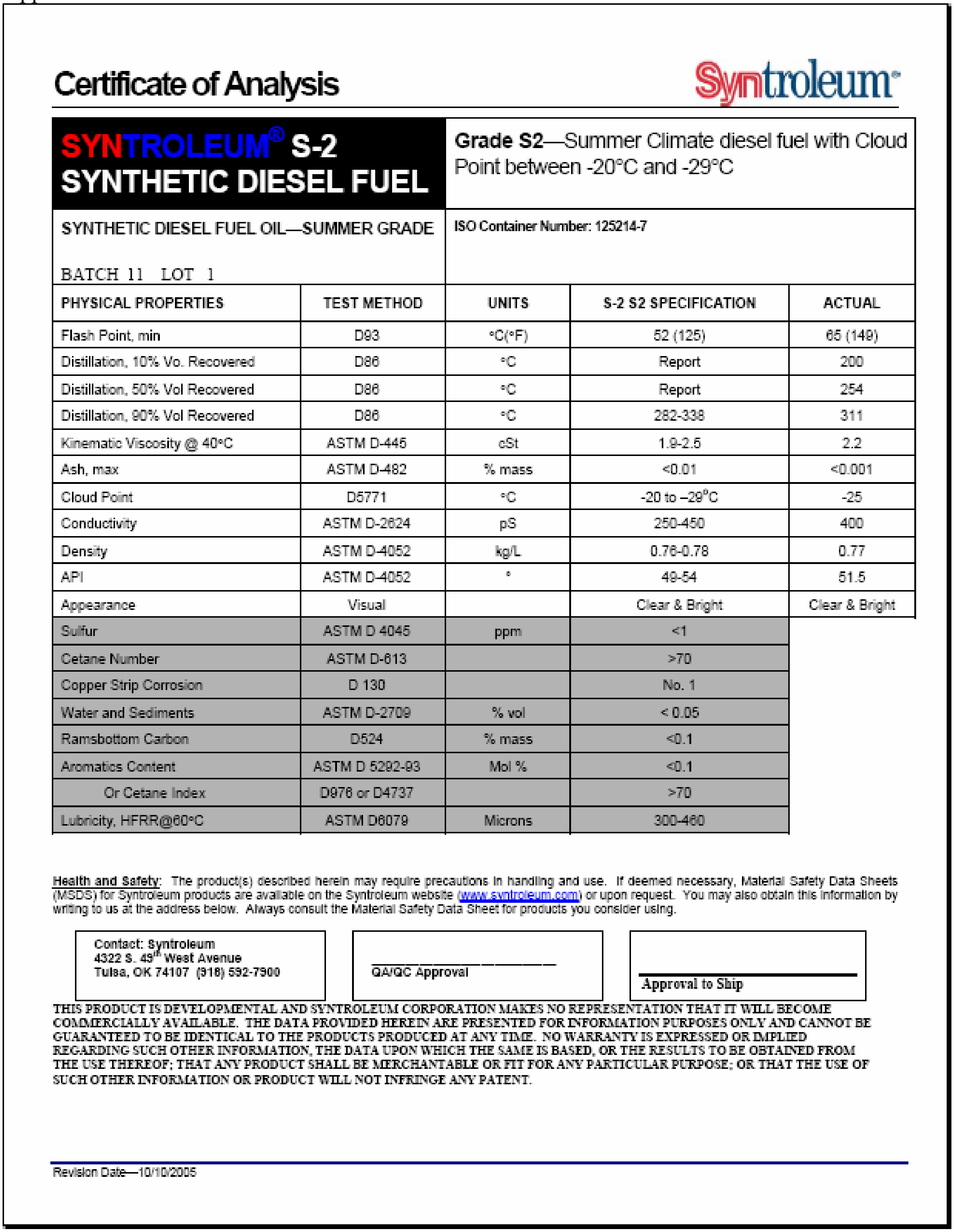
Revision Date—10/10/2005

Appendix 9.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2
SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 1

ISO Container Number: 125214-7

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	65 (149)
Distillation, 10% Vo. Recovered	D86	°C	Report	200
Distillation, 50% Vol Recovered	D86	°C	Report	254
Distillation, 90% Vol Recovered	D86	°C	282-338	311
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.2
Ash, max	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C	-20 to –29°C	-25
Conductivity	ASTM D-2624	pS	250-450	400
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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4322 S. 49th West Avenue
Tulsa, OK 74107 (918) 592-7900

QA/QC Approval

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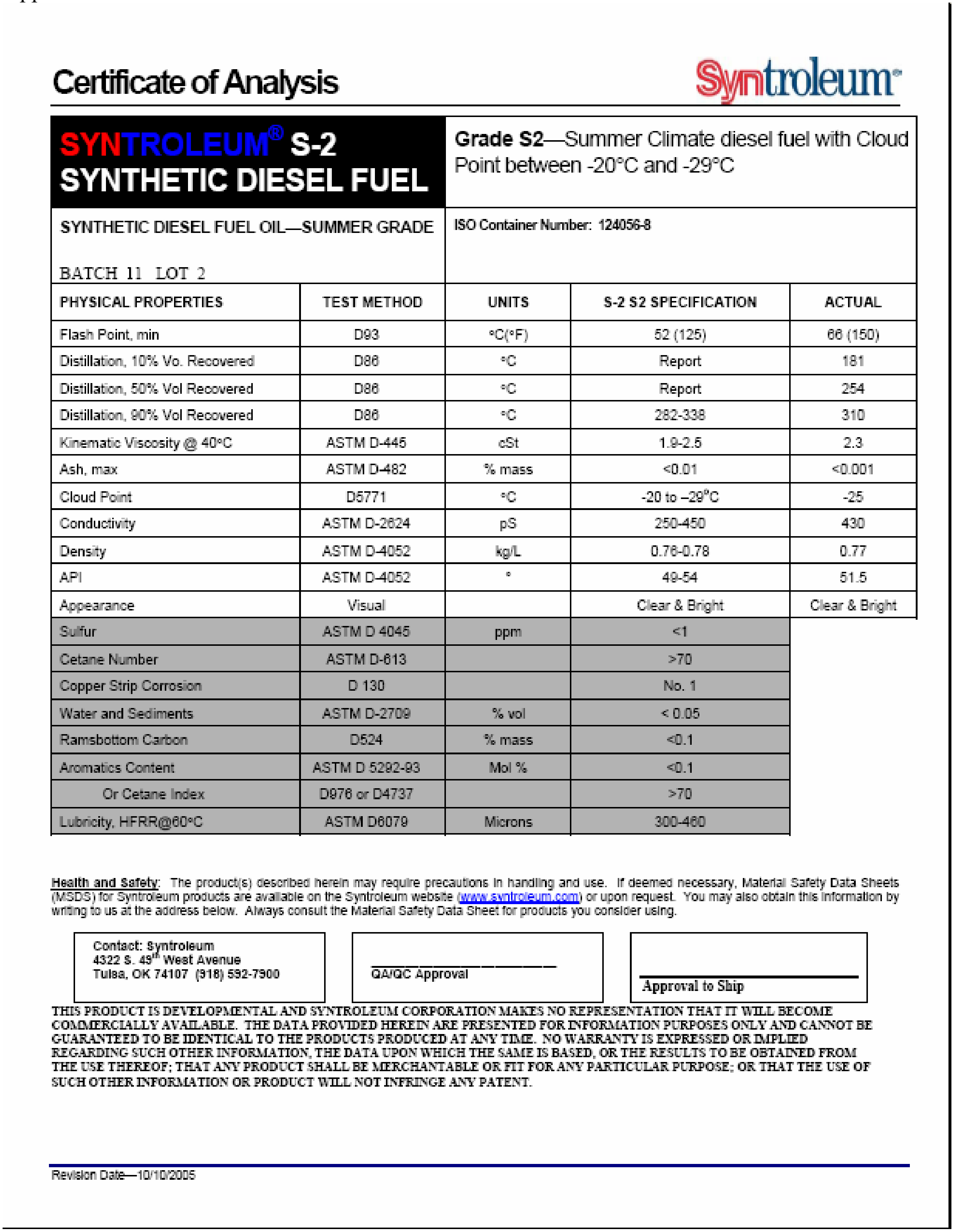
Revision Date—10/10/2005

Appendix 10.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2
SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

ISO Container Number: 124056-8

BATCH 11 LOT 2

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	66 (150)
Distillation, 10% Vo. Recovered	D86	°C	Report	181
Distillation, 50% Vol Recovered	D86	°C	Report	254
Distillation, 90% Vol Recovered	D86	°C	282-338	310
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.3
Ash, max	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C	-20 to –29°C	-25
Conductivity	ASTM D-2624	pS	250-450	430
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Tulsa, OK 74107 (918) 592-7900

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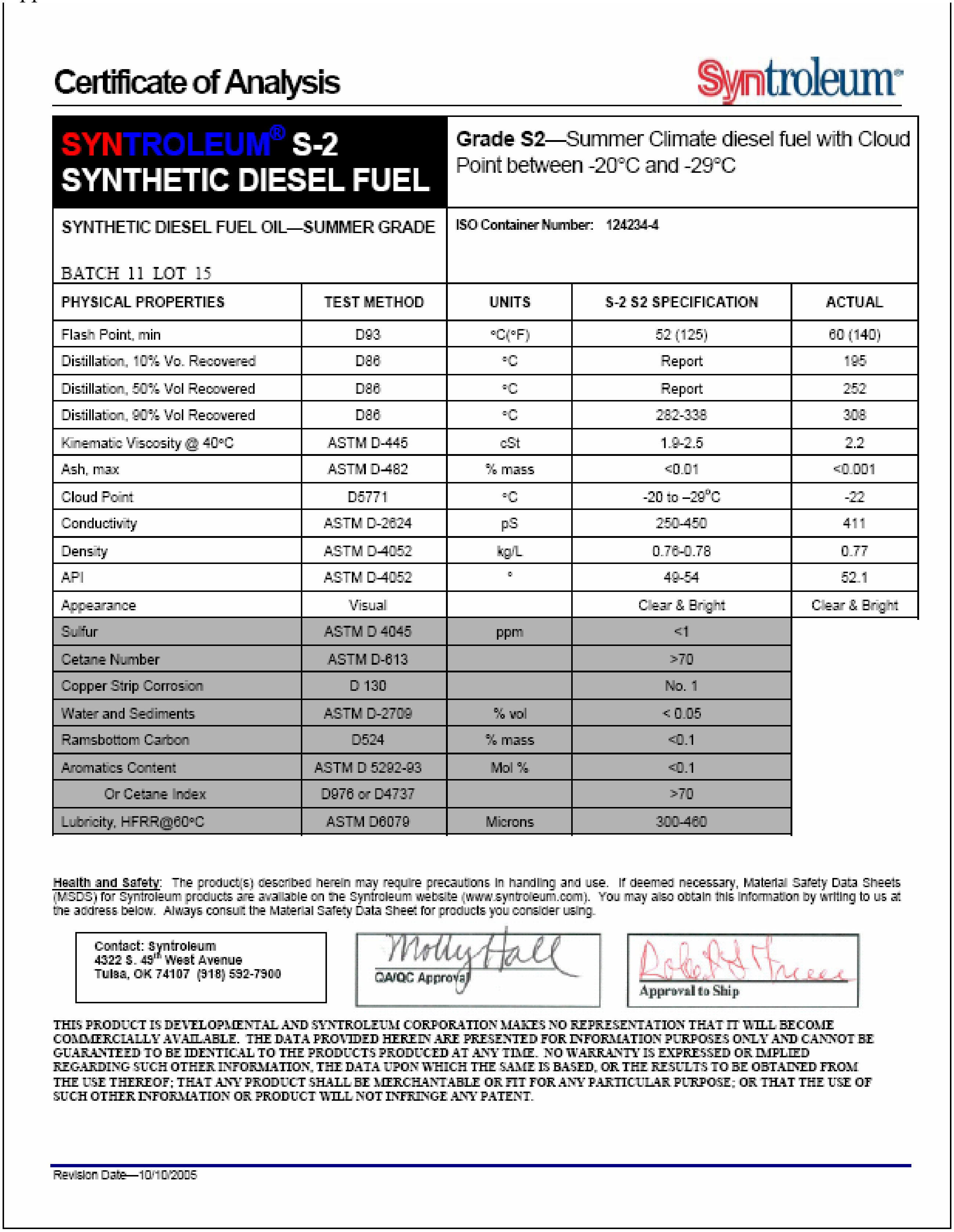
Revision Date—10/10/2005

Appendix 11.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 15

ISO Container Number: 124234-4

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	60 (140)
Distillation, 10% Vo. Recovered	D86	°C	Report	195
Distillation, 50% Vol Recovered	D86	°C	Report	252
Distillation, 90% Vol Recovered	D86	°C	282-338	308
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.2
Ash, max	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C	-20 to –29°C	-22
Conductivity	ASTM D-2624	pS	250-450	411
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	52.1
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Tulsa, OK 74107 (918) 592-7900

Molly Hall
QA/QC Approval

Approval to Ship

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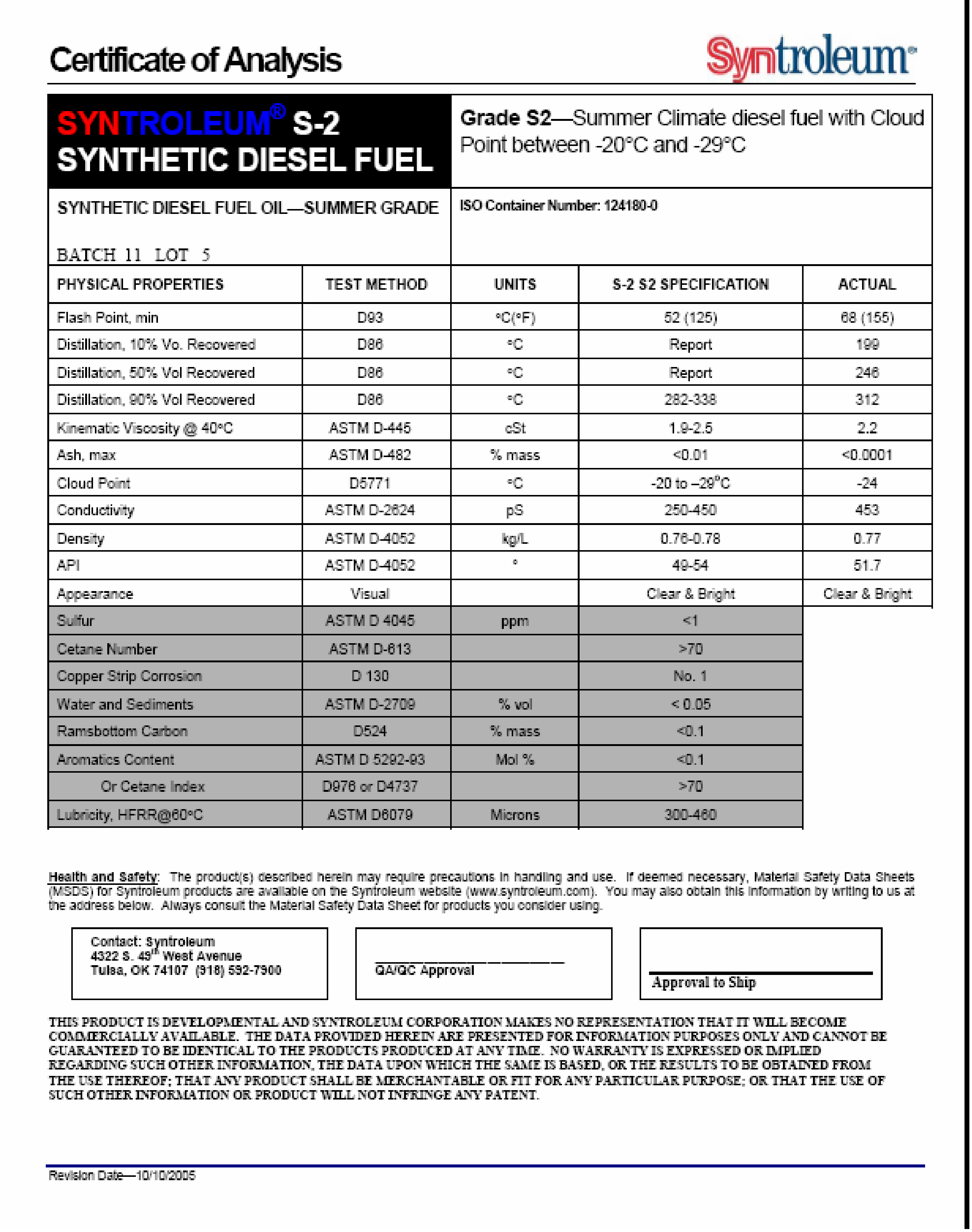
Revision Date—10/10/2005

Appendix 12.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 5

ISO Container Number: 124180-0

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	68 (155)
Distillation, 10% Vo. Recovered	D86	°C	Report	199
Distillation, 50% Vol Recovered	D86	°C	Report	246
Distillation, 90% Vol Recovered	D86	°C	282-338	312
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.2
Ash, max	ASTM D-482	% mass	<0.01	<0.0001
Cloud Point	D5771	°C	-20 to –29°C	-24
Conductivity	ASTM D-2624	pS	250-450	453
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.7
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Tulsa, OK 74107 (918) 592-7900

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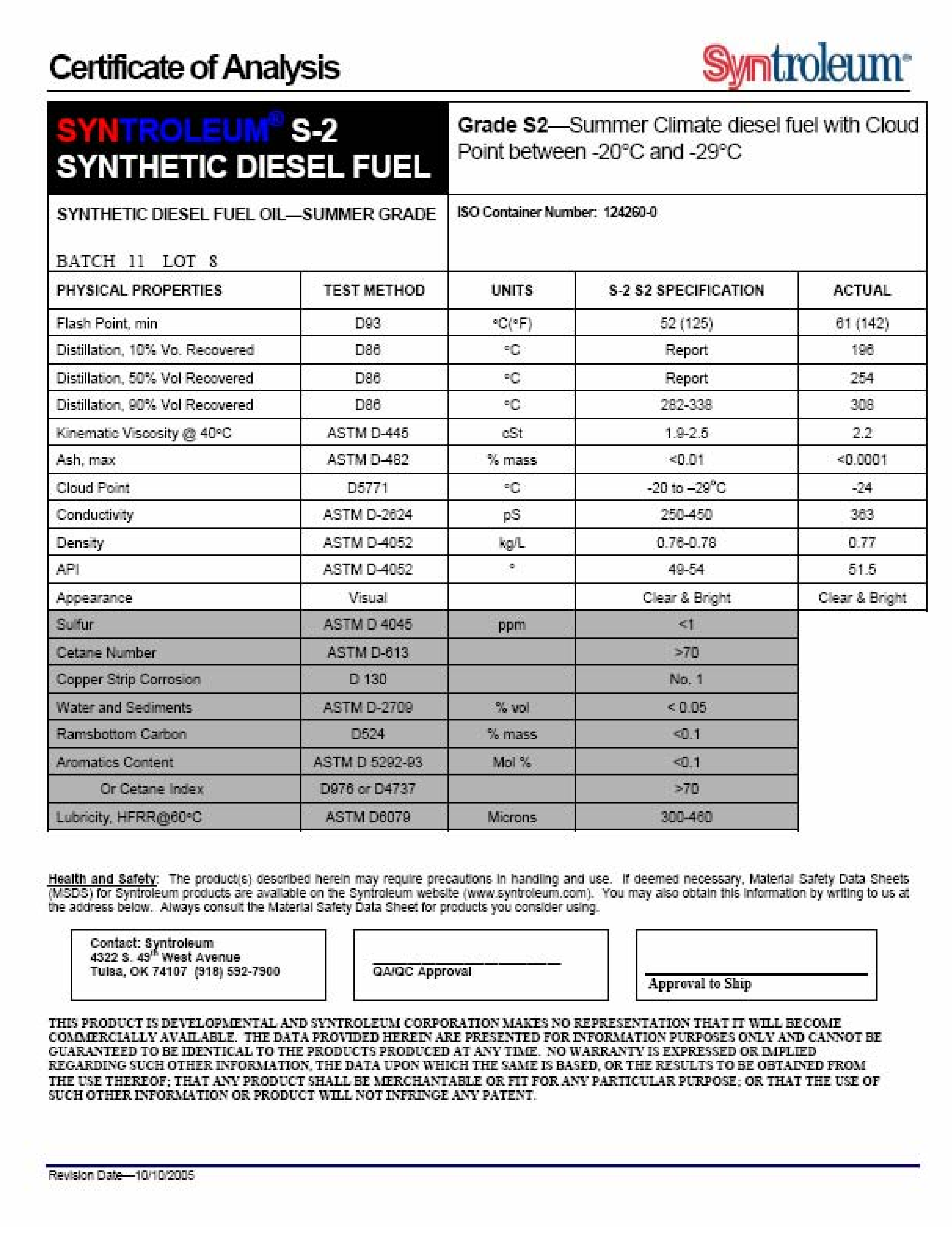
Revision Date—10/10/2005

Appendix 13.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 8

ISO Container Number: 124260-0

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	61 (142)
Distillation, 10% Vo. Recovered	D86	°C	Report	196
Distillation, 50% Vol Recovered	D86	°C	Report	254
Distillation, 90% Vol Recovered	D86	°C	282-338	308
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.2
Ash, max	ASTM D-482	% mass	<0.01	<0.0001
Cloud Point	D5771	°C	-20 to –29°C	-24
Conductivity	ASTM D-2624	pS	250-450	363
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Tulsa, OK 74107 (918) 592-7900

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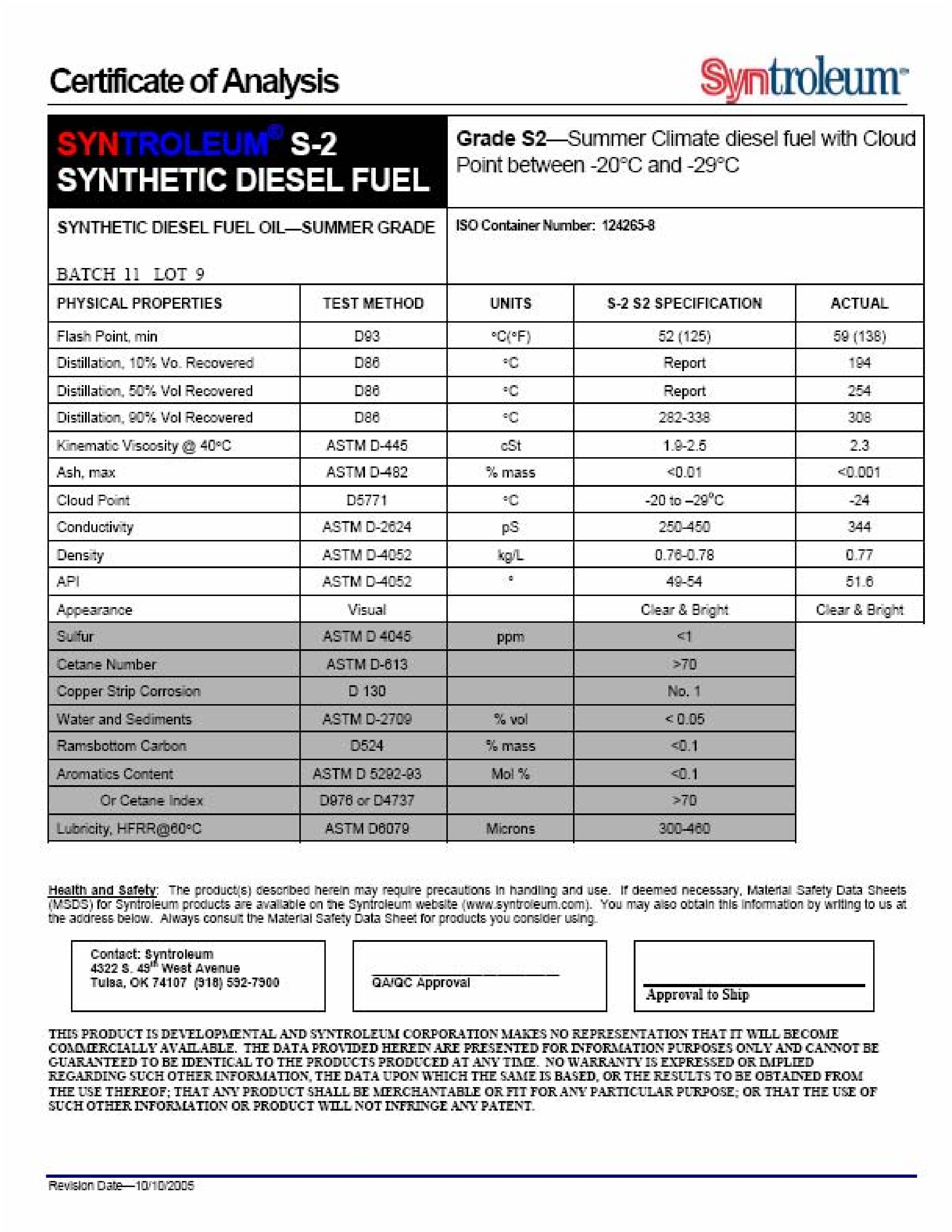
Revision Date—10/10/2005

Appendix 14.



Certificate of Analysis

Syntroleum

SYNTROLEUM® S-2
SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 9

ISO Container Number: 124265-8

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	59 (138)
Distillation, 10% Vo. Recovered	D86	°C	Report	194
Distillation, 50% Vol Recovered	D86	°C	Report	254
Distillation, 90% Vol Recovered	D86	°C	282-338	308
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.3
Ash, max	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C	-20 to –29°C	-24
Conductivity	ASTM D-2624	pS	250-450	344
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.6
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Tulsa, OK 74107 (918) 592-7900

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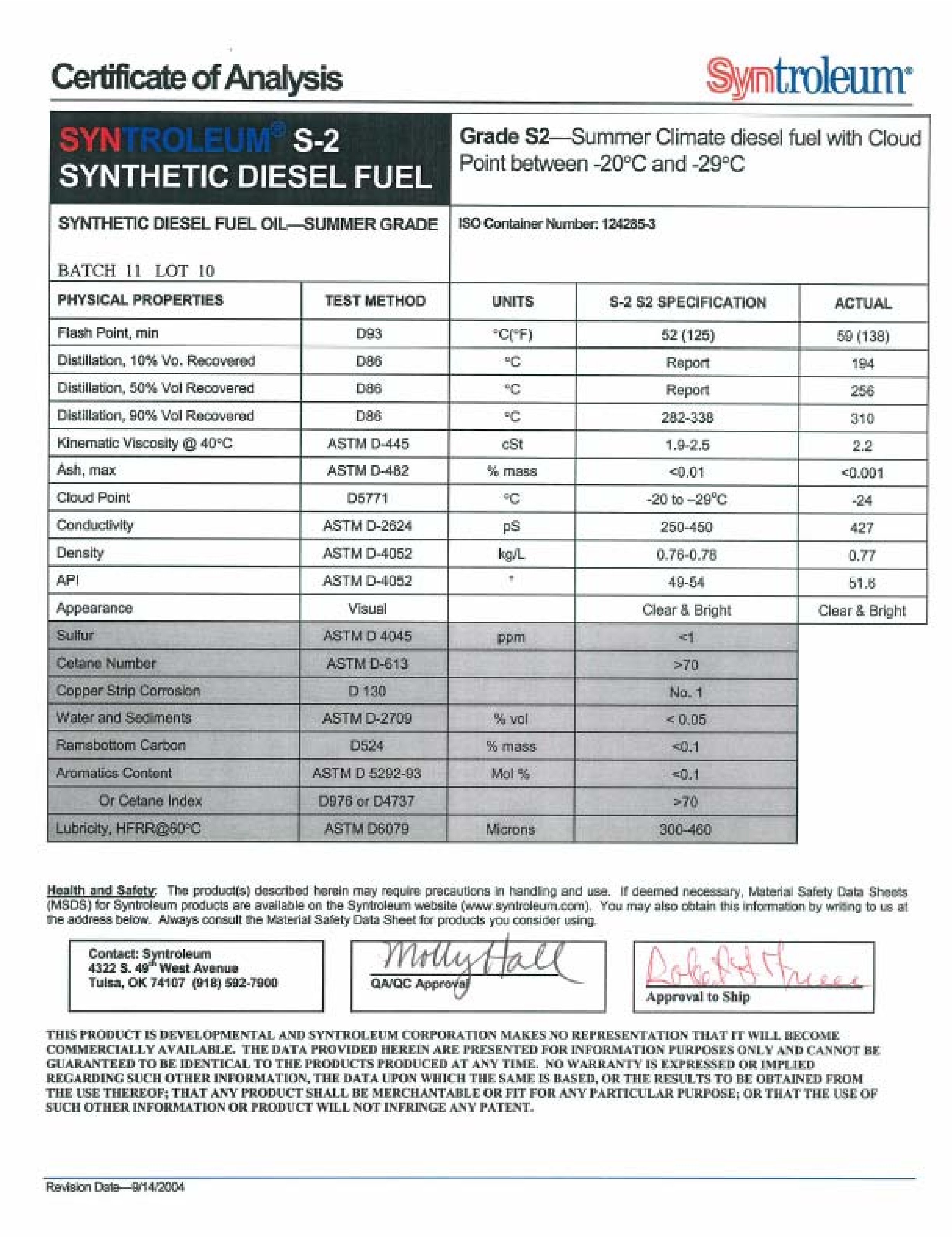
Revision Date—10/10/2005

Appendix 15.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

ISO Container Number: 124285-3

BATCH 11 LOT 10

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	59 (138)
Distillation, 10% Vo. Recovered	D86	°C	Report	194
Distillation, 50% Vol Recovered	D86	°C	Report	256
Distillation, 90% Vol Recovered	D86	°C	282-338	310
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.2
Ash, max	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C	-20 to –29°C	-24
Conductivity	ASTM D-2624	pS	250-450	427
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.8
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

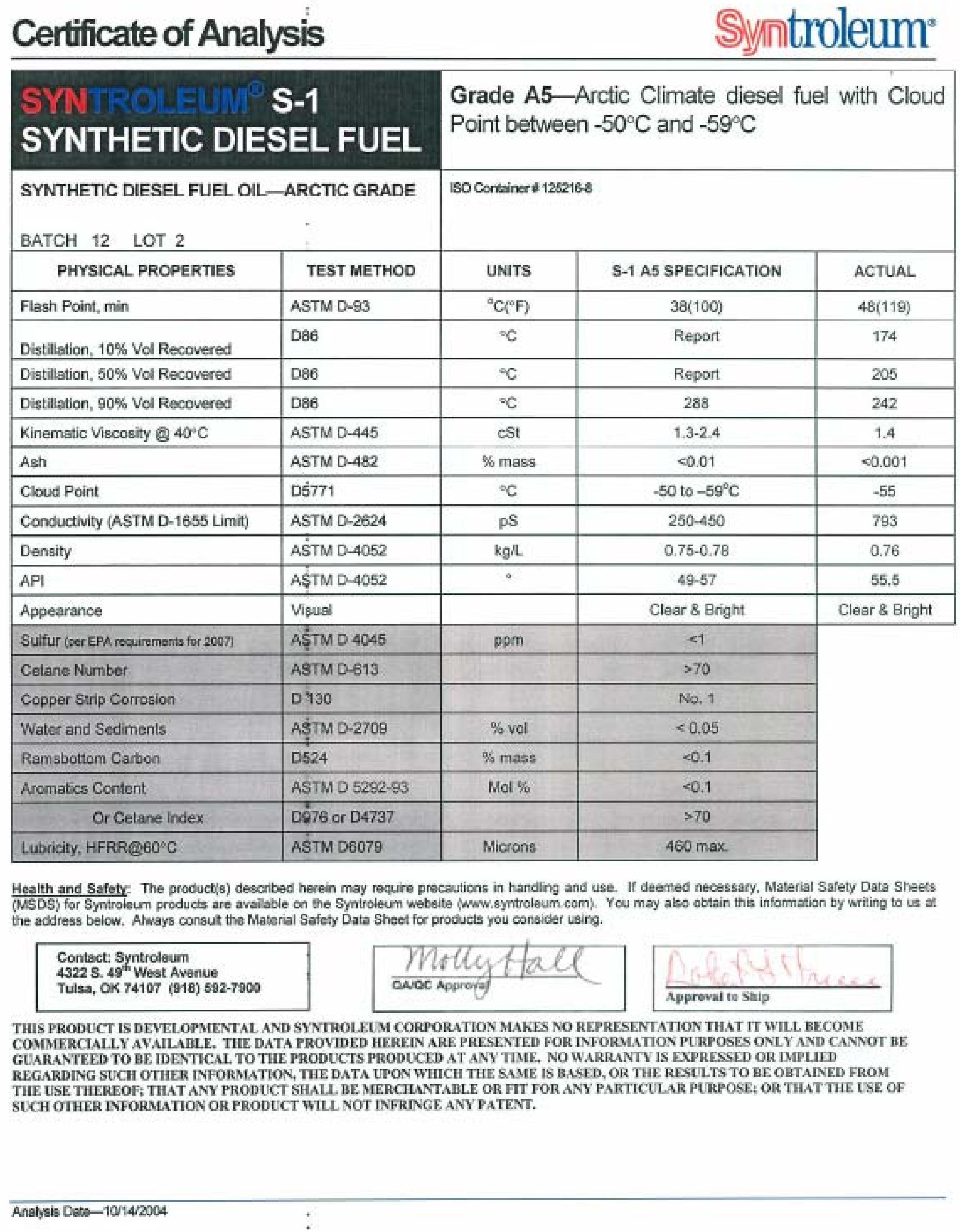
Health and Safety: The product(s) described herein may require precautions in handling and use. If deemed necessary, Material Safety Data Sheets (MSDS) for Syntroleum products are available on the Syntroleum website (www.syntroleum.com). You may also obtain this information by writing to us at the address below. Always consult the Material Safety Data Sheet for products you consider using.

Contact: Syntroleum
4322 S. 49th West Avenue
Tulsa, OK 74107 (918) 592-7900

Molly Hall
QA/QC Approval

Approval to Ship

Appendix 16.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-1
SYNTHETIC DIESEL FUEL

Grade A5—Arctic Climate diesel fuel with Cloud Point between -50°C and -59°C

SYNTHETIC DIESEL FUEL OIL—ARCTIC GRADE

ISO Container # 125216-8

BATCH 12 LOT 2

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-1 A5 SPECIFICATION	ACTUAL
Flash Point, min	ASTM D-93	°C(°F)	38(100)	48(119)
Distillation, 10% Vol Recovered	D86	°C	Report	174
Distillation, 50% Vol Recovered	D86	°C	Report	205
Distillation, 90% Vol Recovered	D86	°C	288	242
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.3-2.4	1.4
Ash	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C	-50 to -59°C	-55
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	793
Density	ASTM D-4052	kg/L	0.75-0.78	0.76
API	ASTM D-4052	°	49-57	55.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur (per EPA requirements for 2007)	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	460 max.	

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Molly Hall
QA/QC Approval

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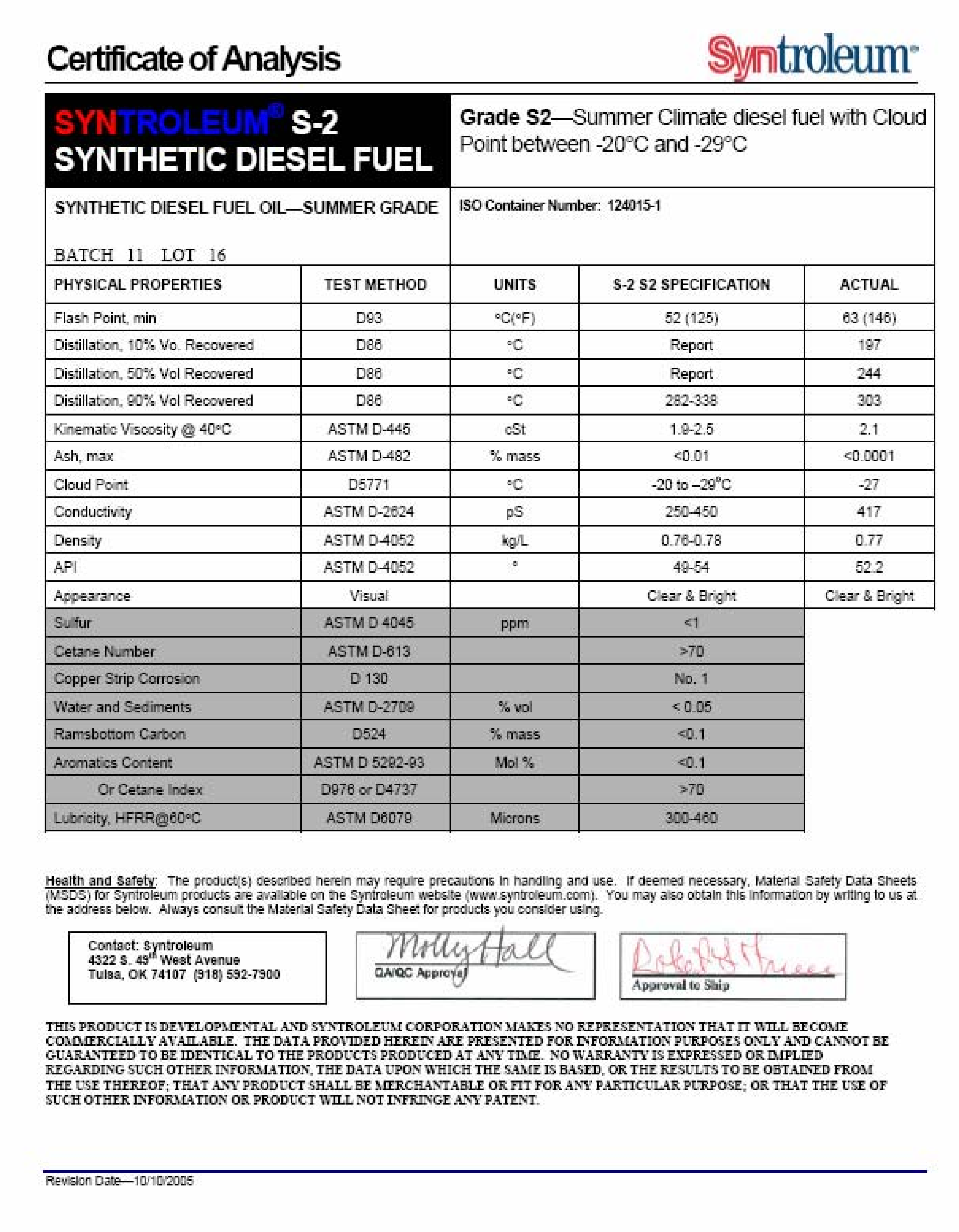
Analysis Date—10/14/2004

Appendix 17.



Certificate of Analysis

Syntroleum

SYNTROLEUM® S-2
SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 16

ISO Container Number: 124015-1

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	63 (146)
Distillation, 10% Vo. Recovered	D86	°C	Report	197
Distillation, 50% Vol Recovered	D86	°C	Report	244
Distillation, 90% Vol Recovered	D86	°C	282-338	303
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.1
Ash, max	ASTM D-482	% mass	<0.01	<0.0001
Cloud Point	D5771	°C	-20 to –29°C	-27
Conductivity	ASTM D-2624	pS	250-450	417
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	52.2
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Tulsa, OK 74107 (918) 592-7900

Molly Hall
QA/QC Approval

Approval to Ship

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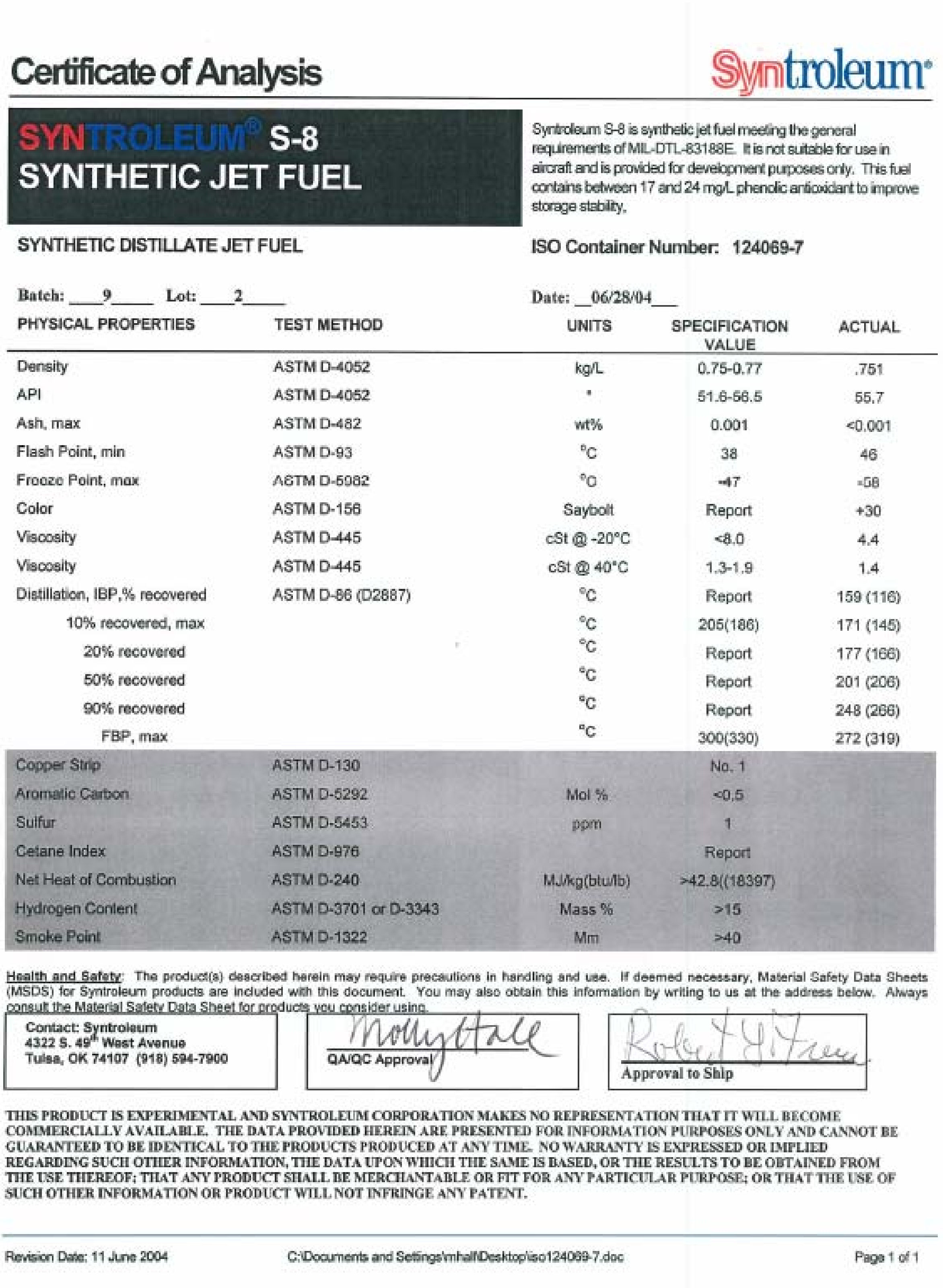
Revision Date—10/10/2005

Appendix 18.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-8
SYNTHETIC JET FUEL

Syntroleum S-8 is synthetic jet fuel meeting the general requirements of MIL-DTL-83188E. It is not suitable for use in aircraft and is provided for development purposes only. This fuel contains between 17 and 24 mg/L phenolic antioxidant to improve storage stability.

SYNTHETIC DISTILLATE JET FUEL

ISO Container Number: 124069-7

Batch: ___9____ **Lot:** ___2____

Date: __06/28/04___

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	ACTUAL
Density	ASTM D-4052	kg/L	0.75-0.77	.751
API	ASTM D-4052	°	51.6-56.5	55.7
Ash, max	ASTM D-482	wt%	0.001	<0.001
Flash Point, min	ASTM D-93	°C	38	46
Freeze Point, max	ASTM D-5082	°C	-47	-58
Color	ASTM D-156	Saybolt	Report	+30
Viscosity	ASTM D-445	cSt @ -20°C	<8.0	4.4
Viscosity	ASTM D-445	cSt @ 40°C	1.3-1.9	1.4
Distillation, IBP,% recovered	ASTM D-86 (D2887)	°C	Report	159 (116)
10% recovered, max		°C	205(186)	171 (145)
20% recovered		°C	Report	177 (166)
50% recovered		°C	Report	201 (206)
90% recovered		°C	Report	248 (266)
FBP, max		°C	300(330)	272 (319)
Copper Strip	ASTM D-130		No. 1	
Aromatic Carbon	ASTM D-5292	Mol %	<0.5	
Sulfur	ASTM D-5453	ppm	1	
Cetane Index	ASTM D-976		Report	
Net Heat of Combustion	ASTM D-240	MJ/kg(btu/lb)	>42.8((18397)	
Hydrogen Content	ASTM D-3701 or D-3343	Mass %	>15	
Smoke Point	ASTM D-1322	Mm	>40	

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Contact: Syntroleum
4322 S. 49th West Avenue
Tulsa, OK 74107 (918) 594-7900

Molly Hall
QA/QC Approval

Approval to Ship

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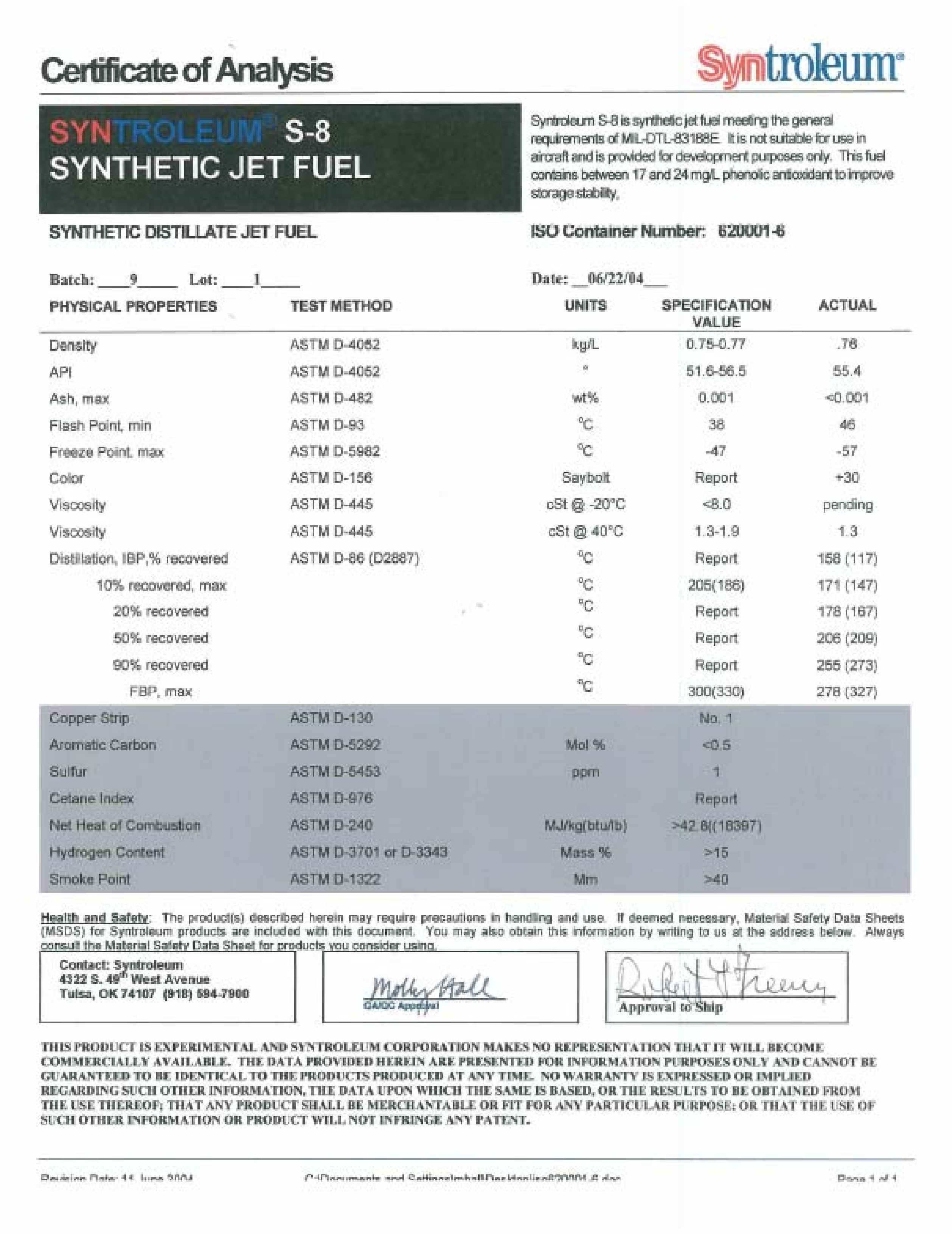
Revision Date: 11 June 2004 C:\Documents and Settings\mhall\Desktop\iso124069-7.doc Page 1 of 1

Appendix 19.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-8
SYNTHETIC JET FUEL

Syntroleum S-8 is synthetic jet fuel meeting the general requirements of MIL-DTL-83188E. It is not suitable for use in aircraft and is provided for development purposes only. This fuel contains between 17 and 24 mg/L phenolic antioxidant to improve storage stability.

SYNTHETIC DISTILLATE JET FUEL

ISO Container Number: 620001-6

Batch: 9 **Lot:** 1

Date: 06/22/04

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	ACTUAL
Density	ASTM D-4052	kg/L	0.75-0.77	.76
API	ASTM D-4052	°	51.6-56.5	55.4
Ash, max	ASTM D-482	wt%	0.001	<0.001
Flash Point, min	ASTM D-93	°C	38	46
Freeze Point, max	ASTM D-5982	°C	-47	-57
Color	ASTM D-156	Saybolt	Report	+30
Viscosity	ASTM D-445	cSt @ -20°C	<8.0	pending
Viscosity	ASTM D-445	cSt @ 40°C	1.3-1.9	1.3
Distillation, IBP,% recovered	ASTM D-86 (D2887)	°C	Report	158 (117)
10% recovered, max		°C	205(186)	171 (147)
20% recovered		°C	Report	178 (167)
50% recovered		°C	Report	206 (209)
90% recovered		°C	Report	255 (273)
FBP, max		°C	300(330)	278 (327)
Copper Strip	ASTM D-130		No. 1	
Aromatic Carbon	ASTM D-5292	Mol %	<0.5	
Sulfur	ASTM D-5453	ppm	1	
Cetane Index	ASTM D-976		Report	
Net Heat of Combustion	ASTM D-240	MJ/kg(btu/lb)	>42.8((18397)	
Hydrogen Content	ASTM D-3701 or D-3343	Mass %	>15	
Smoke Point	ASTM D-1322	Mm	>40	

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Contact: Syntroleum
4322 S. 49th West Avenue
Tulsa, OK 74107 (918) 594-7900

Molly Hall
QA/QC Approval

Approval to Ship

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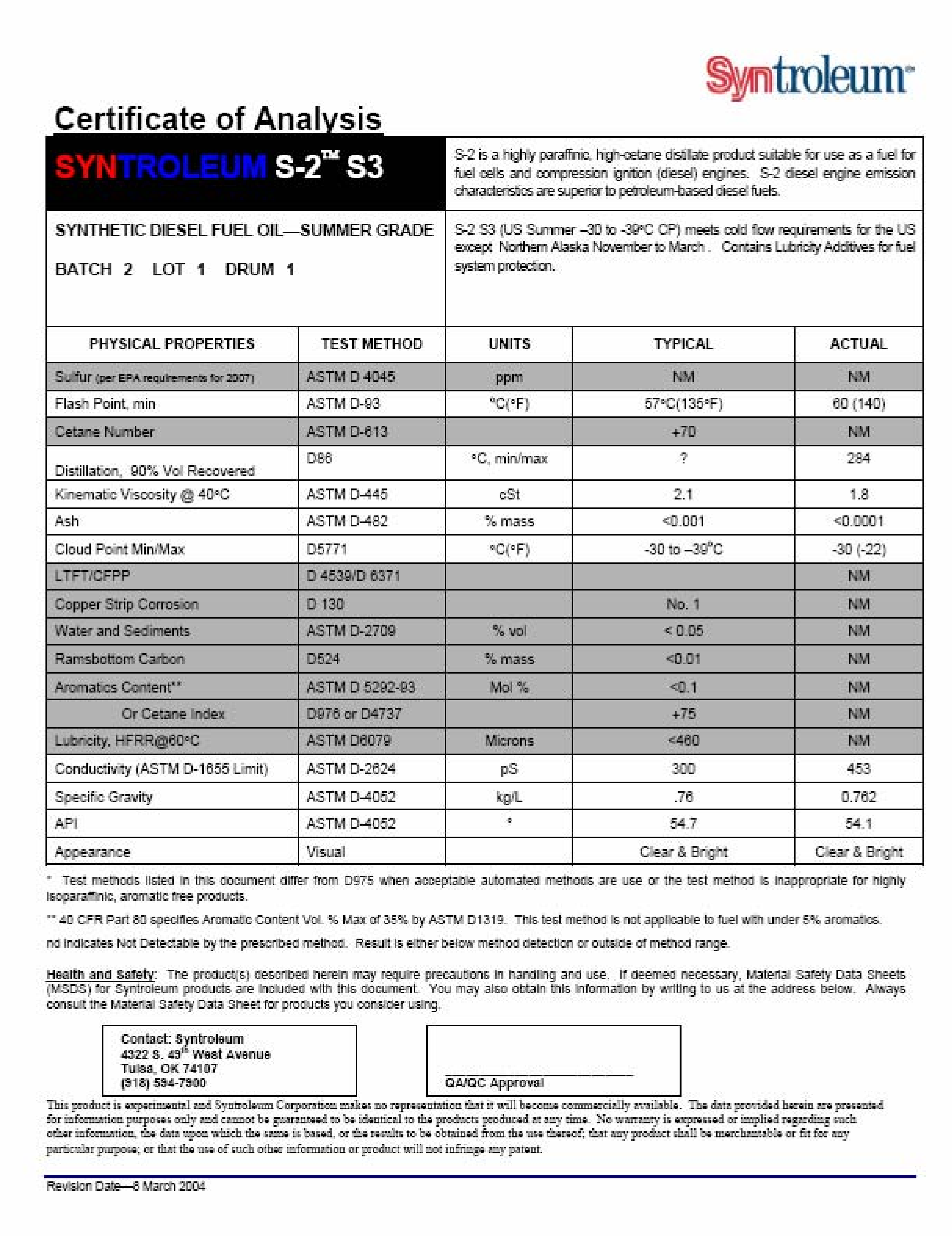
Appendix 20.



Syntroleum

Certificate of Analysis

SYNTROLEUM S-2™ S3

S-2 is a highly paraffinic, high-cetane distillate product suitable for use as a fuel for fuel cells and compression ignition (diesel) engines. S-2 diesel engine emission characteristics are superior to petroleum-based diesel fuels.

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 2 LOT 1 DRUM 1

S-2 S3 (US Summer –30 to -39°C CP) meets cold flow requirements for the US except Northern Alaska November to March. Contains Lubricity Additives for fuel system protection.

PHYSICAL PROPERTIES	TEST METHOD	UNITS	TYPICAL	ACTUAL
Sulfur (per EPA requirements for 2007)	ASTM D 4045	ppm	NM	NM
Flash Point, min	ASTM D-93	°C(°F)	57°C(135°F)	60 (140)
Cetane Number	ASTM D-613		+70	NM
Distillation, 90% Vol Recovered	D86	°C, min/max	?	284
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	2.1	1.8
Ash	ASTM D-482	% mass	<0.001	<0.0001
Cloud Point Min/Max	D5771	°C(°F)	-30 to –39°C	-30 (-22)
LTFT/CFPP	D 4539/D 6371			NM
Copper Strip Corrosion	D 130		No. 1	NM
Water and Sediments	ASTM D-2709	% vol	< 0.05	NM
Ramsbottom Carbon	D524	% mass	<0.01	NM
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	NM
Or Cetane Index	D976 or D4737		+75	NM
Lubricity, HFRR@60°C	ASTM D6079	Microns	<460	NM
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	300	453
Specific Gravity	ASTM D-4052	kg/L	.76	0.762
API	ASTM D-4052	°	54.7	54.1
Appearance	Visual		Clear & Bright	Clear & Bright

* Test methods listed in this document differ from D975 when acceptable automated methods are use or the test method is inappropriate for highly isoparaffinic, aromatic free products.

** 40 CFR Part 80 specifies Aromatic Content Vol. % Max of 35% by ASTM D1319. This test method is not applicable to fuel with under 5% aromatics.

nd indicates Not Detectable by the prescribed method. Result is either below method detection or outside of method range.

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Contact: Syntroleum
4322 S. 49th West Avenue
Tulsa, OK 74107
(918) 594-7900

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QA/QC Approval

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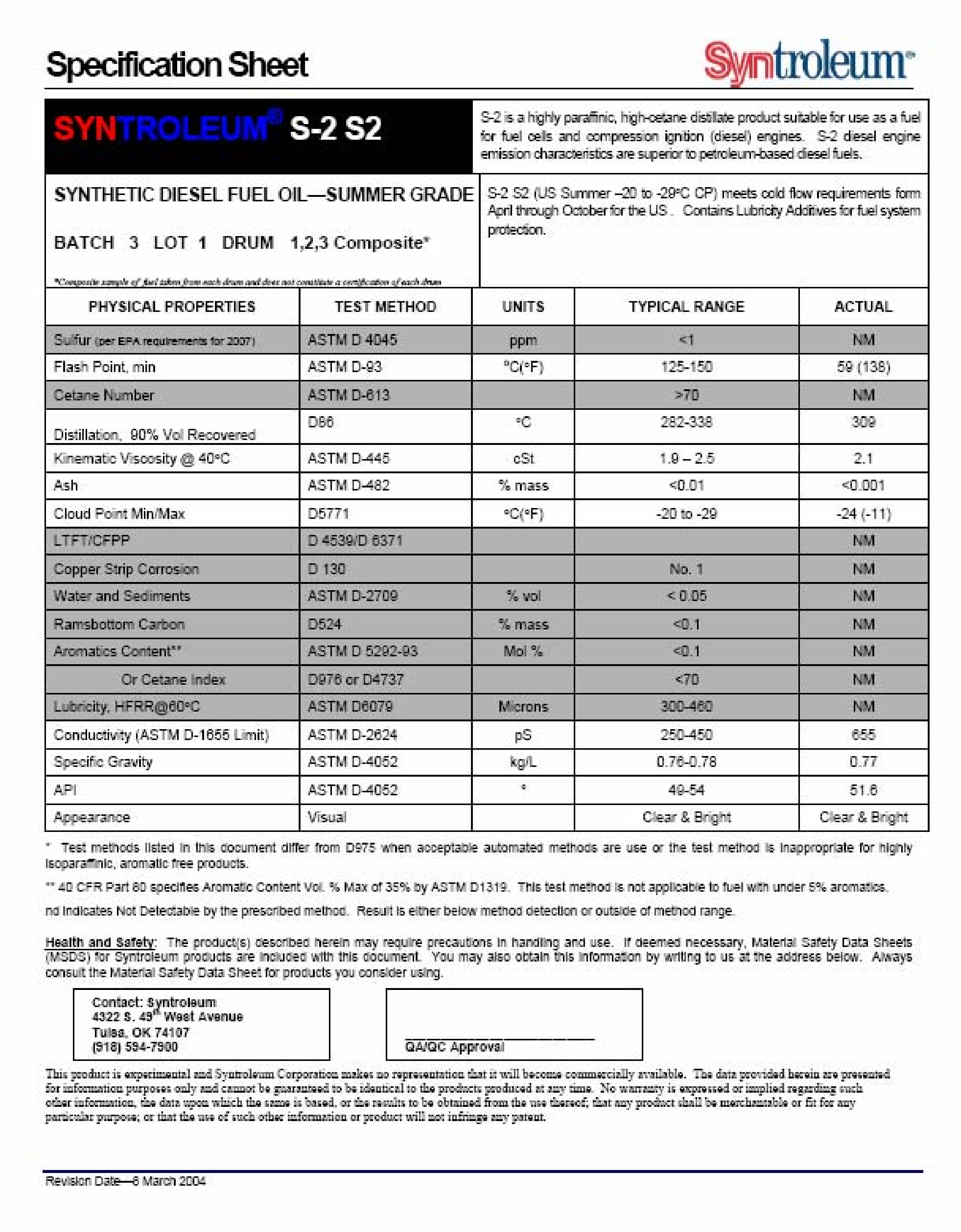
Revision Date—8 March 2004

Appendix 21.



Specification Sheet

Syntroleum

SYNTROLEUM® S-2 S2

S-2 is a highly paraffinic, high-cetane distillate product suitable for use as a fuel for fuel cells and compression ignition (diesel) engines. S-2 diesel engine emission characteristics are superior to petroleum-based diesel fuels.

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 3 LOT 1 DRUM 1,2,3 Composite*

*Composite sample of fuel taken from each drum and does not constitute a certification of each drum

S-2 S2 (US Summer –20 to -29°C CP) meets cold flow requirements form April through October for the US . Contains Lubricity Additives for fuel system protection.

PHYSICAL PROPERTIES	TEST METHOD	UNITS	TYPICAL RANGE	ACTUAL
Sulfur (per EPA requirements for 2007)	ASTM D 4045	ppm	<1	NM
Flash Point, min	ASTM D-93	°C(°F)	125-150	59 (138)
Cetane Number	ASTM D-613		>70	NM
Distillation, 90% Vol Recovered	D86	°C	282-338	309
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9 – 2.5	2.1
Ash	ASTM D-482	% mass	<0.01	<0.001
Cloud Point Min/Max	D5771	°C(°F)	-20 to -29	-24 (-11)
LTFT/CFPP	D 4539/D 6371			NM
Copper Strip Corrosion	D 130		No. 1	NM
Water and Sediments	ASTM D-2709	% vol	< 0.05	NM
Ramsbottom Carbon	D524	% mass	<0.1	NM
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	NM
Or Cetane Index	D976 or D4737		<70	NM
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	NM
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	655
Specific Gravity	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.6
Appearance	Visual		Clear & Bright	Clear & Bright

* Test methods listed in this document differ from D975 when acceptable automated methods are use or the test method is inappropriate for highly isoparaffinic, aromatic free products.

** 40 CFR Part 80 specifies Aromatic Content Vol. % Max of 35% by ASTM D1319. This test method is not applicable to fuel with under 5% aromatics.

nd indicates Not Detectable by the prescribed method. Result is either below method detection or outside of method range.

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Tulsa, OK 74107
(918) 594-7900

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QA/QC Approval

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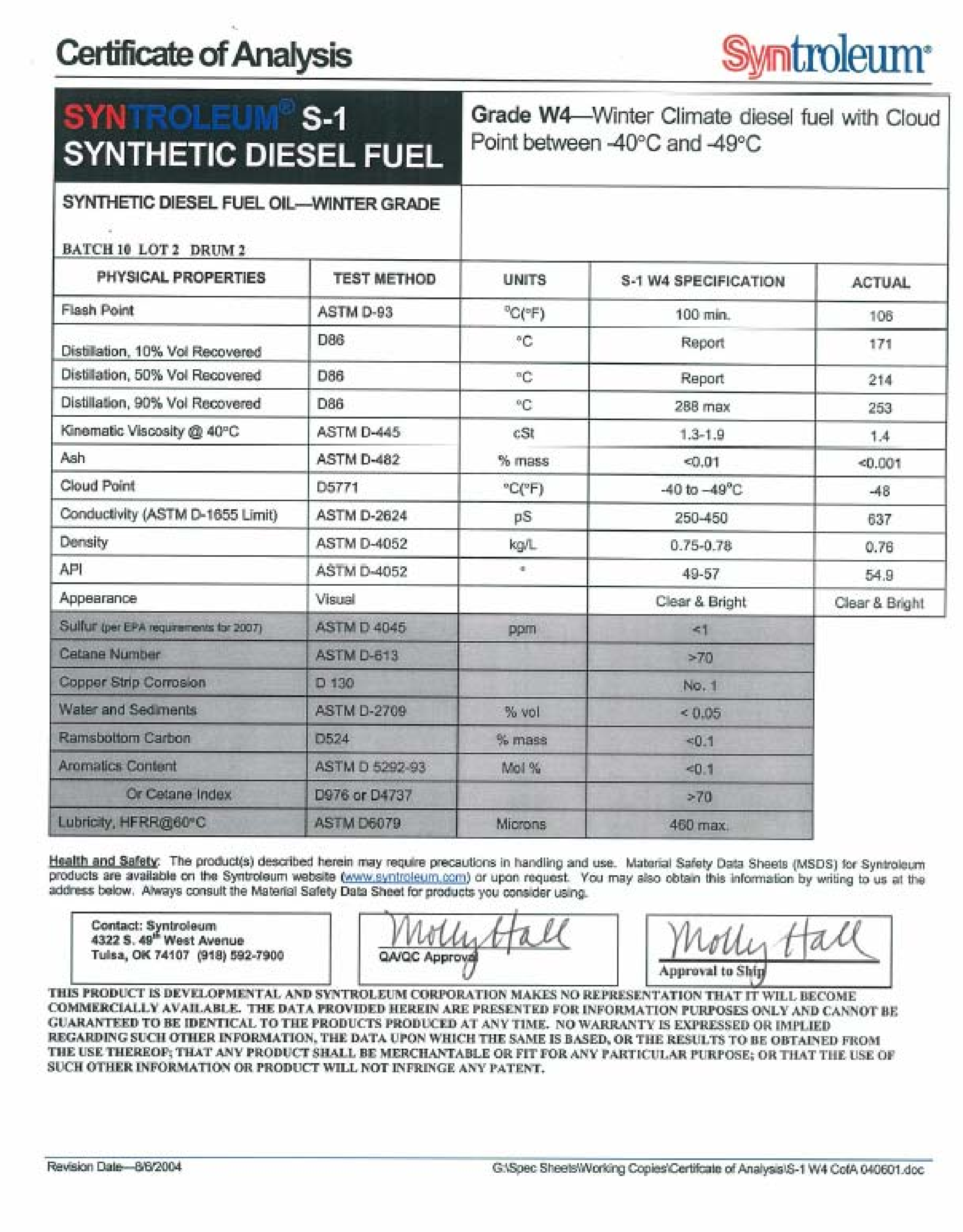
Revision Date—6 March 2004

Appendix 22.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-1 SYNTHETIC DIESEL FUEL

Grade W4—Winter Climate diesel fuel with Cloud Point between -40°C and -49°C

SYNTHETIC DIESEL FUEL OIL—WINTER GRADE

BATCH 10 LOT 2 DRUM 2

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-1 W4 SPECIFICATION	ACTUAL
Flash Point	ASTM D-93	°C(°F)	100 min.	106
Distillation, 10% Vol Recovered	D86	°C	Report	171
Distillation, 50% Vol Recovered	D86	°C	Report	214
Distillation, 90% Vol Recovered	D86	°C	288 max	253
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.3-1.9	1.4
Ash	ASTM D-482	% mass	<0.01	<0.001
Cloud Point	D5771	°C(°F)	-40 to –49°C	-48
Conductivity (ASTM D-1655 Limit)	ASTM D-2624	pS	250-450	637
Density	ASTM D-4052	kg/L	0.75-0.78	0.76
API	ASTM D-4052	°	49-57	54.9
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur (per EPA requirements for 2007)	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	460 max.	

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Tulsa, OK 74107 (918) 592-7900

Molly Hall
QA/QC Approval

Molly Hall
Approval to Ship

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Revision Date—8/6/2004

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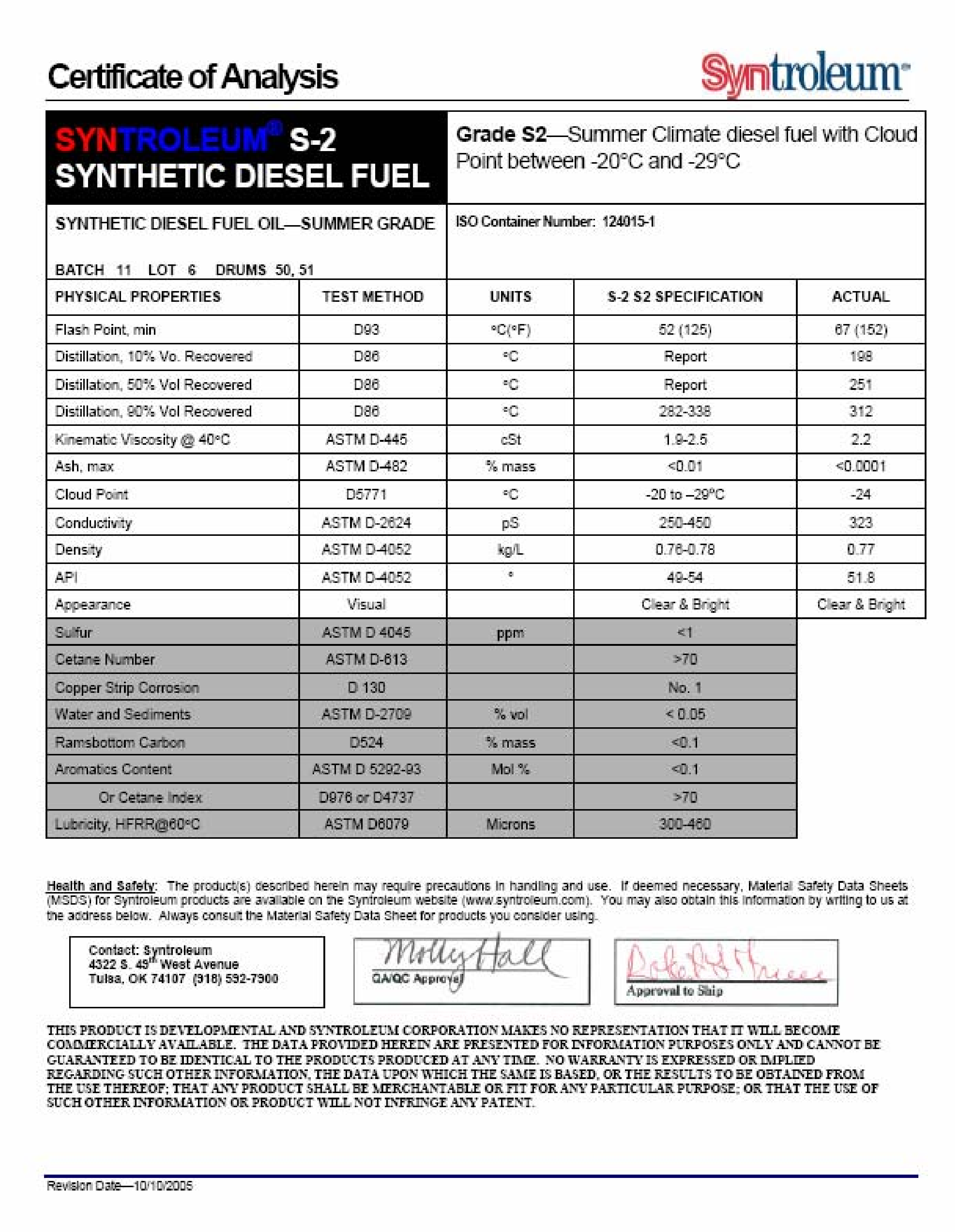
Appendix 23.



Certificate of Analysis

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 6 DRUMS 50, 51

ISO Container Number: 124015-1

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	67 (152)
Distillation, 10% Vo. Recovered	D86	°C	Report	198
Distillation, 50% Vol Recovered	D86	°C	Report	251
Distillation, 90% Vol Recovered	D86	°C	282-338	312
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.2
Ash, max	ASTM D-482	% mass	<0.01	<0.0001
Cloud Point	D5771	°C	-20 to –29°C	-24
Conductivity	ASTM D-2624	pS	250-450	323
Density	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.8
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

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Molly Hall
QA/QC Approval

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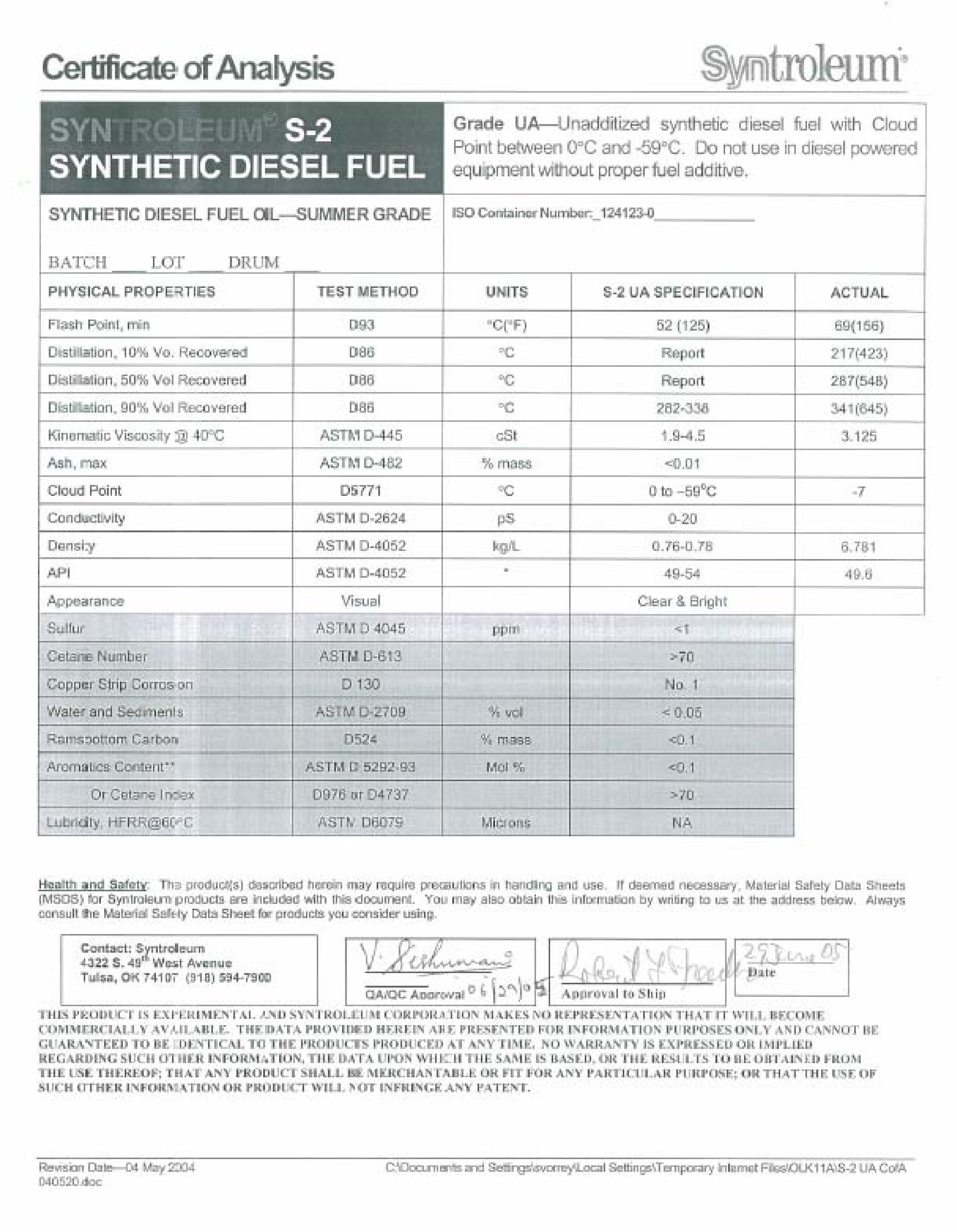
Appendix 24.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2 SYNTHETIC DIESEL FUEL

Grade UA—Unadditized synthetic diesel fuel with Cloud Point between 0°C and -59°C. Do not use in diesel powered equipment without proper fuel additive.

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

ISO Container Number:_124123-0____________

BATCH ____ LOT ____ DRUM ____

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 UA SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	69(156)
Distillation, 10% Vo. Recovered	D86	°C	Report	217(423)
Distillation, 50% Vol Recovered	D86	°C	Report	287(548)
Distillation, 90% Vol Recovered	D86	°C	282-338	341(645)
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-4.5	3.125
Ash, max	ASTM D-482	% mass	<0.01	
Cloud Point	D5771	°C	0 to -59°C	-7
Conductivity	ASTM D-2624	pS	0-20	
Density	ASTM D-4052	kg/L	0.76-0.78	6.781
API	ASTM D-4052	°	49-54	49.6
Appearance	Visual		Clear & Bright	
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	NA	

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QA/QC Approval 06/29/05

Approval to Ship

29 June 05
Date

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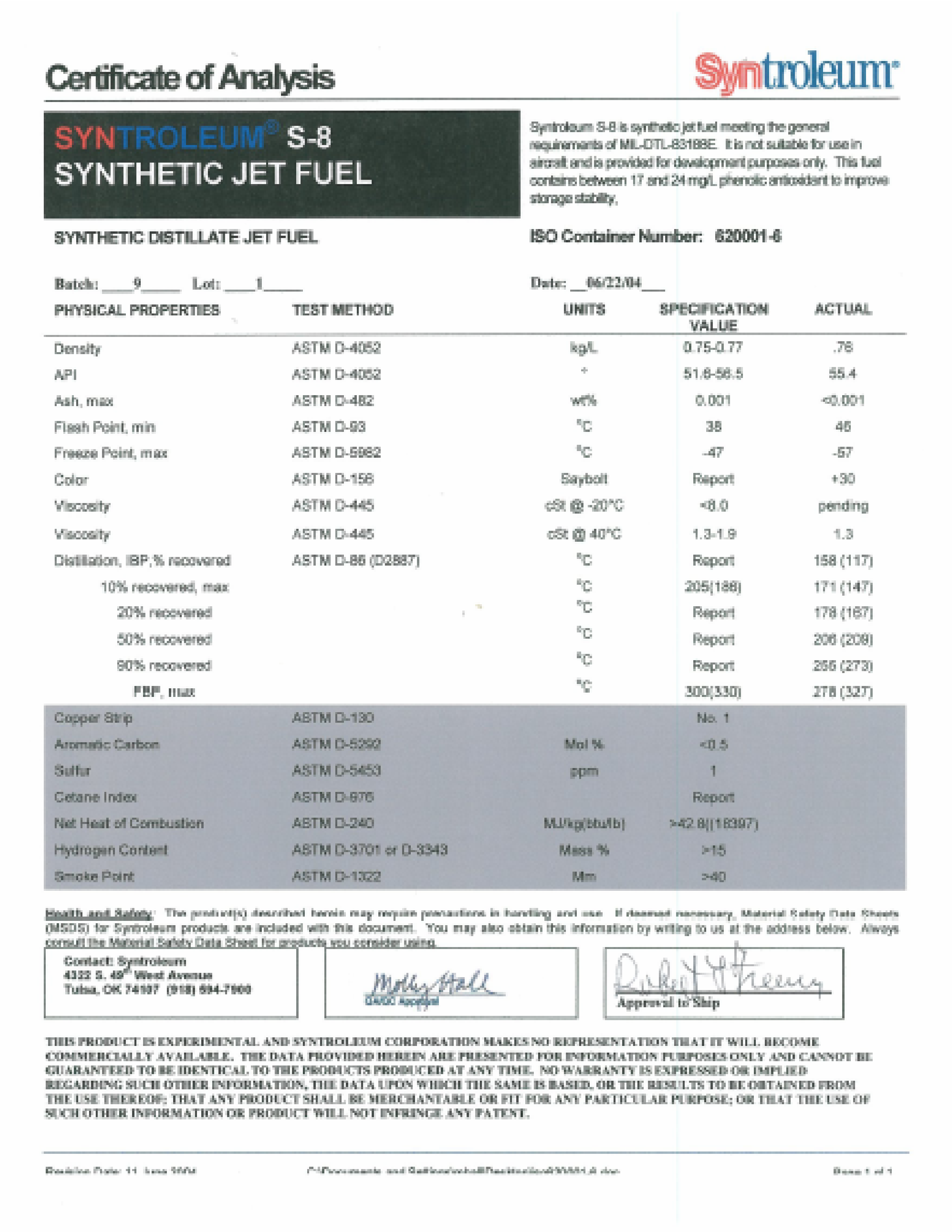
Appendix 25.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-8
SYNTHETIC JET FUEL

Syntroleum S-8 is synthetic jet fuel meeting the general requirements of MIL-DTL-83188E. It is not suitable for use in aircraft and is provided for development purposes only. This fuel contains between 17 and 24 mg/L phenolic antioxidant to improve storage stability.

SYNTHETIC DISTILLATE JET FUEL

ISO Container Number: 620001-6

Batch: ____9_____ **Lot:** ____1_____

Date: __06/22/04___

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	ACTUAL
Density	ASTM D-4052	kg/L	0.75-0.77	.76
API	ASTM D-4052	°	51.6-56.5	55.4
Ash, max	ASTM D-482	wt%	0.001	<0.001
Flash Point, min	ASTM D-93	°C	38	46
Freeze Point, max	ASTM D-5982	°C	-47	-57
Color	ASTM D-156	Saybolt	Report	+30
Viscosity	ASTM D-445	cSt @ -20°C	<8.0	pending
Viscosity	ASTM D-445	cSt @ 40°C	1.3-1.9	1.3
Distillation, IBP,% recovered	ASTM D-86 (D2887)	°C	Report	158 (117)
10% recovered, max		°C	205(186)	171 (147)
20% recovered		°C	Report	178 (167)
50% recovered		°C	Report	206 (208)
90% recovered		°C	Report	255 (273)
FBP, max		°C	300(330)	278 (327)
Copper Strip	ASTM D-130		No. 1	
Aromatic Carbon	ASTM D-5292	Mol %	<0.5	
Sulfur	ASTM D-5453	ppm	1	
Cetane Index	ASTM D-976		Report	
Net Heat of Combustion	ASTM D-240	MJ/kg(btu/lb)	>42.8((18397)	
Hydrogen Content	ASTM D-3701 or D-3343	Mass %	>15	
Smoke Point	ASTM D-1322	Mm	>40	

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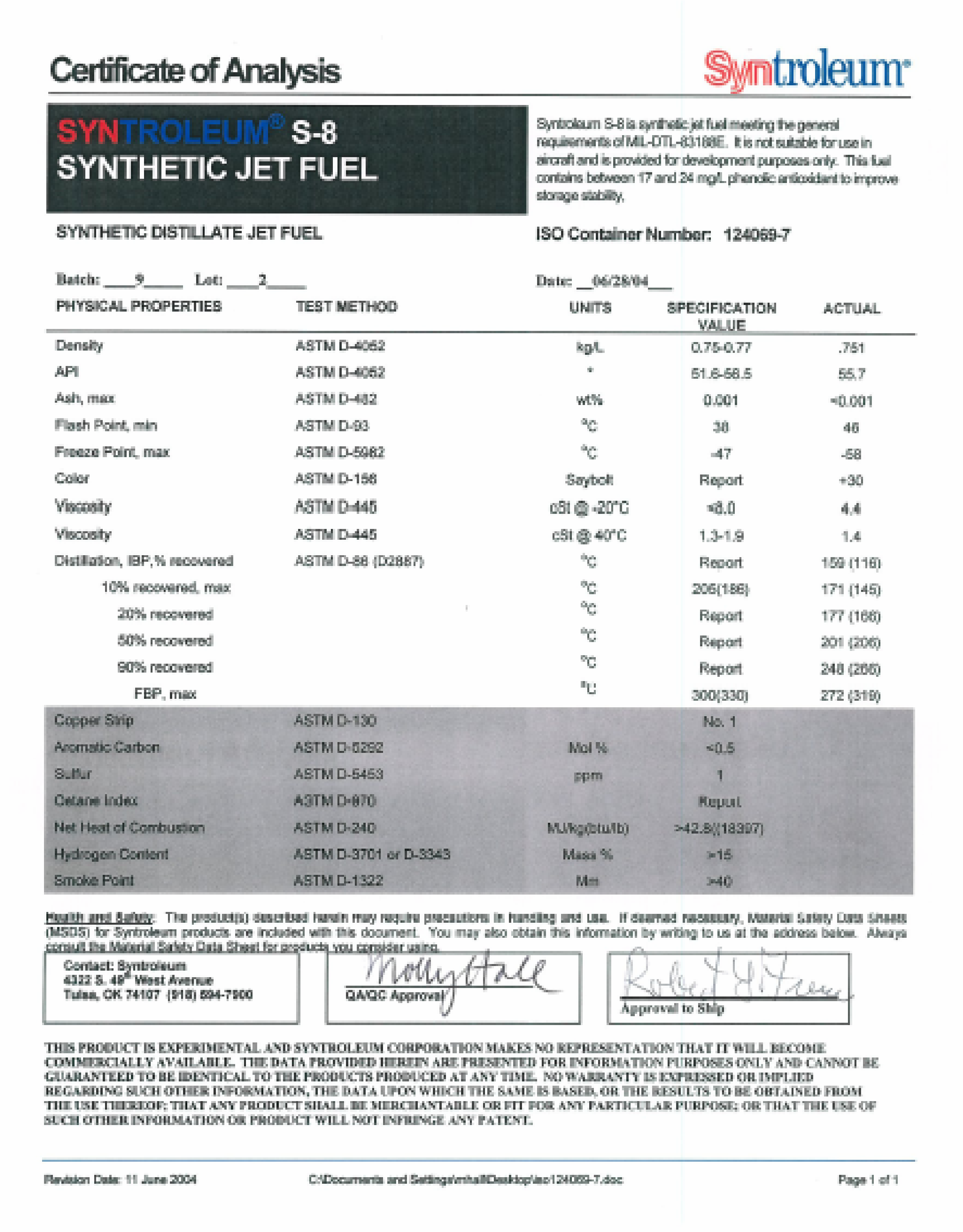
Appendix 26.



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Syntroleum®

SYNTROLEUM® S-8
SYNTHETIC JET FUEL

Syntroleum S-8 is synthetic jet fuel meeting the general requirements of MIL-DTL-83188E. It is not suitable for use in aircraft and is provided for development purposes only. This fuel contains between 17 and 24 mg/L phenolic antioxidant to improve storage stability.

SYNTHETIC DISTILLATE JET FUEL

ISO Container Number: 124069-7

Batch: ____9_____ Lot: ____2_____

Date: __06/28/04___

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	ACTUAL
Density	ASTM D-4052	kg/L	0.75-0.77	.751
API	ASTM D-4052	°	51.6-58.5	55.7
Ash, max	ASTM D-482	wt%	0.001	<0.001
Flash Point, min	ASTM D-93	°C	38	46
Freeze Point, max	ASTM D-5982	°C	-47	-58
Color	ASTM D-156	Saybolt	Report	+30
Viscosity	ASTM D-445	cSt @ -20°C	<8.0	4.4
Viscosity	ASTM D-445	cSt @ 40°C	1.3-1.9	1.4
Distillation, IBP,% recovered	ASTM D-86 (D2887)	°C	Report	159 (116)
10% recovered, max		°C	206(186)	171 (145)
20% recovered		°C	Report	177 (166)
50% recovered		°C	Report	201 (206)
90% recovered		°C	Report	248 (266)
FBP, max		°C	300(330)	272 (319)
Copper Strip	ASTM D-130		No. 1	
Aromatic Carbon	ASTM D-5292	Mol %	<0.5	
Sulfur	ASTM D-5453	ppm	1	
Cetane Index	ASTM D-976		Report	
Net Heat of Combustion	ASTM D-240	MJ/kg(btu/lb)	>42.8((18397)	
Hydrogen Content	ASTM D-3701 or D-3343	Mass %	>15	
Smoke Point	ASTM D-1322	Mm	>40	

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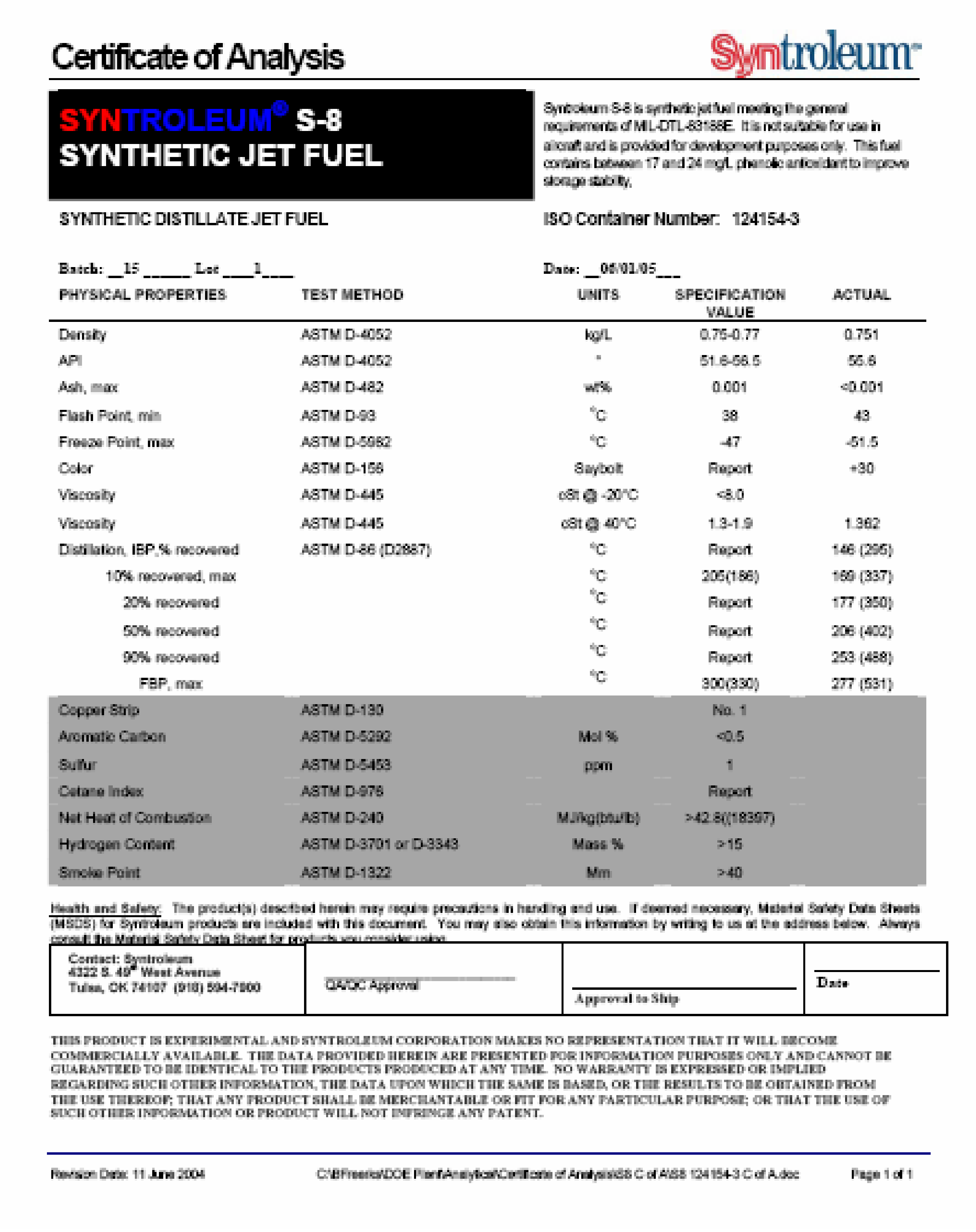
Appendix 27.



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Syntroleum

SYNTROLEUM® S-8
SYNTHETIC JET FUEL

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SYNTHETIC DISTILLATE JET FUEL

ISO Container Number: 124154-3

Batch: __15 ______ Lot ____1____

Date: __06/01/05___

PHYSICAL PROPERTIES	TEST METHOD	UNITS	SPECIFICATION VALUE	ACTUAL
Density	ASTM D-4052	kg/L	0.75-0.77	0.751
API	ASTM D-4052	°	51.6-56.5	56.8
Ash, max	ASTM D-482	wt%	0.001	<0.001
Flash Point, min	ASTM D-93	°C	38	43
Freeze Point, max	ASTM D-5982	°C	-47	-51.5
Color	ASTM D-156	Saybolt	Report	+30
Viscosity	ASTM D-445	cSt @ -20°C	<8.0	
Viscosity	ASTM D-445	cSt @ 40°C	1.3-1.9	1.362
Distillation, IBP,% recovered	ASTM D-86 (D2887)	°C	Report	146 (295)
10% recovered, max		°C	205(186)	169 (337)
20% recovered		°C	Report	177 (350)
50% recovered		°C	Report	206 (402)
90% recovered		°C	Report	253 (488)
FBP, max		°C	300(330)	277 (531)
Copper Strip	ASTM D-130		No. 1	
Aromatic Carbon	ASTM D-5292	Mol %	<0.5	
Sulfur	ASTM D-5453	ppm	1	
Cetane Index	ASTM D-976		Report	
Net Heat of Combustion	ASTM D-240	MJ/kg(btu/lb)	>42.8((18397)	
Hydrogen Content	ASTM D-3701 or D-3343	Mass %	>15	
Smoke Point	ASTM D-1322	Mm	>40	

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Report Issued: August 2006

AVL Report on Bus-Engine Fuel-System Durability and Emissions
DOE Contract: DE-FC26-01NT41099

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Written by	Approved by	Approved by
Brian Woodward Tech Specialist **Connie Henderlong** Project Engineer	**Tony Brakora** Skill Team Leader; Mech. Development	**Mick Winship** Engineering Director; AVL PEI

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1. Introduction

AVL Powertrain Engineering Inc. (AVLPEI) performed the investigation of the durability of the fuel systems of two medium-duty diesel transit-bus engines running 1500 hours each on Syntroleum Corporation's S-2; a high cetane, zero sulfur, ultra-clean diesel fuel produced from natural gas using Syntroleum's Fischer-Tropsch (F-T) process. The 1500 hour durability segment using Syntroleum fuel was followed with emission testing of each engine on each of three fuels; Syntroleum S-2, Washington Metropolitan Area Transportation Authority's (WMATA) low sulfur No. 1 diesel fuel and Denali National Park's "Jet A" fuel.

Two diesel engines were tested: a Detroit Diesel Corporation (DDC) Series 50 provided by WMATA, and a new 2004MY Caterpillar C7 provided by Doyon/Aramark, owner and operator of the buses at Denali National Park in Alaska. All testing was conducted at AVL Mechanical Development and Validation Facility, Ann Arbor, Michigan between June 2004 and May 2005.

The dynamometer-laboratory emission measurements from the two engines were an add-on task to the fuel-system durability test programs, motivated primarily by data obtained when West Virginia University (WVU) measured emissions "in the field" from six buses equipped with Caterpillar C-7 engines at Denali National Park. The test plan at Denali unfortunately did not include direct comparison of emissions from the same bus or buses on the two fuels used in the Denali demonstration program, S-2 and the No. 1 diesel fuel normally used by the Denali buses, which is actually Jet A fuel. The purpose of the dynamometer-based emission measurements at AVL was to obtain direct comparisons of emissions, especially NOx, with each of three fuels from the same two engines.

Several previous studies of the effects of fuel properties on diesel engine emissions have shown that zero-sulfur, ultra-clean F-T fuels reduce both NOx and particulate emissions compared to conventional diesel fuels. Data obtained by WVU at both WMATA and Denali followed this pattern, with the exception of NOx emission results at Denali, which appeared to be somewhat higher with S-2 than with Jet A, albeit in different buses. See WVU's companion report for complete emission results, including an explanation of the unexpected NOx results based upon WVU's further investigation of the new technology believed to be operative within the Caterpillar C-7 engine control system.

In view of the WVU NOx results at Denali, the AVL dynamometer-based, direct-comparison of emissions program was designed to determine cost effectively, under well controlled laboratory conditions, whether or not S-2 fuel would cause an inherent increase in the NOx emissions from the Caterpillar C-7 engine over emission levels obtained from the same engine with the identical Jet A fuel used as No.1 diesel fuel at Denali National Park, and further, to compare NOx emission results with the more conventional low-sulfur No. 1 diesel fuel used by WMATA.

Since NOx and particulate emissions are known to “trade-off” under some conditions in diesel engine emission control technology, particulate mass emissions were also measured with the Caterpillar C-7 engine on all three fuels. And since the older technology DDC Series 50 engine was also available, gaseous emissions from it were also measured with the same three fuels to obtain yet another direct comparison of the effects of the three fuels on diesel NOx emissions. Filter Smoke Number (FSN) (similar to soot) emissions were also measured from the DDC engine to give an approximate indication of relative particulate emissions with the three fuels.

2. Summary

Durability

The Fuel-System Durability segment evaluated two medium duty Syntroleum fueled diesel engines for fuel system wear and performance over 1500 hours of Chicago Transit Authority cycles.

- The DDC Series 50 performed 1500 hours of Syntroleum fueled repetitive CTA cycles without incident. There was no indication of any fuel system performance problem at the end of the test.

- The Caterpillar C7 performed 1500 hours of Syntroleum fueled repetitive CTA cycles. Engine peak power decreased approximately 20% over the 1500 hour duration.

- Fuel injectors were inspected by Jim McCandless of AVL who has several decades experience related to diesel fuel systems, injector design and practical field knowledge. The DDC injectors showed only slight polish to their internal spill valves. Some of the Caterpillar injector nozzle holes were severely fouled with deposits; material yet to be determined. Jim's PowerPoint report on all injectors is included in Appendix 6.3. The fouled injectors were shipped to Robert Freerks of Syntroleum for electron microscope and other deposit analysis as measured at the University of Tulsa. Results of the Syntroleum/Tulsa inspection are not included in this report.

Emissions

The Emission investigation compared Syntroleum, Denali and WMATA fuels on a time and power weighted emission test cycle. WMATA fuel, a conventional low-sulfur No. 1 diesel, is defined in this study as the 'reference' fuel. For each engine, three AVL 8 Mode emission tests were performed on each of the three fuels.

The AVL 8-Mode is a hot start test originally designed to correlate with exhaust emission results of the US FTP Heavy-Duty Transient Cycle. The weighted brake specific emissions were compared for each pollutant by averaging three emission tests to a one value result. NOx and particulate matter (PM) were the pollutants of primary interest.

For the DDC engine tailpipe Filter Smoke Number (FSN) was measured. FSN values indicate exhaust stain amount to a filter paper, similar to a Bosch smoke number test. For the CAT engine an AVL 472 SPC 'Smart Sampler', a partial flow exhaust sampling system, provided tailpipe PM mass emissions.

- **Syntroleum NOx decreased 12% (DDC) and 19% (CAT) from the reference WMATA fuel.**
- **Syntroleum PM decreased 42% (CAT only) from the reference WMATA fuel.**
- **Syntroleum 'soot' (DDC only) was based on an AVL 415S smoke meter. Filter Smoke Number (FSN) is the output. Syntroleum FSN was approximately 38% lower than the WMATA reference fuel in Modes 3, 4 and 5.**
- **Diesel Oxidation Catalyst on the CAT engine showed similar conversion efficiencies of CO and THC across all three fuels except for Mode 5 carbon monoxide emission. Mode 5 CO conversion showed Syntroleum fuel was the most reactive at a conversion efficiency of 77%, WMATA fuel followed at 14% and Denali fuel at 5%.**

Complete results shown in **Section 4 Emission Tests**, and Appendix.

3. Durability

3.1 Engine Configuration

Description of the CTA Cycle

The Chicago Transit Authority (CTA) cycle is a simple, idealized five minute dynamometer cycle intended to simulate “hard-running” urban transit bus service. The first three minutes consist of typical acceleration and cruise modes from seven “stops”, during which the engine idles. The final two minutes are at rated speed and full power.

The five minute CTA cycle was repeated to accumulate 1500 engine hours. CTA ideal and actual representative speed/load traces for both engines are shown in **Figure 1.** Both the DDC Series 50 and CAT C7 followed the CTA speed/load traces similarly even with required differences in the dynamometer control strategy.

Speed/Torque Control Method for CTA Cycle

The Chicago Transit Authority (CTA) transit bus cycle test was written as an “Automatic” test using AVL PUMA Open data acquisition system. The engine rack command behaves differently between the DDC and CAT engines. The DDC system is simple: at a fixed speed the DDC engine rack position results in a generally stable engine torque output. The CTA cycle dynamometer control was operated in Speed/Torque mode with no problems; Speed controlled by the dyno and crankshaft Torque set by automated rack positioning.

The CAT ACERT system uses rack position as a speed input request to the engine processor. At full power this is not a problem; rack position is commanded to 100% and full torque is met as the dyno holds RPM at the desired speed. In Speed/Torque control mode and at low engine power the rack commanded rpm can conflict with the dynamometer speed control. Therefore the CTA cycle dynamometer control was operated in Torque/Speed mode such that the engine processor rack command would be the only speed control loop. Speed request emanates from PUMA control and commands the rack position such that engine rpm reaches the desired value.

The CAT AVL 8 Mode emission tests were operated in Speed/Torque mode. While this solves the problem of holding torque constant (AVL 8 Mode requirement at each mode) it complicates the engine computer speed control strategy. This is discussed in **Section 4: Emission Tests.**

DDC Series 50
CTA Durability Start: July 2004
CTA Durability Finish: September 2004
Approximate Consumption of S-2 Fuel: 15,000 gallons
Oil: Shell Rotella T 15W-40
Oil change intervals: 250 hours

Test Cell (TC) 13 was commissioned to run the DDC engine using an eddy current dynamometer coupled in series with an AVL AFA 460kW ac regenerative dynamometer. The eddy current dyno applied a constant 500 Nm of torque. The AFA dyno and EMCON controller absorbed the remaining load and controlled engine rpm to the target value.
The DDC engine had been previously used for cold start testing on Syntroleum fuel. New fuel injectors and a fuel delivery pump were installed prior to running the Syntroleum fueled fuel system durability test. The new components operated a few hours during final CTA schedule dynamometer control tuning using commercial No. 2 diesel fuel. CTA Cycle Syntroleum fueled durability commenced for a period of 1500 hours.

Engine Specifics
Engine: 2000 MY DDC Series 50, 4 cylinder, 4 Stroke, Direct Injection, TCA (turbo-charged and after-cooled)
Calibration level: Remanufactured DDEC; Detroit Diesel p/n 23519308
Model: 6047MK2E
Rated Speed: 2100 rpm
Rated Power: 275 hp with No. 2 Diesel fuel (with Remanufactured DDEC above
Fuel Delivery System: electronic unit injection (EUI). Fuel quantity and injection timing was electronically controlled by the DDEC engine control module. No emission aftertreatment device was used.
Exhaust Aftertreatment: none

Caterpillar C7
CTA Durability Start: September 2004
CTA Durability Finish: February 2005
Approximate Consumption of S-2 Fuel: 11,500 gallons
Oil: Shell Rotella T 15W-40
Oil change intervals: 250 hours

A new 2004 CAT C7 was purchased by Doyon/Aramark, owner and operator of the Denali National Park buses, at the same time as new buses with the same engine were ordered for the 2004 summer season. This 'spare' new engine was lent to the project for the fuel-system durability test. A 13 hour Break-In at stepped speeds and loads was performed on an AVL AFA 450 kW ac regenerative dynamometer using commercial No. 2 diesel fuel. 1500 hours of Syntroleum fueled CTA Cycle durability was accumulated.

Engine Specifics

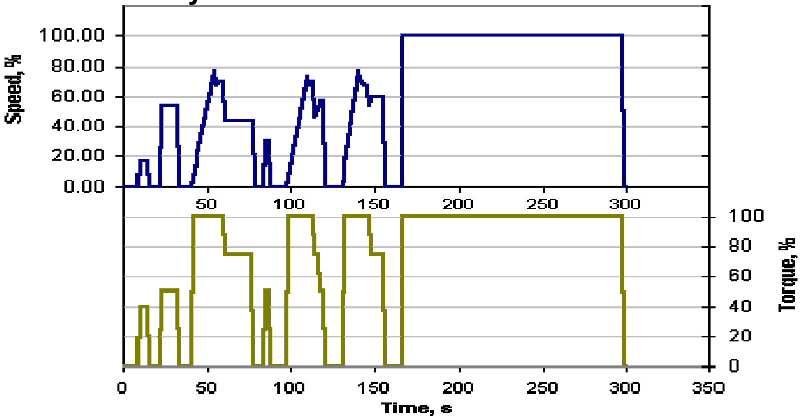
Engine: 2004 MY Caterpillar C7, In-line 6 cylinder, 4 stroke, Direct Injection, TCA
Emission class: 2004 California, On-Highway, Medium Heavy Duty Diesel
Serial Number: KAL 44598
Calibration level: ECM Software 251-7442
Rated Speed: 2400 rpm
Rated Power: 230 hp with #2 Diesel fuel

Fuel Delivery/Engine Control: HEUI fuel injection that utilizes electronically commanded hydraulically actuated unit injectors. Caterpillar's registered ACERT® technology adjusts engine air flow via valve actuation control and rack position is thought to function as a speed command input. Various fueling tables are selected by the engine control module dependent on sensor inputs. Specifics of the ACERT system are confidential within Caterpillar.

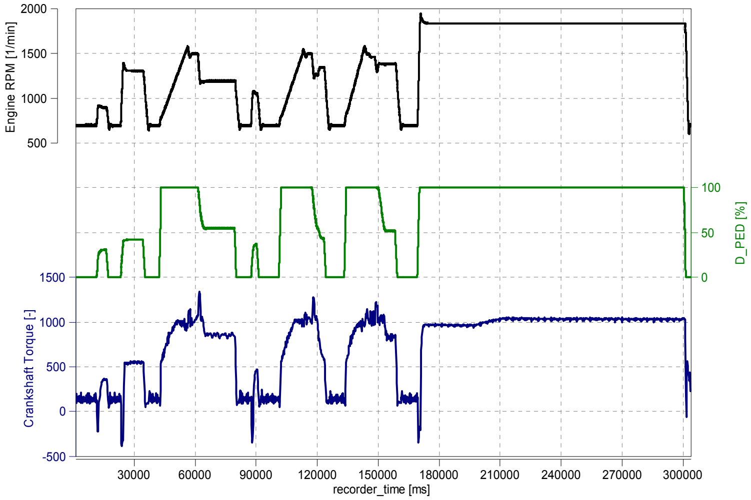
Exhaust Aftertreatment: The emission control in the dynamometer test cell included the same diesel oxidation catalyst (DOC) that was original equipment on-board the 2004 model-year buses at Denali National Park.

Figure 1: Speed/Load Traces CTA

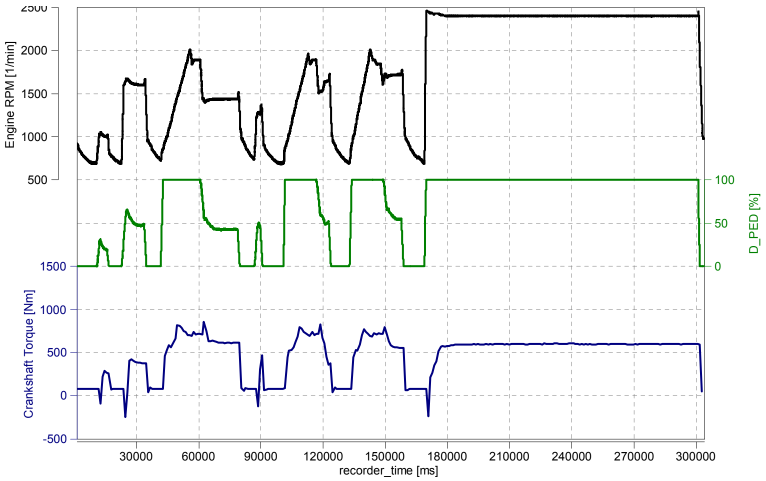
CTA Ideal Cycle



DDC Series 50: CTA Cycle



Caterpillar C7: CTA Cycle Operation



3.2 Fuel Injector Inspection

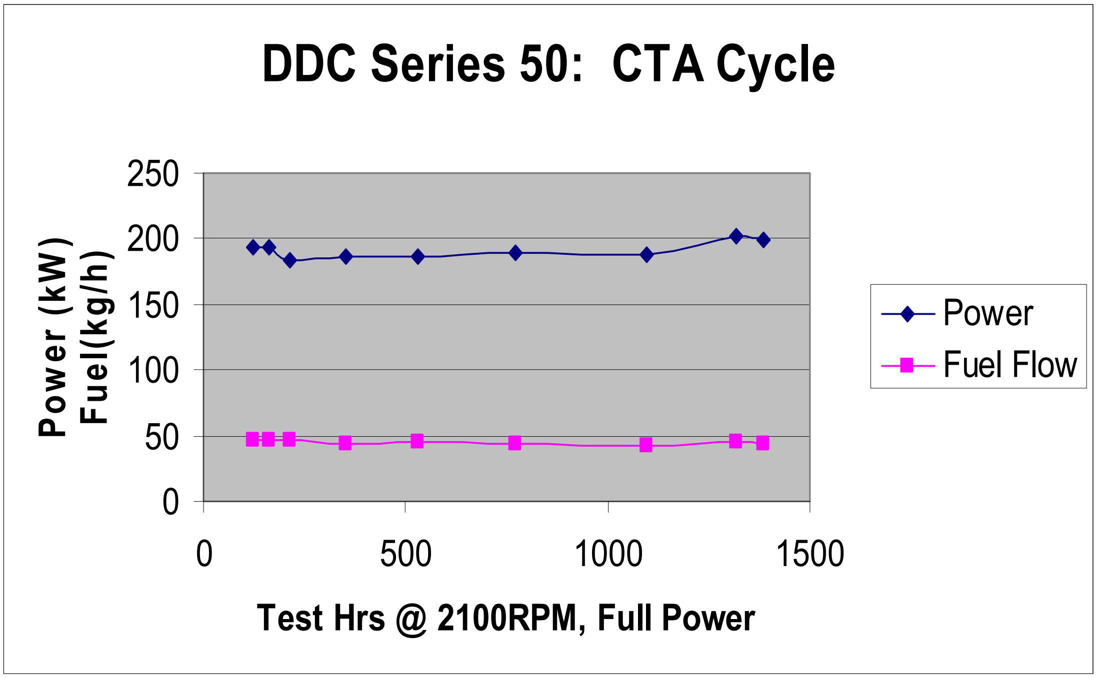
DDC Series 50

Fuel injectors were replaced with ‘new’ injectors from the DDC parts supply system and broken-in for 10 hours on conventional No. 2 diesel fuel at the start of the Fuel-System Durability test. Durability and Gaseous Emission tests were performed on the same set of injectors. Fuel injectors were inspected following emission tests on all three fuels; Syntroleum, Denali and WMATA.

Therefore, by definition, the Emission test data may have been affected by any non-uniform injector wear, etc., which may have occurred during the Durability test.

The DDC engine functioned normally with power and fuel rate remaining mostly flat throughout the 1500 hour CTA cycle. (See **Figure 2** below) The injector inspections showed little wear or distress other than a small amount on one of the four control or ‘spill’ valves. (“New” injectors from the DDC parts supply system reportedly include used injectors remanufactured by DDC, a process in which many used but acceptable parts are apparently re-used. Therefore, it is possible, in view of the very low-wear condition of the other three spill valves in he same engine, that the post-test condition of this fully functional spill valve may not have been significantly different from its pre-test condition.) Injectors were disassembled and inspected by AVL’s Jim McCandless. Refer to **Appendix 2** for Jim’s injector inspection report.

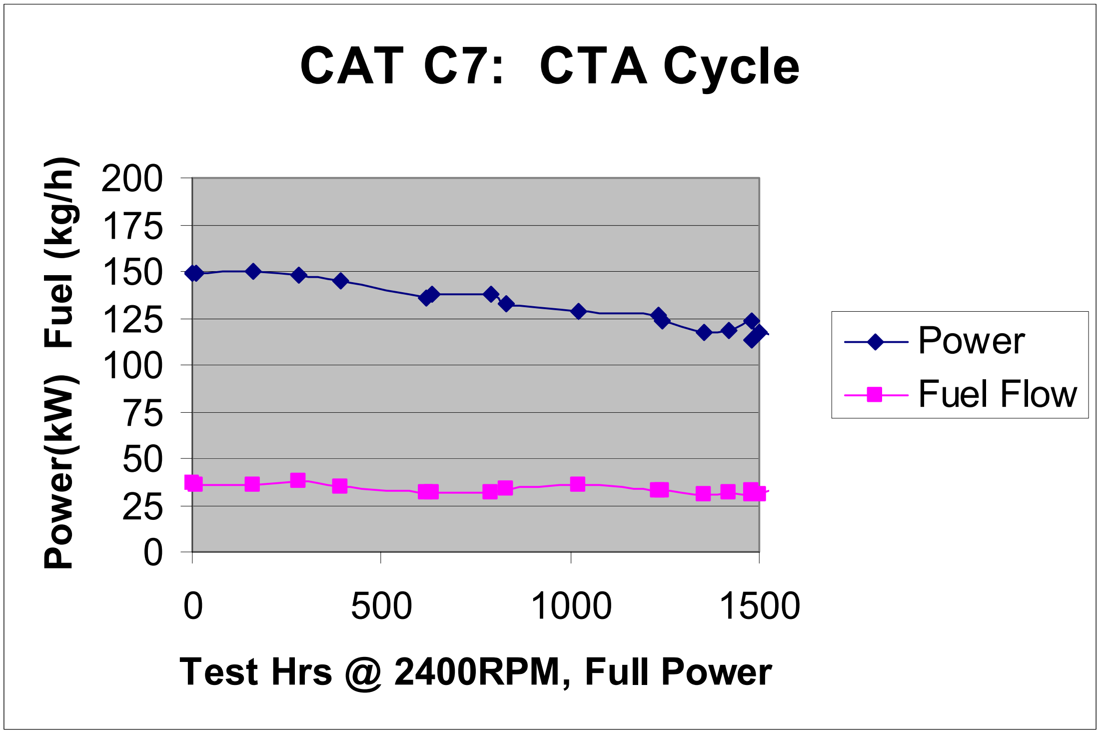
Figure 2



Caterpillar C7
Durability and Emission tests were performed on different sets of fuel injectors. As the Durability test was executed engine power fell approximately 20 % throughout the 1500 hours (see **Figure 3** below). Since the change in maximum power output capability was gradual, this type of change might or might not be noticed by a driver if it occurred in a bus in the field. All fuel injectors were removed following the 1500 hour Durability, disassembled and inspected. A set of six new injectors from the Caterpillar parts supply system were installed just prior to the Emission tests. The engine processor (ECM) was re-flashed by a Michigan-CAT dealer/distributor technician to accept the new injector idle trim code values. The durability Injectors were disassembled and inspected by AVL's Jim McCandless. Refer to **Appendix 2** for Jim's injector inspection report.

With new injectors installed the CAT C7 emission test data was not, by definition, affected by any potential Durability induced injector wear. Emission data represents fuel type induced emission output only. The emission test injectors were not inspected following emission testing, but were left in the engine when it was returned to Doyon/Aramark.

Figure 3



4. Emission Tests: WMATA, Denali, Syntroleum Fuels

AVL 8-Mode Emissions Test

AVL 8 Mode emission tests were conducted with three different fuels: Syntroleum S-2, Washington Metro Area Transportation Authority (WMATA) low-sulfur No. 1 diesel, and Denali Jet A. The AVL 8-Mode test **(Table 1)** is an eight mode steady-state engine test procedure designed to correlate with exhaust emission results of the US FTP Heavy-Duty Transient Cycle. The AVL cycle was chosen as it allows eight individual steps for NOx analysis in addition to the summed modal values. The composite emission values are calculated by applying weight factors to each mode. The weighted mode results are summed to present one emission value over the entire test for each pollutant. NOx, CO and THC (total hydrocarbons) were measured over three runs on each of the three diesel fuels.

The sequential operating points are:

Table 1 AVL 8-Mode Emission Test Cycle-Weight Factors

Mode	% Engine Speed*	% Load	Weight factor**
1	0	0	35.00
2	11	25	6.34
3	21	63	2.91
4	32	84	3.34
5	100	18	8.40
6	95	40	10.45
7	95	69	10.21
8	89	95	7.34

* - Normalized speed: 0% = low idle, 100% = rated speed

** - Relative weight factors, not normalized (they do not add to 100%)

Relative weights of particular modes are represented by the area of bubbles in **Figure 4**.

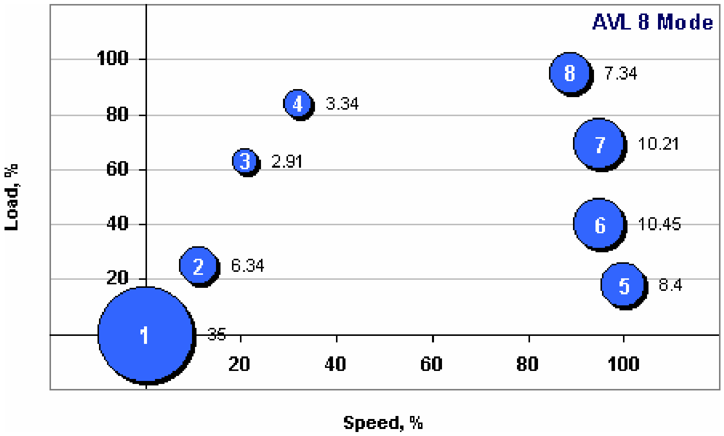


Figure 4 AVL 8-Mode Emission Test Cycle-Visual Weight Factors

DDC Series 50

Prior to AVL 8 Mode testing, the emissions bench, AVL 415S smoke meter and Lambda meter were connected. Engine mass flow was calculated using measured fuel rate, measured emissions based air/fuel ratio and raw emission analyzer values.

- NOx mass emission output was corrected for ambient air humidity.
- CO and CO2 raw emissions were converted from dry to wet based values to match with wet based values for THC and NOx.

DDC powertrain components and measuring devices are shown in **Figure 5**. True PM sampling equipment was not available for the DDC Series 50 engine. As a substitute an AVL 415S Smoke Meter allowed relative comparison of soot emissions between the three fuels. The device draws a metered amount of raw exhaust, passes it across a clean filter paper and then measures the light reflectance. Filter Smoke Number (FSN) is the output of the 415S. The technique cannot distinguish fuel/oil makeup of the soot nor can it derive a PM mass emission value directly. The values reported (**Table 2**) may be compared among the three fuels as a relative indicator of soot emission but are not meant to substitute for properly sampled and weighed PM emission output.

Overall Emission results are shown in Appendix 1
Averaged results of the three AVL 8 Mode tests per fuel are shown here:

DDC Series 50						
Fuel Type	Weighted Emission: g/kW-hr			% Difference from WMATA		
	NOx	CO	THC	NOx	CO	THC
WMATA	8.64	0.40	0.11	0	0	0
Denali	7.78	0.40	0.17	-10	0	55
Syntroleum	7.61	0.26	0.12	-12	-35	4

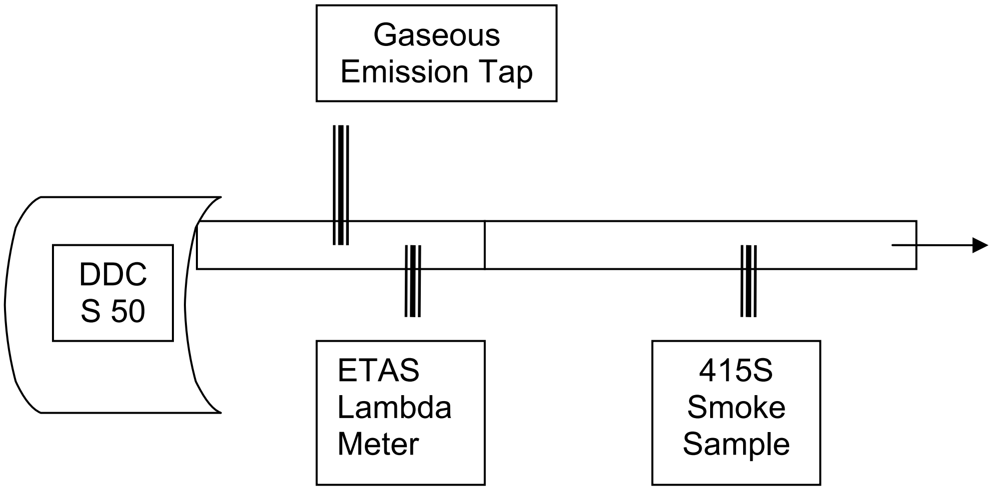


Figure 5: Exhaust System Layout – DDC Series 50

Table 2.

FSN Averages Over 3 Runs on each Fuel			
Mode	Syntroleum	WMATA	Denali
1	0.03	0.02	0.01
2	0.05	0.03	0.04
3	0.17	0.23	0.35
4	0.11	0.22	0.22
5	0.12	0.19	0.18
6	0.07	0.10	0.13
7	0.06	0.05	0.07
8	0.03	0.06	0.08

Caterpillar C7

Prior to AVL 8 Mode testing, the gaseous emissions sample taps, AVL 472 SPC and Merriam laminar air flow meter system were connected. Engine mass flow was calculated using measured air rate, measured fuel rate, and raw emission analyzer values.

- A carbon balance check verified emission based total carbon matched measured fuel mass carbon within +/- 3 percent.
- NOx mass emission output was corrected for ambient air humidity.
- CO and CO2 raw emissions were converted from dry to wet based values to match wet based values for THC and NOx.

The CAT C7 exhaust system also included a Diesel Oxidation Catalyst (DOC) installed between the turbocharger outlet and tailpipe **(Figure 6).** This particular DOC had been used in one of the 2004 model-year buses at Denali National Park during the summer of 2004. It was included in the dynamometer test-cell set-up for emission measurements because the primary reason for these emission tests was to understand better the NOx results that had been obtained by WVU at Denali national Park. Although NOx emissions are not expected to be influenced by a DOC (the results indeed confirm this expectation), the intent was to evaluate the effects of different fuels on emissions from the same engine, with all factors as close to identical as possible to the conditions at Denali.

AVL 472 SPC pm filter samples were drawn *downstream* of the DOC. Therefore, PM emission data are considered “tailpipe” values and represent pollutants reaching the atmosphere.

Gaseous mass emissions of NOx, CO, CO2 and THC were calculated based on the *Pre-DOC* emission concentrations. The emission values reported are therefore “engine out” emissions of the three fuels without influence of DOC aftertreatment.

Gaseous emissions were also measured *Post-DOC*. Exhaust mass flow was equal for Pre and Post DOC locations since both sets of data were measured at stabilized engine conditions on the same test runs. Therefore Pre and Post DOC emission concentrations were compared directly to determine DOC conversion efficiency. Results are shown in **Table 3**.

For the CAT C7 only, particulate matter (PM) mass emission was measured using an AVL Smart Sampler 472 SPC. The SPC uses a partial flow exhaust dilution technique to proportionally sample, dilute and time weight PM collection onto 47mm high efficiency particulate filters. SPC mass flowmeters and software control the PM exhaust sample mass flow to be proportionally constant to engine exhaust system mass flow rate. SPC filter loading time values match the weight factors listed in **Table 1**. PM filters were humidity stabilized and weighed pre and post test to EPA 2007 year weighing requirements. The final PM data gives a one value, weighted, PM mass emission over each AVL 8 Mode test.

Speed Control Problem-Potential Emissions Impact

As stated in Section 3.1 the CAT engine utilizes rack position as an engine processor speed command input. The AVL 8 Mode tests were operated in Speed/Torque dynamometer control mode such that the 8 Mode calculated desired engine torque could be maintained automatically. However this control method caused a problem at low power levels, as in Modes 1 and 2. The fueling strategy may have been 'confused' jumping between ECM fueling tables as the dual speed control loops of dynamometer and engine computer may have influenced one another. This basic understanding of the CAT fuel and rack control strategy did not occur until all CAT emission tests were completed. A Michigan CAT dealer technician was called in but could find no fault codes in the engine computer. ACERT operating principles are proprietary to Caterpillar Engineering and are not shared with Caterpillar dealers. The result appears to be random high CO and HC emissions in Modes 1 and 2. This problem also impacted NOx production in Modes 1 and 2.

However, as described in WVU's report, Caterpillar's multiple-fuel-injection-event strategy is apparently used as a means to obtain a partially pre-mixed fuel-air charge under some low load operating conditions. Whether or not, and to what extent, this strategy is employed at a particular operating condition is apparently determined on a real-time basis by the engine ECM based upon streaming data being obtained from several sensors. This control strategy may have caused or contributed to the CO, HC, and NOx variability observed at the low-load conditions.

Diesel Oxidation Catalyst (DOC) results (**Table 3**):

1. No NOx conversion increase or reduction within the limits of measurement. All OK since the oxidation catalyst should not affect NOx.
2. Modes 1 and 2: show no conversion of CO. All fuels exhibited DOC inlet temperature of under 190 degrees C for these modes; likely too cold for to activate the DOC CO conversion.
3. Modes 3 through 8: HC and CO conversions are similar with all fuels except in Mode 5. Mode 5 HC and particularly CO conversion efficiency were highest with Syntroleum.
4. Mode 5 has the highest engine load at lowest speed. Catalyst inlet temperature was 269 +/- 3 degrees C for all three fuels; very consistent from run to run and from one fuel to another. Based on the improved CO oxidation percentage Syntroleum is a more reactive fuel than Denali or WMATA with this particular DOC.

Overall Emission results are shown in Appendix 1
Averaged results of the three AVL 8 Mode tests per fuel are shown below:

2004 Caterpillar C7								
Fuel Type	**Weighted Emission: g/kW-hr**				**% Difference from WMATA**			
	NOx	**CO**	**THC**	**PM**	**NOx**	**CO**	**THC**	**PM**
WMATA	4.54	10.38	1.83	0.052	0	0	0	0
Denali	4.73	10.13	1.95	0.054	4	-2	7	5
Syntroleum	3.67	9.28	1.26	0.030	-19	-11	-31	-42

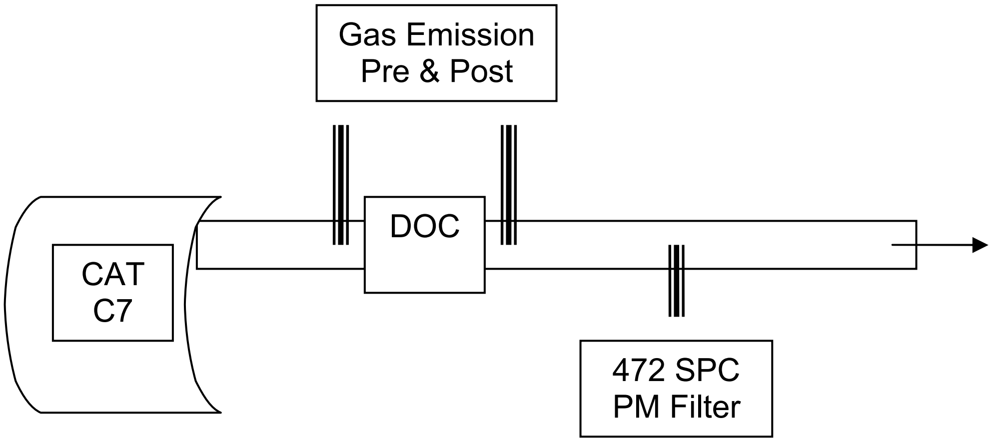


Figure 6: Exhaust System Layout – Caterpillar C7 Only

Table 3.

Summary: DOC Converter Efficiency - Three Fuels

Three AVL 8 Mode Tests Averaged for each of the three fuels

Percent Conversion Efficiency = 100 x (Pre_{conc} - $\text{Post}_{\text{conc}}$) / Pre_{conc}

Fuel →	**Syntroleum (F-T Process, 0 Sulfur)**	**WMATA (Low Sulfur, #1 Diesel)**	**Denali (#1 Diesel-Jet A)**
Mode	**NOx Conversion %**	**NOx Conversion %**	**NOx Conversion %**
1	-1	7	7
2	1	0	2
3	1	1	0
4	-2	0	0
5	-1	-1	-1
6	-1	-1	0
7	-1	-1	-2
8	-1	1	0
Mode	**CO Conversion %**	**CO Conversion %**	**CO Conversion %**
1	0	1	0
2	2	-1	3
3	99	99	98
4	96	96	93
5	77	14	5
6	89	92	87
7	88	88	87
8	85	85	84
Mode	**HC Conversion %**	**HC Conversion %**	**HC Conversion %**
1	50	52	56
2	43	37	43
3	82	70	84
4	89	85	87
5	60	53	47
6	72	76	72
7	79	81	80
8	81	83	82

5. Observations

Durability

Both engines exhibited a power loss when operated on Denali and Syntroleum fuels as compared to WMATA #1 diesel "reference". The power loss is explained by the relative density differences between the three fuels. (**Table 4**) It was beyond the scope of the project to alter engine processor fuel delivery to account for fuel density differences. Both DDC and the CAT diesel fuel systems control fuel *volume* delivery and not fuel *mass.* **Table 3** demonstrates measured engine power decreasing as fuel density also decreases.

Table 4: Effect of Measured Fuel Density on Brake Power (kilowatt)

Fuel Type	Fuel Density @ 25 deg. C (grams/liter)	DDC Series 50 kW @ 1900 rpm	CAT C7 kW @ 2200 rpm
WMATA	830	189	156
Denali	806	179	147
Syntroleum S-2	768	180	144

Emissions

DDC Series 50

NOx specific weighted emissions are high in the 7 to 9 g/kW-hr range for all fuels. Both CO and THC emissions are very low; CO around 0.25 and THC around 0.15 g/kW-hr. Injection timing was not measured but advanced injection timing could explain the combination of high NOx mass emissions coupled with low THC and CO emissions.

PM emissions were not measured. FSN was measured as a relative comparison of soot emissions.

Caterpillar C7

AVL 472 SPC partial flow sampler, weighed filter methodology PM values are reported.
Modes 1 and 2 high CO specific mass emissions and the variation in HC values are related to the previously discussed problem of operating the engine in Speed/Torque mode. (refer to Section 4: Emission Tests).

6. Appendices

6.1 Appendix- Emission Data

Caterpillar C7

Three AVL 8 Mode tests on each of three fuels are displayed. Specific emission units are in metric “grams / kilowatt-hour” and not in USA mixed unit standard “grams / horsepower-hour”.

DDC Series 50

Three AVL 8 Mode tests on each of three fuels are displayed. Specific emission units are in metric “grams / kilowatt-hour” and not in USA mixed unit standard “grams / horsepower-hour”.

AVL 8 Mode: Average Weighted Brake Specific Emissions

Engine: CAT C7 2004	**Rated Speed:** 2400	**Rated Power:** 230 HP	**Disp. (L)** 7.2	**Fuel Type** Syntroleum

PUMA File
5758_synt_19Apr05 2319

SPC File
1012

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	799	-5.08	-0.43	45.69	3857	14.68	10.68	-0.15	15.99	1350	5.14	3.74	
2	6.34	887	138.67	12.88	90.96	11651	36.28	13.58	0.82	5.77	739	2.30	0.86	
3	2.91	1057	407.28	45.08	212.46	32936	156.72	19.52	1.31	6.18	958	4.56	0.57	
4	3.34	1244	614.46	80.05	307.23	59771	176.26	27.46	2.67	10.26	1996	5.89	0.92	
5	8.4	2399.6	94.79	23.82	111.67	36998	96.14	73.54	2.00	9.38	3108	8.08	6.18	
6	10.45	2315	234.08	56.75	181.94	56862	109.51	76.47	5.93	19.01	5942	11.44	7.99	
7	10.21	2315	402.43	97.56	250.3	85128	1122.7	98.76	9.96	25.56	8692	114.63	10.08	
8	7.34	2213.1	587.04	136.05	474.75	102940	848.88	76.87	9.99	34.85	7556	62.31	5.64	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									32.53	127.00	30341	214.34	35.98	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**3.90**	**933**	**6.59**	**1.11**	**0.030**

PUMA File
5776_synt_19Apr05 2322

SPC File
1013

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	800.1	-6.63	-0.56	23.6	3861	329.34	30.67	-0.20	8.26	1351	115.27	10.73	
2	6.34	887	138.49	12.86	75.27	11649	213.61	22.24	0.82	4.77	739	13.54	1.41	
3	2.91	1057	408.31	45.19	214.78	33157	145.07	17.75	1.32	6.25	965	4.22	0.52	
4	3.34	1244	612.92	79.85	313.92	59655	167.19	24.05	2.67	10.48	1992	5.58	0.80	
5	8.4	2400.2	100.17	25.18	113.78	37027	96.52	72.84	2.12	9.56	3110	8.11	6.12	
6	10.45	2315	232.76	56.43	183.01	56133	108.11	76.06	5.90	19.12	5866	11.30	7.95	
7	10.21	2314.9	402.12	97.48	255.04	85166	1119.6	95.81	9.95	26.04	8695	114.31	9.78	
8	7.34	2213	586.74	135.98	466.52	102416	849.89	77.42	9.98	34.24	7517	62.38	5.68	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									32.55	118.73	30236	334.72	43.00	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**3.65**	**929**	**10.28**	**1.32**	**0.030**

PUMA File
5780_synt_19Apr05 2328

SPC File
1014

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	800	-0.79	-0.07	22.21	3619	370.26	32.55	-0.02	7.77	1267	129.59	11.39	
2	6.34	887	138.07	12.82	66.3	11687	226.9	23.4	0.81	4.20	741	14.39	1.48	
3	2.91	1057	405.54	44.89	199.48	33035	153.75	19.38	1.31	5.80	961	4.47	0.56	
4	3.34	1244	613.8	79.96	293.75	59954	179.97	27.68	2.67	9.81	2002	6.01	0.92	
5	8.4	2399.7	95.56	24.01	107.3	37256	101.29	74.33	2.02	9.01	3130	8.51	6.24	
6	10.45	2314.9	232.29	56.31	171.09	56223	110.39	76.35	5.88	17.88	5875	11.54	7.98	
7	10.21	2315.1	402.45	97.57	245.63	84632	1161.91	97.8	9.96	25.08	8641	118.63	9.99	
8	7.34	2213	586.65	135.95	449.18	103196	872.24	81	9.98	32.97	7575	64.02	5.95	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									32.61	112.53	30192	357.16	44.52	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**3.45**	**926**	**10.95**	**1.37**	**0.030**

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→   3.67   929   9.28   1.26   0.030

AVL 8 Mode: Average Weighted Brake Specific Emissions

Engine: CAT C7 2004
Rated Speed: 2400
Rated Power: 230 HP
Disp. (L) 7.2
Fuel Type Denali

PUMA File
5781_Denali_21Apr05 | 2343

SPC File
2343

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	g/kw-hr
1	35	799.7	7.17	0.6	34.36	3310	528.08	76.23	0.21	12.03	1158	184.83	26.68	
2	6.34	887	156.02	14.49	83.51	12570	322.69	34.95	0.92	5.29	797	20.46	2.22	
3	2.91	1057	427.24	47.29	251.2	35532	194.03	28.16	1.38	7.31	1034	5.65	0.82	
4	3.34	1244	628.55	81.88	369.42	63054	225.74	41.06	2.73	12.34	2106	7.54	1.37	
5	8.4	2399.7	100.69	25.3	143.05	39587	169.8	145.64	2.13	12.02	3325	14.26	12.23	
6	10.45	2215	239.1	55.46	200.09	55202	146.38	119.5	5.80	20.91	5769	15.30	12.49	
7	10.21	2215	410.1	95.13	274.02	83096	1346.6	147.32	9.71	27.98	8484	137.49	15.04	
8	7.34	2212.9	600.02	139.05	555.74	108281	1003.91	115.91	10.21	40.79	7948	73.69	8.51	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→→									33.08	138.66	30621	459.21	79.36	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→										**4.19**	**926**	**13.88**	**2.40**	**0.059**

PUMA File
5774_Denali_22Apr05 | 2349

SPC File
2349

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	g/kw-hr
1	35	799.7	5.9	0.49	96.1	3828	37.2	16.92	0.17	33.64	1340	13.02	5.92	
2	6.34	887	157.13	14.6	184.65	12840	187.79	24.52	0.93	11.71	814	11.91	1.55	
3	2.91	1057	428.38	47.42	251.8	35489	178.23	24.5	1.38	7.33	1033	5.19	0.71	
4	3.34	1244	626.03	81.55	362.78	63147	217.94	35.81	2.72	12.12	2109	7.28	1.20	
5	8.4	2399.6	97.46	24.49	139.34	38469	180.81	154.07	2.06	11.70	3231	15.19	12.94	
6	10.45	2315	238.15	57.73	213.31	59454	149.34	123.59	6.03	22.29	6213	15.61	12.92	
7	10.21	2315	411.01	99.64	305.32	89354	1355.52	145.31	10.17	31.17	9123	138.40	14.84	
8	7.34	2213.1	600.09	139.07	546.04	108001	1023.5	111.28	10.21	40.08	7927	75.12	8.17	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→→									33.67	170.03	31790	281.71	58.25	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→										**5.05**	**944**	**8.37**	**1.73**	**0.051**

PUMA File
5701_Denali_22Apr05 | 2353

SPC File
2353

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	g/kw-hr
1	35	800.1	3.23	0.27	90.25	3942	51.58	18.24	0.09	31.59	1380	18.05	6.38	
2	6.34	887	158.22	14.7	198.6	13215	37.17	16.34	0.93	12.59	838	2.36	1.04	
3	2.91	1057	430.48	47.65	251.06	35858	192.66	24.5	1.39	7.31	1043	5.61	0.71	
4	3.34	1244	627.46	81.74	358.96	63384	221.43	35.84	2.73	11.99	2117	7.40	1.20	
5	8.4	2400.1	103.55	26.03	139.19	39523	180.5	150.34	2.19	11.69	3320	15.16	12.63	
6	10.45	2314.9	238.4	57.79	209.82	60245	150.68	123.81	6.04	21.93	6296	15.75	12.94	
7	10.21	2314.9	411.28	99.7	288.44	89273	1348.39	145.29	10.18	29.45	9115	137.67	14.83	
8	7.34	2213.1	600.76	139.23	555.21	108832	999.84	111.03	10.22	40.75	7988	73.39	8.15	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→→									33.77	167.29	32096	275.38	57.88	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→										**4.95**	**951**	**8.16**	**1.71**	**0.052**

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→	**4.73**	**940**	**10.13**	**1.95**	**0.054**

AVL 8 Mode: Average Weighted Brake Specific Emissions

Engine: CAT C7 2004 **Rated Speed:** 2400 **Rated Power:** 230 HP **Disp. (L)** 7.2 **Fuel Type** WMATA

PUMA File
5703_WMATA_1_28Apr05 | 2383

SPC File
1019

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	800.6	3.55	0.3	36.36	3527	584.03	81.59	0.11	12.73	1235	204.41	28.56	
2	6.34	887	155.12	14.41	80.55	12472	342.53	38.63	0.91	5.11	791	21.72	2.45	
3	2.91	1057	445.89	49.35	251.62	36239	193.49	30.63	1.44	7.32	1055	5.63	0.89	
4	3.34	1244	714.92	93.13	393.53	69780	240.17	43.23	3.11	13.14	2331	8.02	1.44	
5	8.4	2400.2	112.63	28.31	146.68	39229	173.09	136.01	2.38	12.32	3295	14.54	11.42	
6	10.45	2315	252.17	61.13	224.18	61229	150.3	118.03	6.39	23.43	6398	15.71	12.33	
7	10.21	2315	433.99	105.21	299.48	90564	1509.73	151.25	10.74	30.58	9247	154.14	15.44	
8	7.34	2213	637.01	147.63	564.12	111225	1099.32	109.94	10.84	41.41	8164	80.69	8.07	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									35.91	146.03	32515	504.86	80.61	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**4.07**	**905**	**14.06**	**2.24**	**0.057**

PUMA File
5704_WMATA_2_28Apr05 | 2385

SPC File
1020

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	699.5	0.56	0.04	85.77	3360	40.07	15.45	0.01	30.02	1176	14.02	5.41	
2	6.34	887	156.21	14.51	179.21	12696	193.24	29.47	0.92	11.36	805	12.25	1.87	
3	2.91	1057	447.84	49.57	258.51	36157	184.39	26.95	1.44	7.52	1052	5.37	0.78	
4	3.34	1244.1	716.03	93.29	408.52	68856	238.94	39.34	3.12	13.64	2300	7.98	1.31	
5	8.4	2400.3	112.55	28.29	145.76	39917	166.87	136.27	2.38	12.24	3353	14.02	11.45	
6	10.45	2314.9	252.71	61.26	223.48	61505	142.46	118.95	6.40	23.35	6427	14.89	12.43	
7	10.21	2314.9	435.43	105.56	305.12	90995	1484.9	149.64	10.78	31.15	9291	151.61	15.28	
8	7.34	2213	638.02	147.86	567.31	111296	1094.62	113.71	10.85	41.64	8169	80.35	8.35	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									35.90	170.94	32573	300.48	56.88	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**4.76**	**907**	**8.37**	**1.58**	**0.045**

PUMA File
5777_WMATA_4_29Apr05 | 2390

SPC File
1022

Mode	Weight Factor	Speed	Load	Power	NOx	CO2	CO	THC	Wt Power	Wt NOx	Wt CO2	Wt CO	Wt THC	PM
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	801.1	2.31	0.19	91.54	4255	71.67	20.27	0.07	32.04	1489	25.08	7.09	
2	6.34	887	156.06	14.5	222.71	13120	37.44	18.25	0.92	14.12	832	2.37	1.16	
3	2.91	1057	446.46	49.42	251.13	36193	203.77	25.01	1.44	7.31	1053	5.93	0.73	
4	3.34	1244.1	718.03	93.55	404.77	69441	251.7	36	3.12	13.52	2319	8.41	1.20	
5	8.4	2399.8	108.61	27.3	141.59	39701	167.54	141.01	2.29	11.89	3335	14.07	11.84	
6	10.45	2315	252.38	61.18	216.67	60853	144.67	122.86	6.39	22.64	6359	15.12	12.84	
7	10.21	2315	435.14	105.49	293.97	90806	1561.61	156.39	10.77	30.01	9271	159.44	15.97	
8	7.34	2213.1	638.19	147.9	551.96	111549	1120.03	116.08	10.86	40.51	8188	82.21	8.52	
Weighted Power and Weighted Mass Emission Sums →→→→→→→→									35.86	172.05	32847	312.64	59.35	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→										**4.80**	**916**	**8.72**	**1.66**	**0.053**

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→– 4.54 910 10.38 1.83 0.052

AVL 8 Mode: Average Weighted Brake Specific Emissions

Engine: DDC Series 50	**Rated Speed:** 2100	**Rated Power:** 275 HP	**Disp. (L)** 8.5	**Fuel Type** Syntroleum

Run 1

PUMA File
ICRC_TC13_emission.189
DDC50.1489, D(8)

12-14-04 syntroleum

Mode	**Weight Factor**	**Speed**	**Load**	**Power**	**NOx**	**CO2**	**CO**	**THC**	**Soot(MIRA)**	**Wt Power**	**Wt NOx**	**Wt CO2**	**Wt CO**	**Wt THC**	**FSN**
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	700	0.07	0.01	26.133	3072.05	6.433	3.960	0.035	0.00	9.15	1075	2.25	1.39	0.01
2	6.34	854	275.54	24.64	542.853	16422.71	8.084	3.498	0.195	1.56	34.42	1041	0.51	0.22	0.04
3	2.91	994	682.25	71.02	594.262	41784.71	33.560	4.396	1.299	2.07	17.29	1216	0.98	0.13	0.18
4	3.34	1148	907.42	109.09	715.158	64041.33	45.439	6.150	1.248	3.64	23.89	2139	1.52	0.21	0.12
5	8.4	2100	211.57	46.53	320.760	39627.72	24.922	8.659	2.137	3.91	26.94	3329	2.09	0.73	0.14
6	10.45	2030	443.51	94.28	642.762	65170.90	19.587	8.864	1.114	9.85	67.17	6810	2.05	0.93	0.06
7	10.21	2030	743.66	158.09	1073.637	101425.88	25.970	11.446	1.731	16.14	109.62	10356	2.65	1.17	0.07
8	7.34	1946	867.68	176.82	1152.625	112280.60	25.490	12.057	1.270	12.98	84.60	8241	1.87	0.88	0.05
Weighted Power and Weighted Mass Emission Sums →→→→→→→→										50.15	373.08	34207	13.92	5.65	
Average Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→											**7.44**	**682**	**0.28**	**0.11**	

Run 2

PUMA File
ICRC_TC13_emissions.189
DDC50 Syntroleum.1499,D1(8)
12/15/2004

Mode	**Weight Factor**	**Speed**	**Load**	**Power**	**NOx**	**CO2**	**CO**	**THC**	**Soot(MIRA)**	**Wt Power**	**Wt NOx**	**Wt CO2**	**Wt CO**	**Wt THC**	**FSN**
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	700	1.51	0.11	29.74	3262.25	6.212	4.086	0.102	0.04	10.41	1142	2.17	1.43	0.03
2	6.34	854	275.01	24.59	565.63	16794.65	7.903	3.531	0.194	1.56	35.86	1065	0.50	0.22	0.04
3	2.91	994	682.74	71.07	603.22	42108.53	36.001	4.494	0.995	2.07	17.55	1225	1.05	0.13	0.14
4	3.34	1148	906.54	108.98	766.59	64488.71	41.196	8.207	0.940	3.64	25.60	2154	1.38	0.27	0.09
5	8.4	2100	189.22	41.61	339.53	40132.54	23.196	9.827	1.674	3.50	28.52	3371	1.95	0.83	0.11
6	10.45	2030	443.5	94.28	674.96	65890.42	16.096	9.831	1.485	9.85	70.53	6886	1.68	1.03	0.08
7	10.21	2030	743.44	158.04	1125.83	101878.26	23.538	13.185	1.467	16.14	114.95	10402	2.40	1.35	0.06
8	7.34	1946	865.53	176.38	1164.09	112553.72	23.387	12.839	0.751	12.95	85.44	8261	1.72	0.94	0.03
Weighted Power and Weighted Mass Emission Sums →→→→→→→→										49.74	388.87	34506	12.85	6.20	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→											**7.82**	**694**	**0.26**	**0.12**	

Run 3

PUMA File
ICRC_TC13_emissions.189
DDC50 Syntroleum.1499,D2(8)
12/15/2004

Mode	**Weight Factor**	**Speed**	**Load**	**Power**	**NOx**	**CO2**	**CO**	**THC**	**Soot(MIRA)**	**Wt Power**	**Wt NOx**	**Wt CO2**	**Wt CO**	**Wt THC**	**FSN**
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	700	0.05	0.00	19.895	2219.29	4.601	3.050	0.098	0.00	6.96	777	1.61	1.07	0.04
2	6.34	854	274.89	24.58	522.711	15617.30	7.120	3.914	0.273	1.56	33.14	990	0.45	0.25	0.06
3	2.91	994	681.21	70.91	597.619	41521.14	32.914	4.139	1.286	2.06	17.39	1208	0.96	0.12	0.18
4	3.34	1148	907.83	109.14	745.863	63507.20	41.755	4.217	1.335	3.65	24.91	2121	1.39	0.14	0.13
5	8.4	2100	202.39	44.51	319.395	38156.02	22.293	8.707	1.717	3.74	26.83	3205	1.87	0.73	0.12
6	10.45	2030	444.02	94.39	663.912	64668.48	17.204	10.655	1.269	9.86	69.38	6758	1.80	1.11	0.07
7	10.21	2030	743.79	158.12	1106.841	100272.73	22.180	13.667	0.953	16.14	113.01	10238	2.26	1.40	0.04
8	7.34	1946	864.72	176.22	1175.839	111706.07	21.332	12.452	0.247	12.93	86.31	8199	1.57	0.91	0.01
Weighted Power and Weighted Mass Emission Sums →→→→→→→→										49.95	377.93	33496	11.91	5.73	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→											**7.57**	**671**	**0.24**	**0.11**	

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→→	**7.61**	**682**	**0.26**	**0.12**

AVL 8 Mode: Average Weighted Brake Specific Emissions

Engine: DDC Series 50 | **Rated Speed:** 2100 | **Rated Power:** 275 HP | **Disp. (L)** 8.5 | **Fuel Type** Denali

Run1

PUMA File
ICRC_TC13_emission.189,
DDC50 Denali.1520,D(8)

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Soot(MIRA) (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	FSN
1	35	700	-0.58	-0.04	24.257	2474.07	10.373	4.317	0.074	-0.01	8.49	866	3.63	1.51	0.03
2	6.34	854	275.21	24.61	529.770	16191.88	10.577	4.827	0.180	1.56	33.59	1027	0.67	0.31	0.04
3	2.91	994	681.51	70.94	589.726	42132.93	39.724	5.505	2.707	2.06	17.16	1226	1.16	0.16	0.37
4	3.34	1148	907.13	109.05	734.179	64859.23	47.676	6.662	2.511	3.64	24.52	2166	1.59	0.22	0.24
5	8.4	2100	213.22	46.89	323.693	39316.03	38.250	15.246	2.774	3.94	27.19	3303	3.21	1.28	0.19
6	10.45	2030	444.1	94.41	651.195	66421.54	26.313	11.666	2.003	9.87	68.05	6941	2.75	1.22	0.11
7	10.21	2030	743.61	158.08	1092.262	102263.97	32.895	17.758	1.415	16.14	111.52	10441	3.36	1.81	0.06
8	7.34	1946	868.34	176.95	1160.548	113797.91	32.554	15.413	0.978	12.99	85.18	8353	2.39	1.13	0.04
Weighted Power and Weighted Mass Emission Sums →→→→→→→→										50.18	375.70	34322	18.76	7.64	
Average Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→											**7.49**	**684**	**0.37**	**0.15**	

Run2

PUMA File
ICRC_TC13_emission.189,
DDC50 Denali.1520, D-2(8)

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Soot(MIRA) (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	FSN
1	35	700	0.99	0.07	30.43	3157.48	12.290	5.615	0.000	0.03	10.65	1105	4.30	1.97	0
2	6.34	854	275.51	24.64	569.53	17555.84	11.680	4.842	0.290	1.56	36.11	1113	0.74	0.31	0.06
3	2.91	994	681.93	70.98	607.53	43744.71	42.178	5.777	2.235	2.07	17.68	1273	1.23	0.17	0.3
4	3.34	1148	907.41	109.09	759.53	66597.93	48.921	7.123	2.468	3.64	25.37	2224	1.63	0.24	0.23
5	8.4	2100	216.54	47.62	353.58	42586.21	41.901	13.984	2.854	4.00	29.70	3577	3.52	1.17	0.18
6	10.45	2030	444.05	94.40	674.49	68413.61	31.119	15.404	2.852	9.86	70.48	7149	3.25	1.61	0.15
7	10.21	2030	744.13	158.19	1132.82	105520.07	40.348	19.380	1.962	16.15	115.66	10774	4.12	1.98	0.08
8	7.34	1946	868.46	176.98	1207.02	116326.23	33.892	16.152	2.807	12.99	88.60	8538	2.49	1.19	0.11
Weighted Power and Weighted Mass Emission Sums →→→→→→→→										50.30	394.25	35754	21.28	8.63	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→											**7.84**	**711**	**0.42**	**0.17**	

Run3

PUMA File
ICRC_TC13_emission.189,
DDC50 Denali.1520, D-3(8)

Mode	Weight Factor percent	Speed rpm	Load (Nm)	Power (kw)	NOx (g/hr)	CO2 (g/hr)	CO (g/hr)	THC (g/hr)	Soot(MIRA) (g/hr)	Wt Power (kw)	Wt NOx (g/hr)	Wt CO2 (g/hr)	Wt CO (g/hr)	Wt THC (g/hr)	FSN
1	35	700	0.31	0.02	35.959	3812.76	14.438	7.482	0.000	0.01	12.59	1334	5.05	2.62	0
2	6.34	854	276.19	24.70	572.647	17471.17	10.977	5.032	0.143	1.57	36.31	1108	0.70	0.32	0.03
3	2.91	994	682.08	71.00	604.171	43622.25	41.894	6.346	2.866	2.07	17.58	1269	1.22	0.18	0.38
4	3.34	1148	907.51	109.10	770.156	66609.08	47.067	6.788	2.020	3.64	25.72	2225	1.57	0.23	0.19
5	8.4	2100	189.08	41.58	352.632	41631.81	38.587	14.069	2.606	3.49	29.62	3497	3.24	1.18	0.17
6	10.45	2030	444.13	94.41	680.501	68099.89	27.560	19.719	2.436	9.87	71.11	7116	2.88	2.06	0.13
7	10.21	2030	743.83	158.12	1146.193	105767.69	34.860	18.687	1.464	16.14	117.03	10799	3.56	1.91	0.06
8	7.34	1946	866.39	176.56	1217.850	116179.86	31.396	18.578	2.280	12.96	89.39	8528	2.30	1.36	0.09
Weighted Power and Weighted Mass Emission Sums →→→→→→→→										49.75	399.35	35876	20.53	9.86	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→											**8.03**	**721**	**0.41**	**0.20**	

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→→ 7.78 705 0.40 0.17

AVL 8 Mode: Average Weighted Brake Specific Emissions

Engine: DDC Series 50 **Rated Speed:** 2100 **Rated Power:** 275 HP **Disp. (L)** 8.5 **Fuel Type** WMATA

Run1

PUMA File
ICRC_TC13_emissions.189,
DDC50WMATA.1508,D(24)

Mode	**Weight Factor**	**Speed**	**Load**	**Power**	**NOx**	**CO2**	**CO**	**THC**	**Soot(MIRA)**	**Wt Power**	**Wt NOx**	**Wt CO2**	**Wt CO**	**Wt THC**	**FSN**
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	700	-0.98	-0.07	58.094	4248.88	19.489	5.162369	0.157	-0.03	20.33	1487	6.82	1.81	0.04
2	6.34	854	274.79	24.57	606.567	17928.64	10.029	3.212387	0.197	1.56	38.46	1137	0.64	0.20	0.04
3	2.91	994	681.18	70.91	649.932	44031.76	36.774	4.577715	1.695	2.06	18.91	1281	1.07	0.13	0.23
4	3.34	1148	907.82	109.14	806.148	66956.59	43.937	6.16309	2.388	3.65	26.93	2236	1.47	0.21	0.22
5	8.4	2100	190.73	41.94	370.013	42589.52	36.863	9.914683	3.501	3.52	31.08	3578	3.10	0.83	0.22
6	10.45	2030	442.49	94.07	710.446	68940.71	23.472	9.038217	1.694	9.83	74.24	7204	2.45	0.94	0.09
7	10.21	2030	744.41	158.25	1211.786	106555.22	24.224	12.1377	1.229	16.16	123.72	10879	2.47	1.24	0.05
8	7.34	1946	911.95	185.84	1367.618	122698.05	32.318	13.70031	1.577	13.64	100.38	9006	2.37	1.01	0.06
Weighted Power and Weighted Mass Emission Sums →→→→→→→→→										50.39	434.06	36809	20.39	6.37	
Average Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→											**8.61**	**730**	**0.40**	**0.13**	

Run2

PUMA File
ICRC_TC13_emissions.189,
DDC50WMATA.1508,D(24)

Mode	**Weight Factor**	**Speed**	**Load**	**Power**	**NOx**	**CO2**	**CO**	**THC**	**Soot(MIRA)**	**Wt Power**	**Wt NOx**	**Wt CO2**	**Wt CO**	**Wt THC**	**FSN**
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	700	-0.53	-0.04	59.36	3463.42	20.246	4.901	0.035	-0.01	20.77	1212	7.09	1.72	0.01
2	6.34	854	274.87	24.58	612.28	17728.36	9.722	5.217	0.195	1.56	38.82	1124	0.62	0.33	0.04
3	2.91	994	681.52	70.94	646.15	43773.76	37.721	3.846	1.838	2.06	18.80	1274	1.10	0.11	0.25
4	3.34	1148	906.7	109.00	818.30	67450.33	43.330	4.832	2.185	3.64	27.33	2253	1.45	0.16	0.2
5	8.4	2100	210.28	46.24	374.56	42476.81	36.955	7.336	3.530	3.88	31.46	3568	3.10	0.62	0.22
6	10.45	2030	442.3	94.02	725.42	68475.79	21.094	9.282	2.291	9.83	75.81	7156	2.20	0.97	0.12
7	10.21	2030	744.23	158.21	1219.45	106106.23	25.145	11.841	1.232	16.15	124.51	10833	2.57	1.21	0.05
8	7.34	1946	915.37	186.54	1397.99	122629.86	27.001	11.186	1.841	13.69	102.61	9001	1.98	0.82	0.07
Weighted Power and Weighted Mass Emission Sums →→→→→→→→→										50.81	440.12	36421	20.10	5.94	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→											**8.66**	**717**	**0.40**	**0.12**	

Run3

PUMA File
ICRC_TC13_emissions.189,
DDC50WMATA.1508,D(24)

Mode	**Weight Factor**	**Speed**	**Load**	**Power**	**NOx**	**CO2**	**CO**	**THC**	**Soot(MIRA)**	**Wt Power**	**Wt NOx**	**Wt CO2**	**Wt CO**	**Wt THC**	**FSN**
	percent	rpm	(Nm)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(kw)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	
1	35	700	-0.49	-0.04	63.265	3535.71	21.296	4.036	0.000	-0.01	22.14	1237	7.45	1.41	0
2	6.34	854	275.82	24.67	612.873	17651.61	9.728	2.713	0.097	1.56	38.86	1119	0.62	0.17	0.02
3	2.91	994	681.56	70.94	635.872	43885.63	38.251	3.105	1.522	2.06	18.50	1277	1.11	0.09	0.21
4	3.34	1148	907.76	109.13	819.666	67151.18	43.676	3.946	2.634	3.64	27.38	2243	1.46	0.13	0.24
5	8.4	2100	211.55	46.52	376.519	42457.86	38.191	6.732	2.181	3.91	31.63	3566	3.21	0.57	0.14
6	10.45	2030	442.78	94.13	721.371	68719.78	22.568	7.324	1.695	9.84	75.38	7181	2.36	0.77	0.09
7	10.21	2030	744.49	158.26	1217.656	106072.57	25.923	7.818	1.224	16.16	124.32	10830	2.65	0.80	0.05
8	7.34	1946	911.79	185.81	1369.671	122482.32	29.380	11.329	1.300	13.64	100.53	8990	2.16	0.83	0.05
Weighted Power and Weighted Mass Emission Sums →→→→→→→→→										50.80	438.75	36444	21.01	4.77	
Avgerage Weighted Brake Specific Emissions (weighted g/kw-hr)→→→→→→→											**8.64**	**717**	**0.41**	**0.09**	

Average Weighted Brake Specific Emissions for all 8Mode Tests Above (g/kw-hr) →→→→ 8.64 722 0.40 0.11

6.2 Appendix- DOC Conversion Efficiency Data

Caterpillar C7
A Diesel Oxidation Catalyst was installed as an exhaust aftertreatment device. Three AVL 8 Mode tests on each of three fuels are displayed. Gaseous concentrations are shown and DOC Efficiencies are calculated.

AVL 8 Mode: DOC Converter Efficiency

Engine: CAT C7 2004	**Rated Speed:** 2400	**Rated Power:** 230 HP	**Disp. (L)** 7.2	**Fuel Type** Syntroleum

Mode	Speed rpm	Load (Nm)	Power (kw)	NOx_EO ppm	NOX_TP ppm	NOx Conversion %	CO_EO ppm	CO_TP ppm	CO Conversion %	THC_EO ppm	THC_TP ppm	HC Conversion %	Carbon Bal Check
1	799	-5.08	-0.43	145.7	143.1	2	80.5	79.7	1	109.4	58	47	114
2	887	138.67	12.88	249.6	247.6	1	171.6	167.2	3	120.6	66.1	45	100
3	1057	407.28	45.08	406.4	402.2	1	532.3	5.7	99	120.6	19	84	105
4	1244	614.46	80.05	357.4	365.3	-2	373.6	16.3	96	104.8	11.6	89	105
5	2399.6	94.79	23.82	83.2	86.3	-4	123.9	29.6	76	177.9	69.6	61	101
6	2315	234.08	56.75	118	118.3	0	121.2	13.5	89	160	44.8	72	104
7	2315	402.43	97.56	140.3	146.4	-4	1103.6	137.9	88	176.4	36.5	79	105
8	2213.1	587.04	136.05	264.7	264.8	0	847.9	128.9	85	140.9	26.1	81	103

Mode	Speed rpm	Load (Nm)	Power (kw)	NOX_EO ppm	NOX_TP ppm	NOx Conversion %	CO_EO ppm	CO_TP ppm	CO Conversion %	THC_EO ppm	THC_TP ppm	HC Conversion %	Carbon Bal Check %
1	800.1	-6.63	-0.56	75.2	77.8	-3	1768.4	1764.8	0	311	144.2	54	96
2	887	138.49	12.86	202.9	195.6	4	1018.5	996.7	2	199.6	114.1	43	111
3	1057	408.31	45.19	411.1	409.9	0	498	5.8	99	111.4	15.8	86	108
4	1244	612.92	79.85	369	376.4	-2	356	10.8	97	92.6	9.6	90	104
5	2400.2	100.17	25.18	85.4	85.8	0	123.9	35.1	72	176.9	71.7	59	102
6	2315	232.76	56.43	118.1	118.9	-1	120.8	12.2	90	158.9	45	72	104
7	2314.9	402.12	97.48	141	142.6	-1	1088	128.3	88	173.8	37.2	79	104
8	2213	586.74	135.98	264.2	267.1	-1	849.7	128.7	85	141.6	26.5	81	101

Mode	Speed rpm	Load (Nm)	Power (kw)	NOX_EO ppm	NOX_TP ppm	NOx Conversion %	CO_EO ppm	CO_TP ppm	CO Conversion %	THC_EO ppm	THC_TP ppm	HC Conversion %	Carbon Bal Check %
1	800	-0.79	-0.07	70.8	70.7	0	2005.5	2029.4	-1	339.7	172.8	49	83
2	887	138.07	12.82	186.3	189.1	-2	1086.7	1065.9	2	207.4	125.1	40	108
3	1057	405.54	44.89	383.3	373	3	533	8	98	120.6	27.8	77	108
4	1244	613.8	79.96	343.1	350.9	-2	381.4	16.3	96	106.8	12.6	88	105
5	2399.7	95.56	24.01	79.5	79.1	1	129.5	21.2	84	178.3	74.1	58	110
6	2314.9	232.29	56.31	109.6	111.2	-1	124.7	14.8	88	158.9	44.5	72	103
7	2315.1	402.45	97.57	137.1	132.9	3	1130.3	142	87	173.2	38.2	78	101
8	2213	586.65	135.95	250.8	251.8	0	871.3	133.5	85	147.6	28.1	81	103

AVL 8 Mode: DOC Converter Efficiency

Engine: CAT C7 2004	**Rated Speed:**	2400	**Rated Power:**	230 HP	**Disp. (L)**	7.2	**Fuel Type** Denali

Mode	Speed	Load	Power	NOx_EO	NOX_TP	NOx Conversion	CO_EO	CO_TP	CO Conversion	THC_EO	THC_TP	HC Conversion	Bal Check
	rpm	(Nm)	(kw)	ppm	ppm	%	ppm	ppm	%	ppm	ppm	%	
1	799.7	7.17	0.6	117.2	106.5	9	2790.3	2885.5	-3	785.6	313.9	60	121
2	887	156.02	14.49	226.7	219	3	1506.2	1467.9	3	316.9	169.1	47	96
3	1057	427.24	47.29	475.3	474.8	0	647.1	13.3	98	177.1	31.1	82	107
4	1244	628.55	81.88	428	426.3	0	461.3	30.9	93	157.9	24	85	103
5	2399.7	100.69	25.3	103.2	105.9	-3	208.8	196.8	6	360	182.5	49	108
6	2215	239.1	55.46	136.3	135	1	170.1	18.2	89	271.7	74.3	73	99
7	2215	410.1	95.13	159.1	158.3	1	1339.3	159.8	88	281.9	58.4	79	100
8	2212.9	600.02	139.05	307.8	314	-2	980	161.3	84	217.8	40.1	82	100

Mode	Speed	Load	Power	NOX_EO	NOX_TP	NOx Conversion	CO_EO	CO_TP	CO Conversion	THC_EO	THC_TP	HC Conversion	Carbon Bal Check
	rpm	(Nm)	(kw)	ppm	ppm	%	ppm	ppm	%	ppm	ppm	%	%
1	799.7	5.9	0.49	306.5	309.3	-1	206.8	203.7	1	186.8	84.7	55	138
2	887	157.13	14.6	516.9	507.2	2	905.3	899.1	1	230.2	129.7	44	108
3	1057	428.38	47.42	482.6	484.5	0	599.9	10.5	98	156.9	24.1	85	107
4	1244	626.03	81.55	423.1	416.7	2	452.8	29.6	93	139.8	16.7	88	103
5	2399.6	97.46	24.49	102.6	100.7	2	225.1	207.8	8	367.1	196.7	46	99
6	2315	238.15	57.73	134.5	133.5	1	161.8	20.5	87	259.9	72.8	72	101
7	2315	411.01	99.64	165.9	172.6	-4	1291.8	172.5	87	267.6	53.6	80	102
8	2213.1	600.09	139.07	308.4	306.3	1	1001.5	164.9	84	209.2	38.3	82	102

Mode	Speed	Load	Power	NOX_EO	NOX_TP	NOx Conversion	CO_EO	CO_TP	CO Conversion	THC_EO	THC_TP	HC Conversion	Carbon Bal Check
	rpm	(Nm)	(kw)	ppm	ppm	%	ppm	ppm	%	ppm	ppm	%	%
1	800.1	3.23	0.27	291.1	253.8	13	277.7	273	2	195.7	93.4	52	105
2	887	158.22	14.7	547.7	544.2	1	176.1	166.4	6	150.5	93.3	38	103
3	1057	430.48	47.65	470	468.6	0	637.1	13.3	98	155	25.1	84	103
4	1244	627.46	81.74	414.4	419.3	-1	453.9	31	93	137.3	17.5	87	103
5	2400.1	103.55	26.03	101	103.2	-2	224.7	223	1	371	199.3	46	106
6	2314.9	238.4	57.79	132	134.3	-2	165.3	24.1	85	262.7	71.9	73	101
7	2314.9	411.28	99.7	162.3	165.8	-2	1301.4	169.9	87	265.6	53.9	80	101
8	2213.1	600.76	139.23	310.1	304.2	2	980.9	161.6	84	207.2	37.4	82	101

AVL 8 Mode: DOC Converter Efficiency

Engine: CAT C7 2004	**Rated Speed:** 2400	**Rated Power:** 230 HP	**Disp. (L)** 7.2	**Fuel Type** WMATA

Mode	**Speed** rpm	**Load** (Nm)	**Power** (kw)	**NOX_EO** ppm	**NOx TP** ppm	**NOx Conversion** %	**CO_EO** ppm	**CO_TP** ppm	**CO Conversion** %	**THC_EO** ppm	**THC_EO** ppm	**THC Conversion** %	**Carbon Bal Check** %
1	800.6	3.55	0.3	115.7	103.5	11	3111.7	3176.1	-2	858.6	395.8	54	91
2	887	155.12	14.41	222.1	223.1	0	1601.4	1604.6	0	352.3	201	43	104
3	1057	445.89	49.35	469.1	467.2	0	635	8.3	99	190	52.7	72	103
4	1244	714.92	93.13	442.3	434.5	2	467.1	20.1	96	156.1	26.8	83	101
5	2400.2	112.63	28.31	106.4	106.7	0	214.9	169.3	21	328.3	150.1	54	97
6	2315	252.17	61.13	137.5	138.4	-1	157.1	14.4	91	243.4	57.7	76	101
7	2315	433.99	105.21	163.4	161.3	1	1417.4	174.3	88	273.3	50.5	82	98
8	2213	637.01	147.63	308.5	306.9	1	1048.6	157.5	85	199.5	34.3	83	99

Mode	**Speed** rpm	**Load** (Nm)	**Power** (kw)	**NOX_EO** ppm	**NOx TP** ppm	**NOx Conversion** %	**CO_EO** ppm	**CO_TP** ppm	**CO Conversion** %	**THC_EO** ppm	**THC_EO** ppm	**THC Conversion** %	**Carbon Bal Check** %
1	699.5	0.56	0.04	325.9	312	4	251.8	248.9	1	194.6	78.8	60	105
2	887	156.21	14.51	510.9	496.8	3	921	928.2	-1	275.8	149.7	46	104
3	1057	447.84	49.57	489.9	482.2	2	609.7	2.4	100	169.4	42.1	75	103
4	1244.1	716.03	93.29	434.8	438.3	-1	464.2	20.2	96	144.2	21.5	85	101
5	2400.3	112.55	28.29	104.4	105.6	-1	201.3	176	13	328.7	151.8	54	99
6	2314.9	252.71	61.26	137.1	137.8	-1	149.3	12.3	92	243.2	58.3	76	100
7	2314.9	435.43	105.56	161.8	164.9	-2	1398.9	174.9	87	270.4	50.3	81	98
8	2213	638.02	147.86	311.4	305.3	2	1046.9	154.4	85	205.9	34.6	83	100

Mode	**Speed** rpm	**Load** (Nm)	**Power** (kw)	**NOX_EO** ppm	**NOx TP** ppm	**NOx Conversion** %	**CO_EO** ppm	**CO_TP** ppm	**CO Conversion** %	**THC_EO** ppm	**THC_EO** ppm	**THC Conversion** %	**Carbon Bal Check** %
1	801.1	2.31	0.19	300.1	279.5	7	381	368.5	3	212.5	123.5	42	100
2	887	156.06	14.5	611.2	619.3	-1	176.9	180.9	-2	167.6	130.7	22	104
3	1057	446.46	49.42	460.6	451.3	2	662.1	4.9	99	157	57.5	63	102
4	1244.1	718.03	93.55	432.3	432.8	0	483	22.4	95	129.3	17.7	86	102
5	2399.8	108.61	27.3	100.3	101.1	-1	203.5	186.8	8	335.2	168	50	104
6	2315	252.38	61.18	131.4	132.9	-1	150.8	9.2	94	246.8	60.6	75	99
7	2315	435.14	105.49	157.3	158.9	-1	1449.4	179	88	280.1	54.6	81	101
8	2213.1	638.19	147.9	299.1	298.4	0	1061	158.9	85	209.1	35.7	83	98

6.3 Appendix - Injector Inspection Report

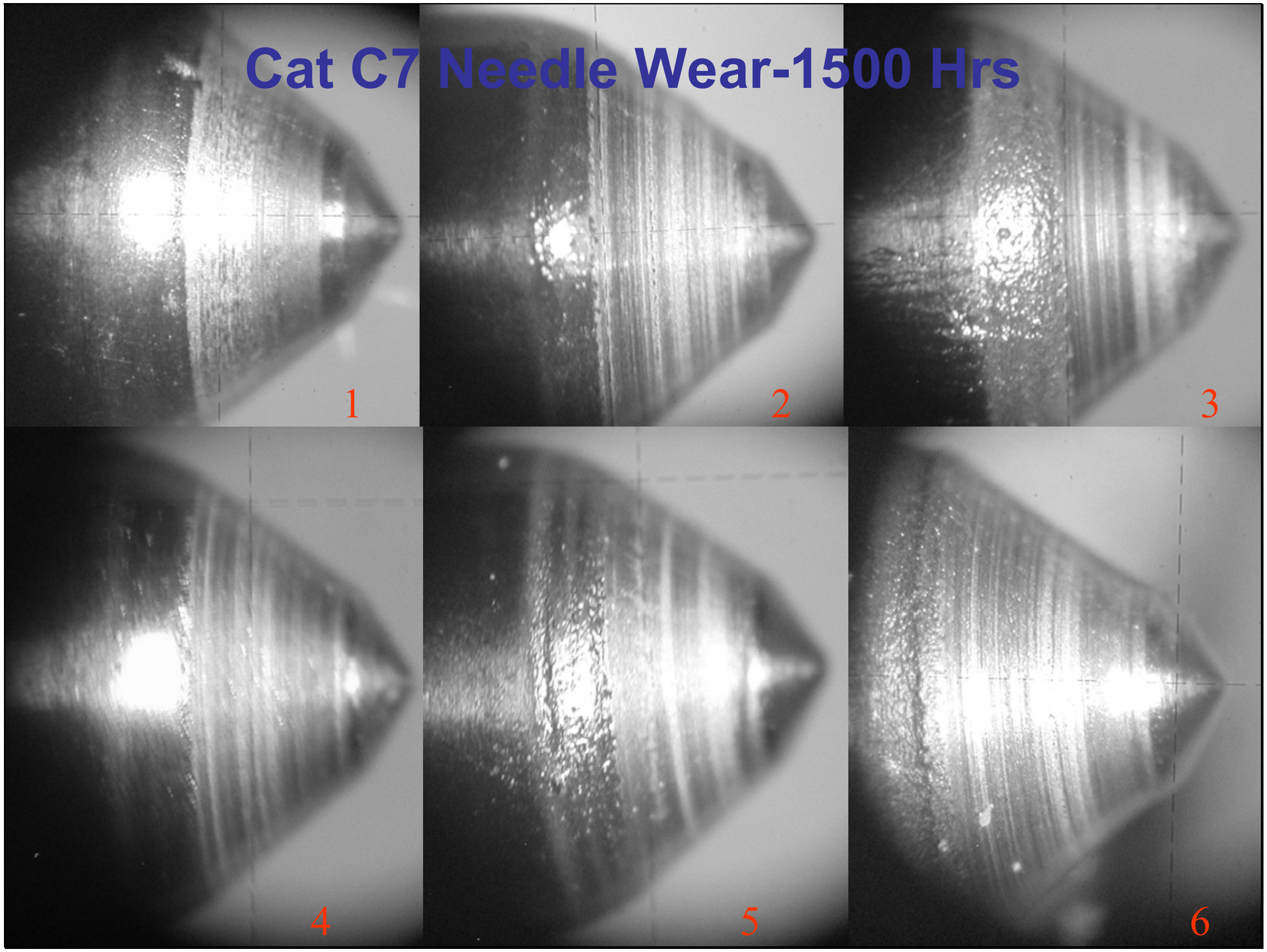
Jim McCandless performed injector inspections.

Cat C7 HEUI-B Injectors

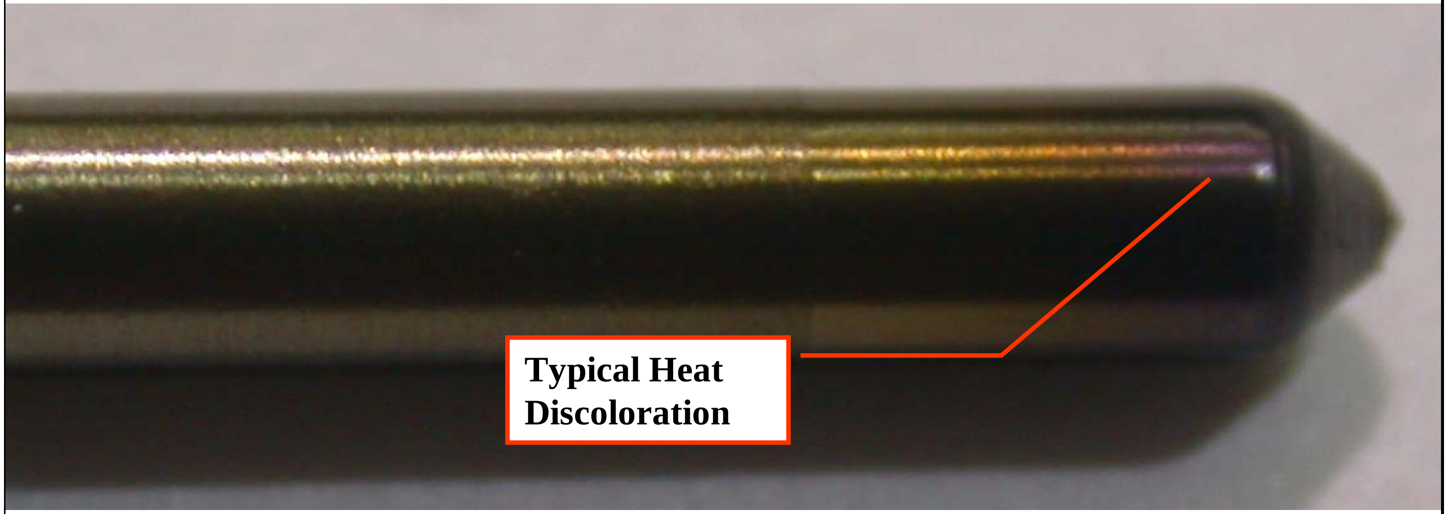
Conclusions

- Low Power Caused By Fouling of Nozzle Orifices
- Nozzle Needle Seat Wear Looks Unusually High But May be Normal
- Nozzle Seat (in the tip) Wear Looks Normal
- Plungers, Barrels & Intensifiers In Very Good Condition
- Overall, Injectors Are Free of Major Problems

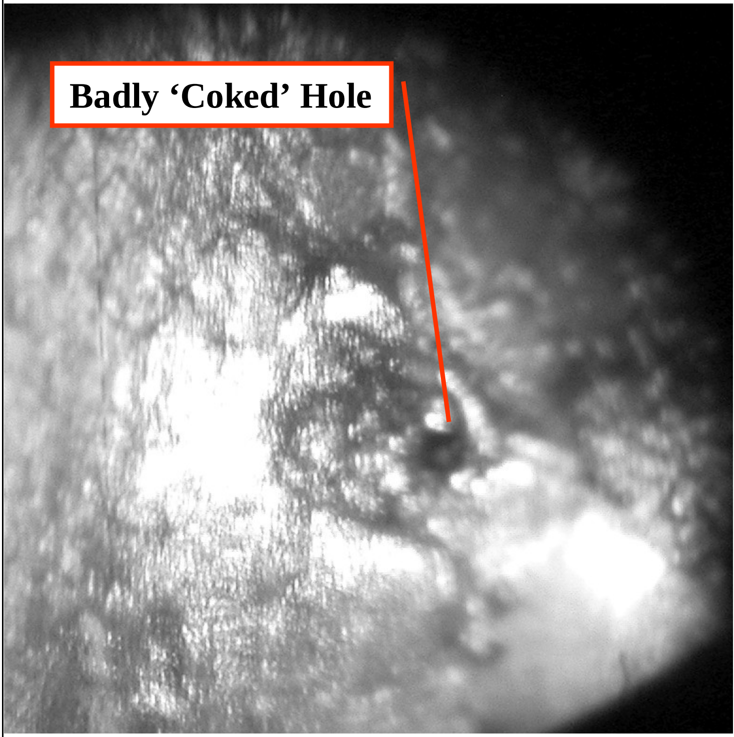
Cat C7 Needle Wear-1500 Hrs



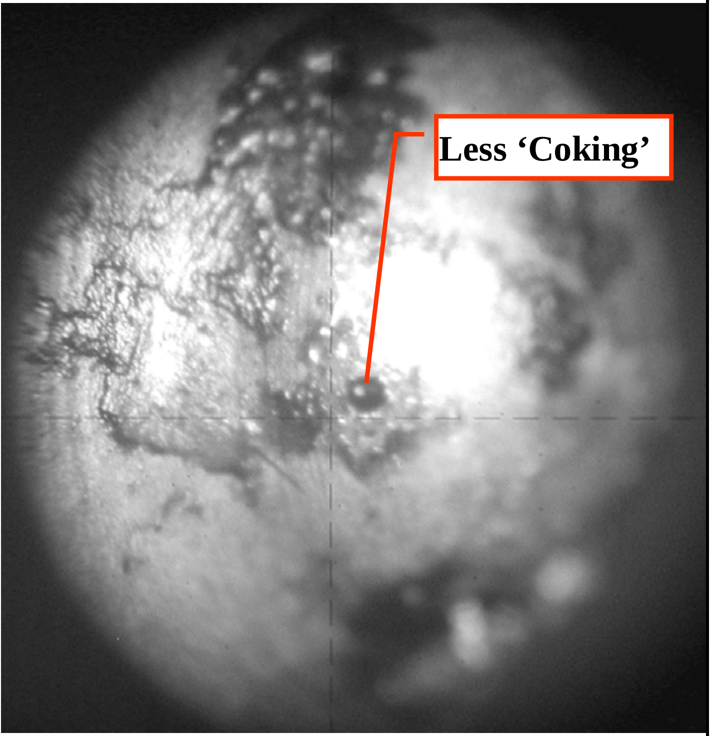
#5 Cat Needle


Typical Heat Discoloration

#6 Cat Nozzle Tip

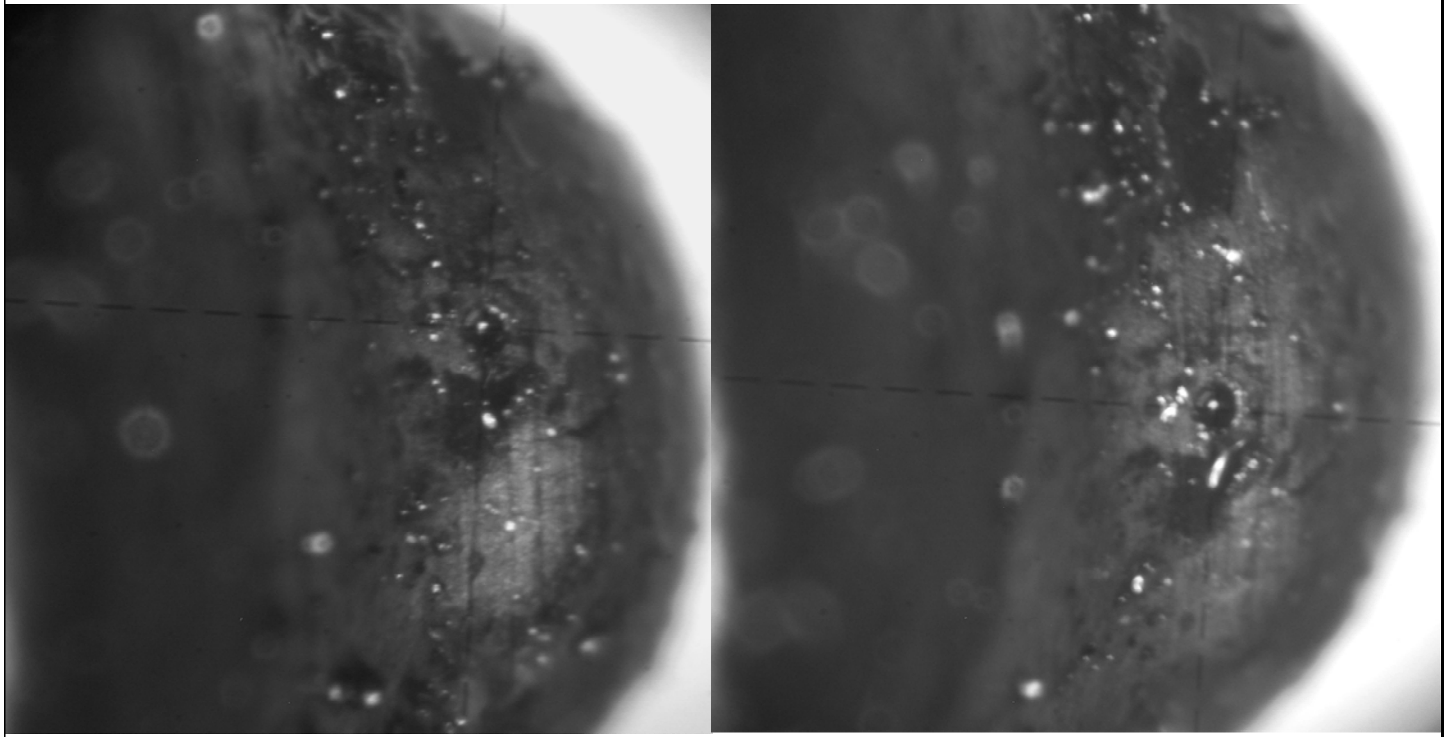


Badly 'Coked' Hole

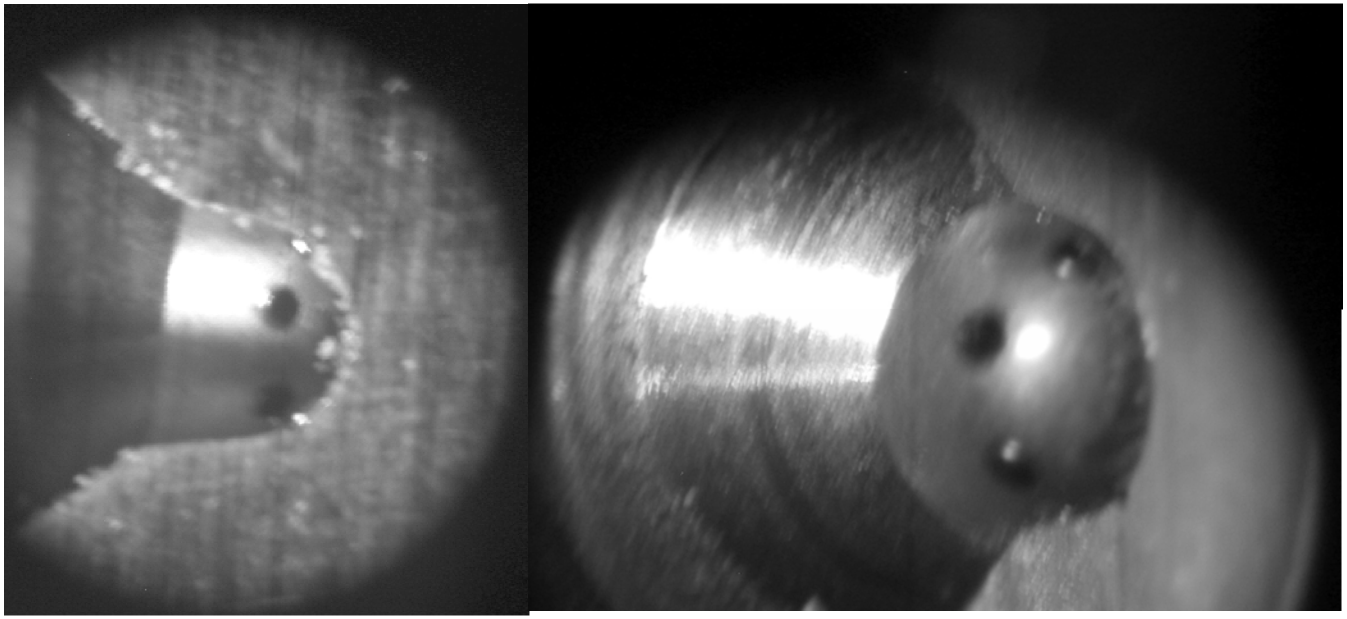


Less 'Coking'

#5 Cat Tip



Cat Nozzle #5 Section



- No Evidence of Deposits in Sac
- Minimal Seat Wear
- No Sign of Overheating

Cat Nozzle #5 Section

- **Would Not Flow Before Sectioning**
- **Deposits Removed From Stem & Tip Before Grinding**
- **Able to Pass .004” Wire Thru 2 Orifices After Grinding**

Cat #1 Nozzle

- Would Not Flow “As Received”, 2000 psi
- Ultrasonic Cleaned 2 Hrs, Still Would Not Flow
- Ultrasonic Cleaned 4 Hrs & Removed Deposits From Tip Outside Surface
  - Flows 35 kg/hr @100 bar
  - All Holes (6) Open
- Nozzle Must Have Been Fouled

Cat #6 Nozzle

- Would Not Flow “As Received”, 2000 psi
- Ultrasonic Cleaned 2 Hrs, Still Would Not Flow
- Ultrasonic Cleaned 4 Hrs & Removed Deposits From Tip Outside Surface
  - Flows 34.5 kg/hr @100 bar
  - All Holes (6) Open
- Nozzle Must Have Been Fouled

Cat Plungers & Intensifiers

Cat Plungers & Intensifiers


4


5


6

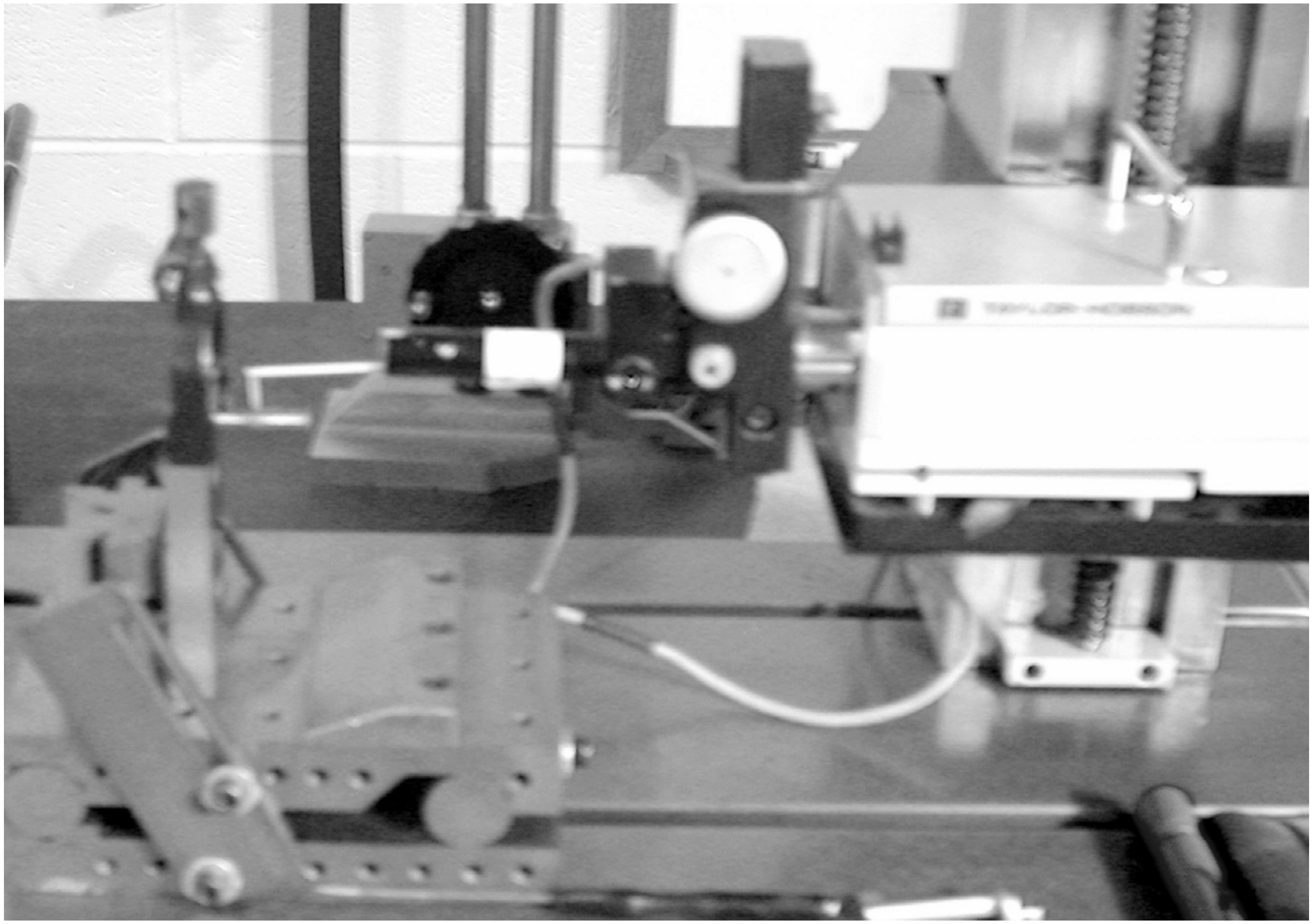
DDC 50 Series Injectors

Conclusions

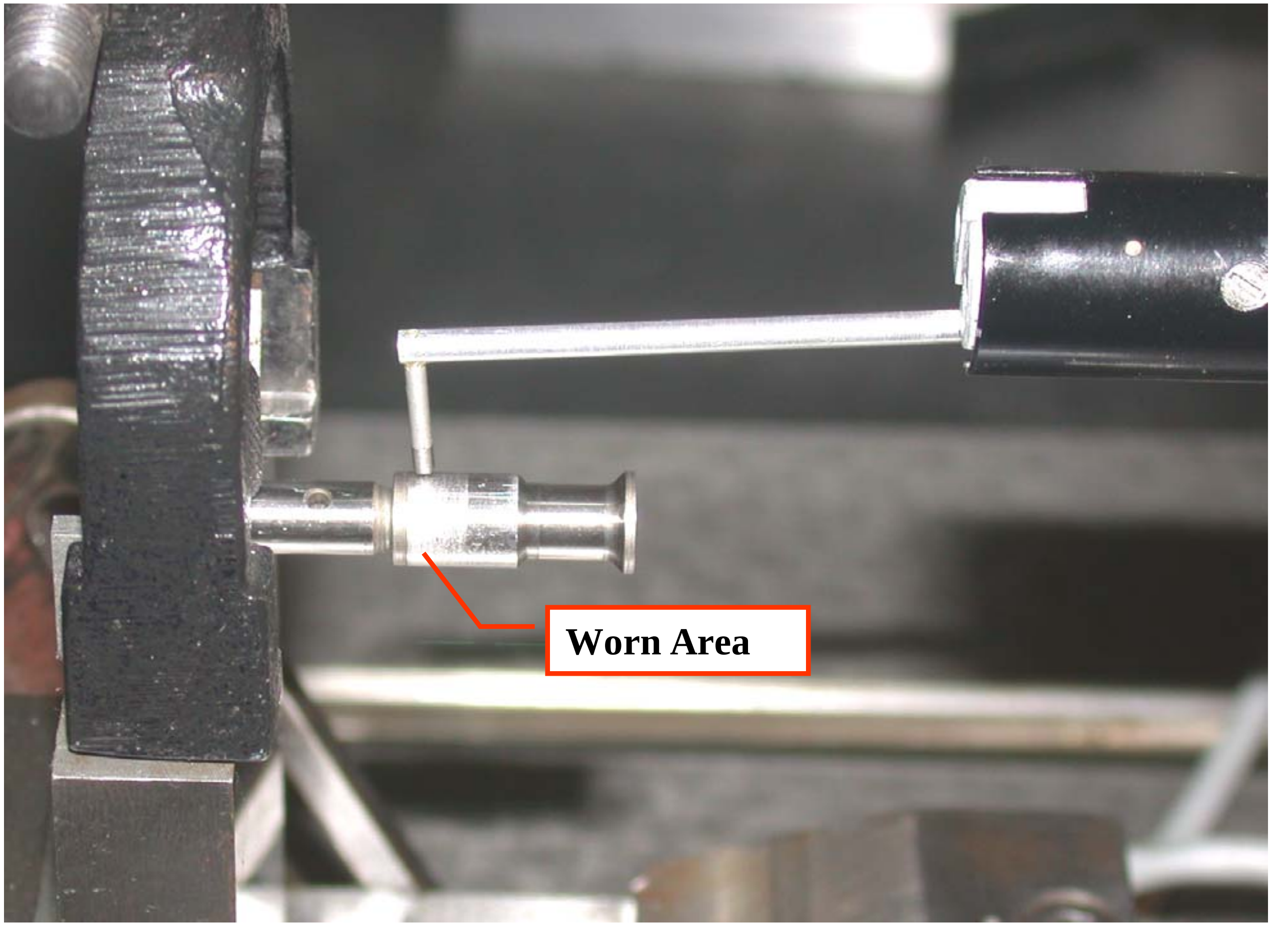
- **All Four (4) Injectors Appeared to be in Excellent Condition**
- **The Only Possible Exception Was Visible Wear or Distress on 1 of the 4 Spill Valves**
- **Measurements Show That The Radial Wear Was 0.6-0.8 Microns-This May Well Be Normal.**
- **The Nozzles Were Not Flowed Because Power Was Relatively Stable Throughout The Test**

#1 Spill Valve Wear Measurement

Wear Measurement Setup



Spill Valve Wear Measurement



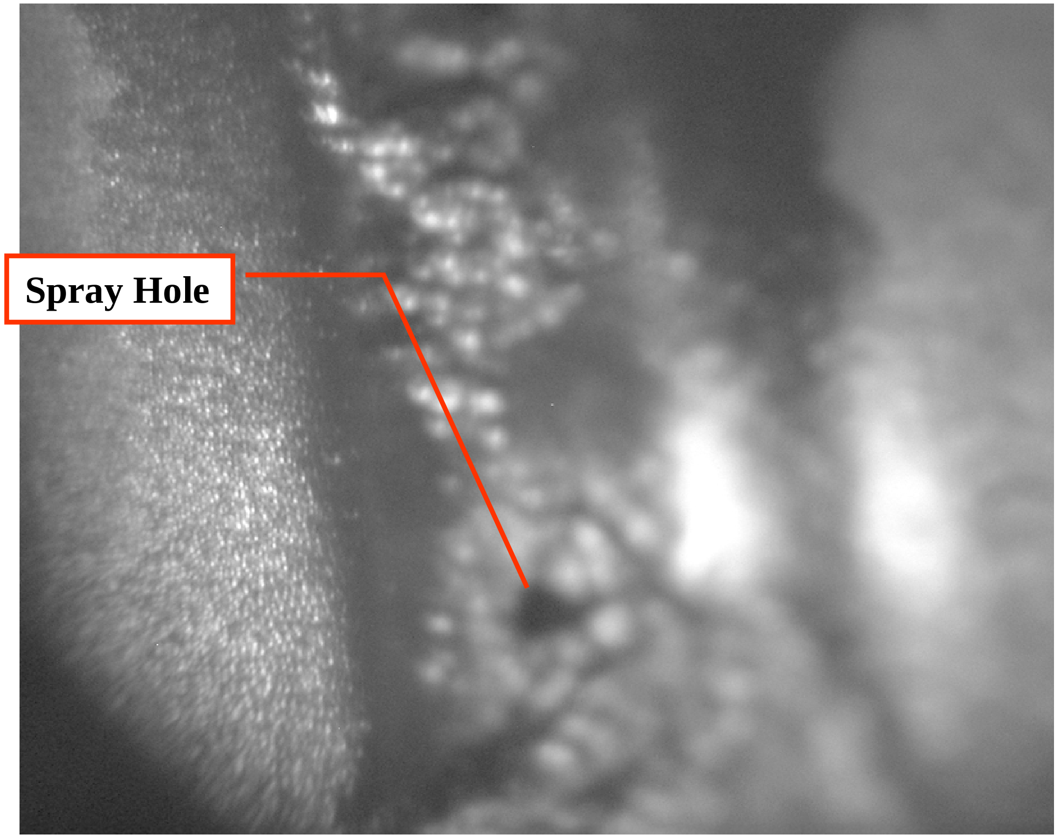
Needle #1 (Typical)

- **No Visible Guide Wear**
- **No Heat Discoloration**

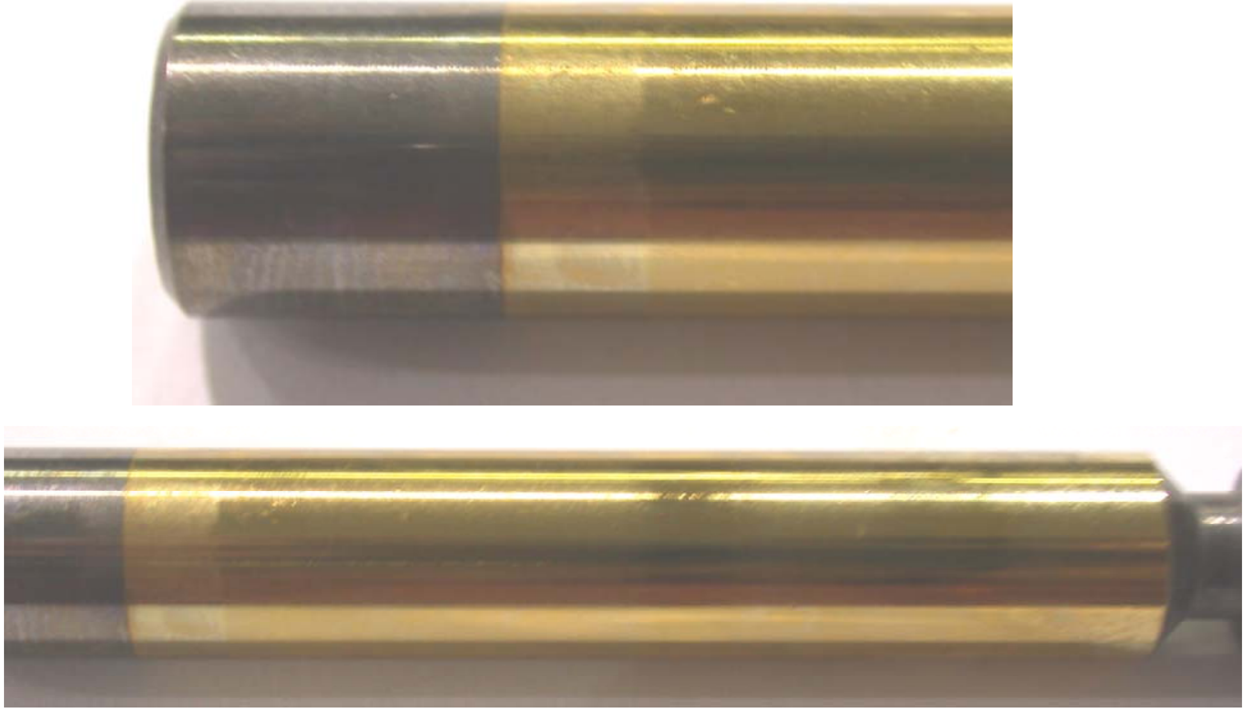
Nozzle Tip #1 (Macro)-Typical

- **Nothing Unusual Visible**

Nozzle Tip #1Carbon Deposits



#1 Plunger (Typical)



- Slight Polishing Wear
- No Obvious Distress

Follow-up Report on Detroit Diesel Poppet Control Valves

Final Report

Reporting Period: July 2001 – June 2006

Principal Authors:
Brad Kelly
Stephen Bergin

Report Issued
August 2006

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ABSTRACT

All fuel systems of all diesel engines used in this overall F-T fuel evaluation project operated normally and none gave any indication of any performance problems attributable to fuel lubricity. At the end of the dynamometer-based fuel-system durability test of a Detroit Diesel Corporation Series 50 engine, its fuel-injectors (which had in fact been re-manufactured by DDC) were disassembled and inspected intensely. One surface of one poppet control valve (of four such valves in the engine) “looked” more worn or distressed than the others. However, this particular poppet control valve, like the others, had operated normally, was within specifications, and indeed would have been re-used and built into the re-manufactured fuel injector in the same condition at DDC’s fuel-injector re-manufacturing facility. This report documents the condition of this particular control valve in relation to other similar valves examined in this program and describes DDC’s re-manufacturing process for fuel injector assemblies.

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Introduction

Syntroleum S-1 and S-2 diesel fuels with their normal, commercially available lubricity additive treatment were run in a total of 20 diesel engines in the overall DoE-NETL Fischer-Tropsch (F-T) Fuels Production and Demonstration Project with no indication of any operational problems related to fuel lubricity. These engines ranged from: Bus engines, both in buses, and in dynamometer laboratories, running on S-2, to; Heavy-duty diesel engines running on S-1 in off-road vehicles used to clear snow near Park-Headquarters through the winter, and then to re-open the main road into Denali National Park in Alaska the following spring, through; Diesel generator sets running on S-1 to produce electricity in Alaska.

Even though there were no operational issues in any engine related to fuel lubricity, the test-plan of dynamometer-based fuel-system durability tests on the bus engines (described below) included post-test inspection of all fuel-lubricated fuel-system components specifically to look even more closely for any possible lubricity related issues. Of all the fuel-system parts inspected, only one, a spill-valve or poppet-control-valve in one of the four Detroit Diesel Corporation (DDC) Series 50 injectors from the dynamometer-test engine, “looked” like it might have (or might not have) had one of its fuel-lubricated surfaces worn or otherwise degraded, even though it had functioned normally throughout the engine-dynamometer test. The subsequent analysis of this valve, and findings from follow-up through the DDC Service Parts System all the way to the re-manufacturing facility, are the subjects of this report.

Dynamometer-Based Fuel-System Durability Tests

One of the key tasks in the overall Project has been to verify in dynamometer-based testing that the commercial lubricity additive technology used in Syntroleum diesel fuel would protect the fuel systems of the bus engines that would be used in the bus-fleet demonstrations of the project. Therefore, the plan for the dynamometer-based fuel-system durability tests of the bus engines was to begin with new fuel-lubricated fuel-system components (fuel-injectors and pumping elements).

Since the Caterpillar C-7 engine provided by Doyon/Aramark (owner and operator of the Denali National Park buses) for this dynamometer test was brand-new, it included all new fuel-system components. The DDC Series 50 engine provided by WMATA for the dynamometer test had been used, but was described by WMATA as “rebuilt.” Before beginning the fuel-system durability test, ICRC replaced all the fuel system components of this Series 50 engine with fuel-injector assemblies, lines, transfer-pumps, etc., purchased as new from the DDC service parts system. It was later learned that the “new” DDC fuel-injector assemblies, which had been purchased through the DDC Service Parts System, had in fact been re-manufactured. Follow-up investigation revealed that this is the common practice within the DDC system, and according to a DDC engineer, re-manufactured injector assemblies are the only injectors sold by DDC parts dealers.

After each engine had run 1500 hours in their respective fuel-system durability tests, the fuel system components were removed, disassembled and inspected. Although the fuel system operated normally, one of the fuel-lubricated surfaces on one of the four poppet-control-valves or spill valves from the DDC engine appeared to be more worn or degraded that the others. This finding launched the investigation that is the primary subject of this report.

Poppet Control Valve

The poppet control valve or spill-valve in a DDC injector controls the pulse width or duration of fuel injection by releasing the high pressure in the injector at the time during the cycle which is controlled by the engine ECM (Electronic Control Module).

Figures 1 and 2 show, respectively, the fuel injector assembly as a solid model and in a cut-away view. The engine camshaft rotates and depresses the plunger which operates in a bore or cavity that is continuously filled with fuel by a low-pressure fuel pump. A drilled passage in the injector body connects the cavity below the plunger to the Poppet Control Valve. When the poppet control valve is open, no pressure can build up and no fuel is injected into the cylinder. When the poppet control valve is closed, the fuel is trapped in the cavity below the plunger and the downward motion of the plunger creates the pressure necessary for the fuel to lift the nozzle-needle and for fuel to be injected into the cylinder.

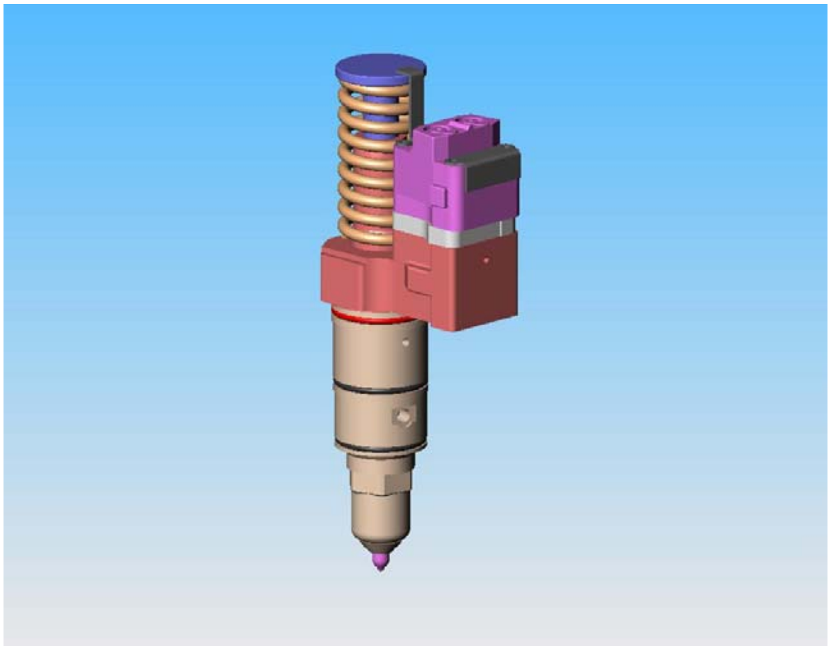

Figure 1. Solid model of DDC Fuel Injector Assembly.

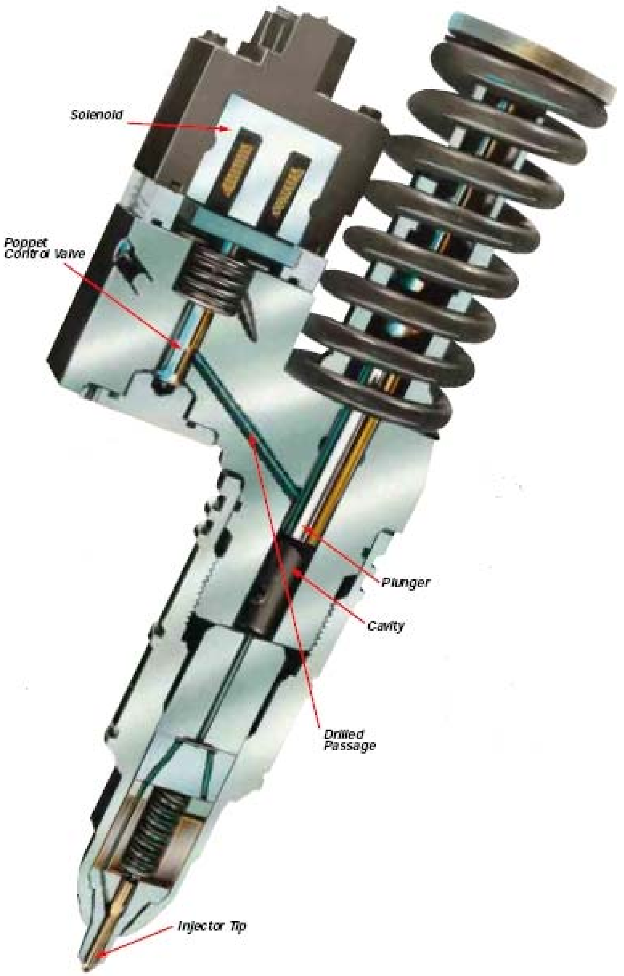

Figure 2. Cut-Away of the DDC Fuel Injector Assembly Showing Poppet Control Valve Location.

The poppet control valve has two primary fuel-lubricated functional surfaces, shown in Figure 3, that allow it to perform its function. The most important of these is the high-pressure sealing surface, which must seal fuel pressures of several thousand pounds per square inch. The other is a "guide" diameter that keeps the valve centered in its bore so it can seal properly, and allows the valve to slide freely between its open and closed positions. This guide surface, on the poppet control valve in cylinder No. 4's injector in the DDC fuel-system durability test engine, allegedly "looked" somewhat worn or degraded when it was inspected at the end of the test.

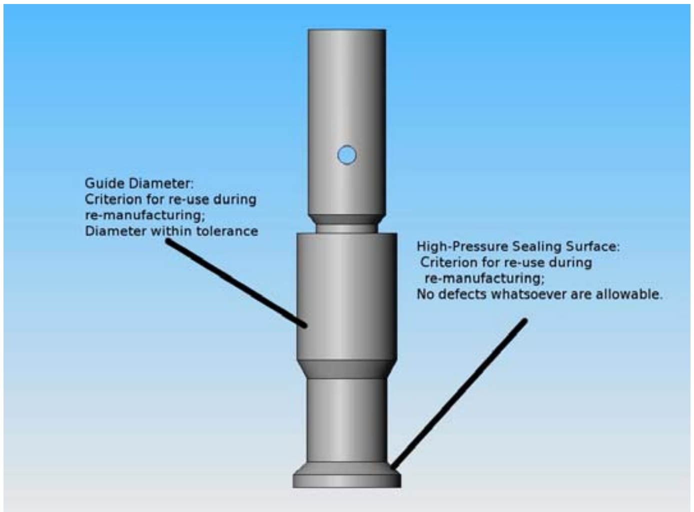

Figure 3. Surfaces of "used" Poppet Control Valves that are inspected during Re-manufacturing.

Figure 4 shows the four poppet control valves from the fuel-system durability test engine, numbered by cylinder number. The guide diameter of the poppet control valve from cylinder No. 4 allegedly "looks worse" than the others.

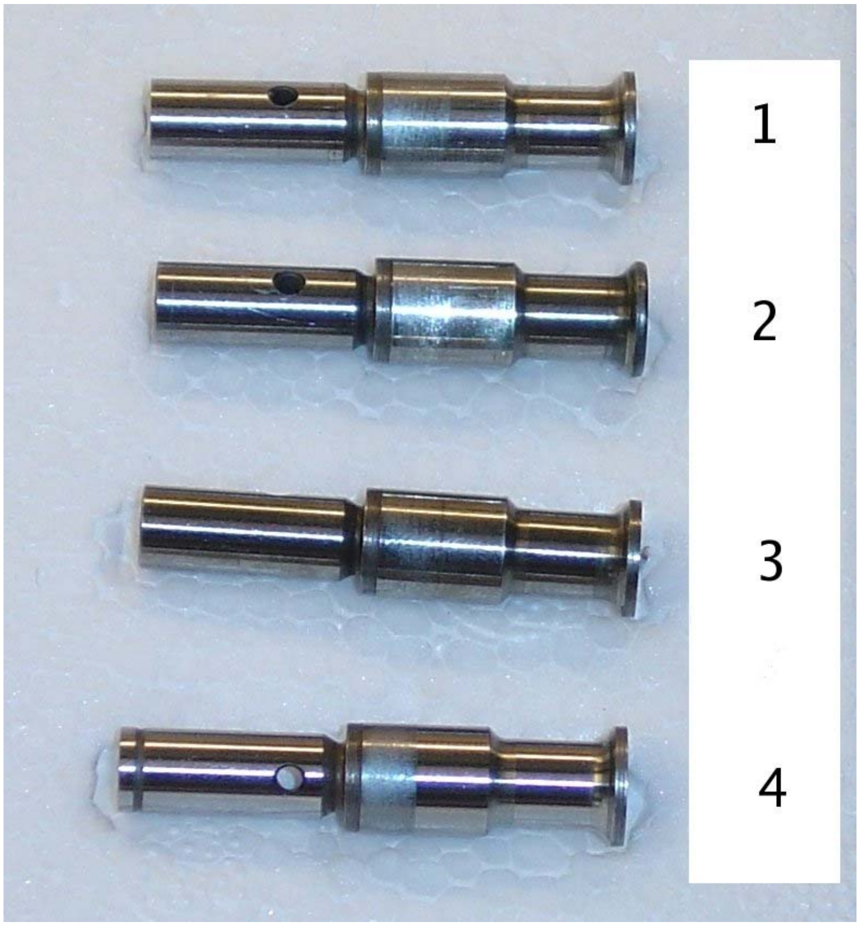

Figure 4. Poppet Control Valves from the fuel-system durability test engine identified by cylinder number. The guide diameter surface of the valve from cylinder No. 4 allegedly "looks worse" than the others.

Figure 5 shows how the "wear-step" between the "worn area" and the remainder of the guide diameter area was measured, using the Form Talysurf set-up shown, and was found to be less than 1 micrometer. Such low wear would not cause a poppet control valve to be rejected during the re-manufacturing process.

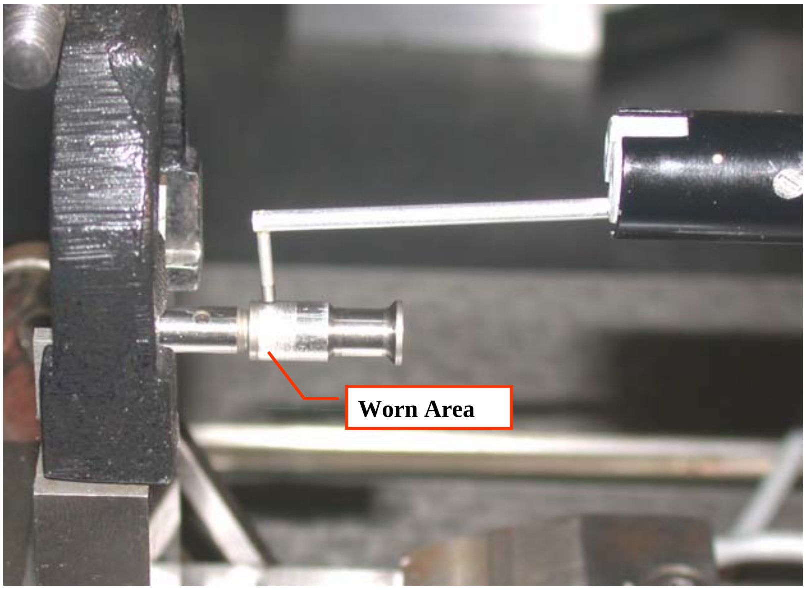

Figure 5. Form Talysurf set-up used to measure the "wear-step" on the guide surface of the poppet control valve from cylinder No. 1.

DDC's Fuel-Injector Remanufacturing Process

Fuel-injector assemblies are replaced more frequently than almost any other diesel engine component, and these assemblies lend themselves to cost-effective re-manufacturing for several reasons. The assemblies consist of several parts, most of which are normally reusable for an indefinite number of re-manufacturing cycles. Furthermore, the individual components that are subject to the greatest in-use stress and that do require replacement on virtually every re-manufacturing cycle, the nozzle-needle assemblies, are expensive precision components, but they account for a relatively small percentage of the total cost and value of the overall injector assembly. And finally, from a vehicle-service and vehicle-downtime perspective, it is much more cost-effective to remove and replace entire injector assemblies, get the engine back in service, and return the used injector assemblies to a central re-manufacturing facility, than it would be for vehicle service technicians to attempt to disassemble and reassemble them in the field to replace nozzles.

DDC's injectors are remanufactured at Detroit Diesel Remanufacturing North (DDRN), a wholly owned DDC subsidiary in Kentwood, Michigan (Grand Rapids metro area). DDC's trademark for re-manufactured injectors and other components is reliabilt® https://www.pressreleasenetwork.com/newsroom/news_view.phtml?news_id=1086

The DDRN reliabilt® process for fuel injectors begins with the returned injector cores being completely disassembled. Each component is cleaned, inspected, tested, qualified and restored to its original specifications. Small wearable parts such as o-rings and screws are 100% replaced. During the remanufacturing process used injector parts are inspected, tested and evaluated for wear and for damage. If a part is out of specification that part is replaced.

Poppet control valves are inspected and measured, and are reused as long as they remain within specifications. A used poppet control valve could have some light scoring and wear, or even small pits caused by of corrosion, on its guide surface and still be within the diameter tolerance specifications and thus be re-used. An engineer at the DDRN facility contacted by ICRC stated that when the poppet control valve is being evaluated for re-use, the critical sealing surface is given the greatest scrutiny. The sealing surface must be free of defects for the poppet control valve to be re-used. When a poppet control valve is replaced during re-manufacturing, a relatively infrequent event, it is usually because the sealing surface is of questionable quality.

When the DDRN engineer was told that ICRC was investigating the possibility that insufficient fuel lubricity might have somehow contributed to the condition of the poppet control valve guide surface in question, he remarked that the plunger would be the injector-assembly component that would most likely be damaged if fuel lubricity were insufficient. As described in AVL's report on the fuel-system durability tests, and as shown in Figure 6, all plungers in all injectors were in excellent condition at the end of the tests.

Figure 6. Plungers from the fuel-system durability test engine identified by cylinder number. None show any sign of wear or distress.

Electron Microscope Analysis of Cylinder No. 4's Poppet Control Valve

Figure 7 shows the guide surface of the cylinder No. 4 poppet control valve that appeared to be worn more than the others. However, for an electron microscope, this level of magnification is just the beginning of its capability. The guide surface does indeed appear to be degraded in the area of contact with its bore. Figures 8 and 9 show, at higher magnification, additional detail of the condition of the guide surface.

Figure 7. Electron micrograph of the guide surface of cylinder No. 4's poppet control valve

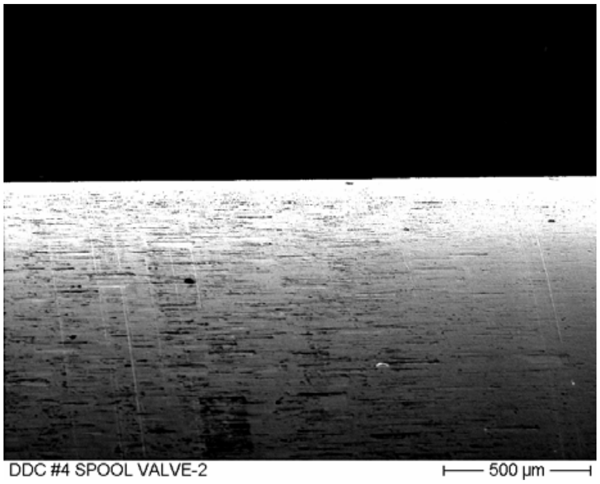

Figure 8. Higher magnification of the "Worn Area" of cylinder No. 4's poppet control valve

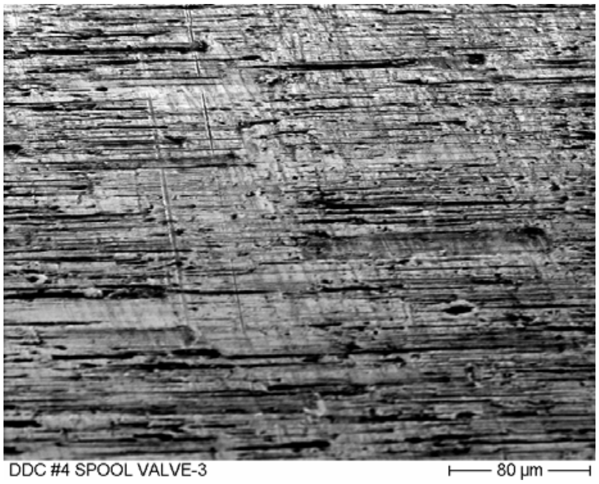

Figure 9. Higher-still magnification of the "Worn Area" of cylinder No. 4's poppet control valve. The surface appears to have suffered corrosive attack at some point in its lifetime, but there is no indication of adhesive wear, which would be expected if metal-to-metal asperity-contact had occurred because of insufficient fuel lubricity.

Although Figures 7 through 9 show some interesting surface characteristics, they don't provide much insight about exactly what happened to the guide surface of the valve or when it happened (i.e. before or after the most recent re-manufacturing cycle).

Views of Other Poppet Control Valves (for Reference)

As referred to previously, Figure 4 shows the four poppet control valves form the dynamometer-based fuel-system durability test engine, and indicates visually that the valve from cylinder No. 3 is the "least worn." Therefore, the valve from cylinder No. 3 was also examined using the electron microscope to see if it "looked better up-close" as well. Figure 10 shows the poppet control valve from cylinder No. 3 at the same scale as Figure 7 shows the valve from cylinder No. 4 (but turned 180 degrees from the orientation of Figure 7). Figures 11 and 12 show successively higher magnifications of an area of the guide surface of the valve from cylinder No. 3. However, the "worn" portion of the surface shown in Figures 11 and 12 is outside the area of apparent normal contact between the valve guide surface and its bore.

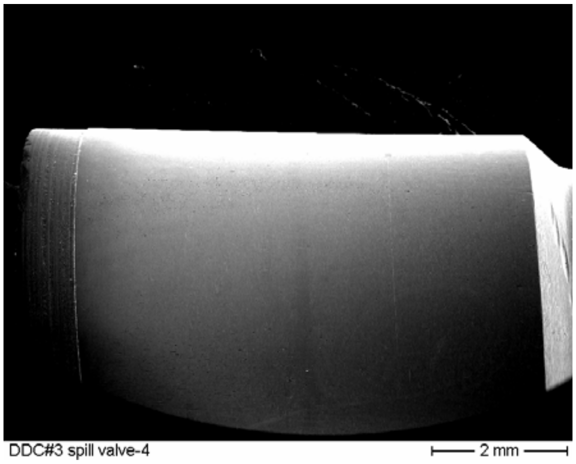

Figure 10. Guide diameter of the "Least Worn" Poppet Control Valve, from cylinder No. 3

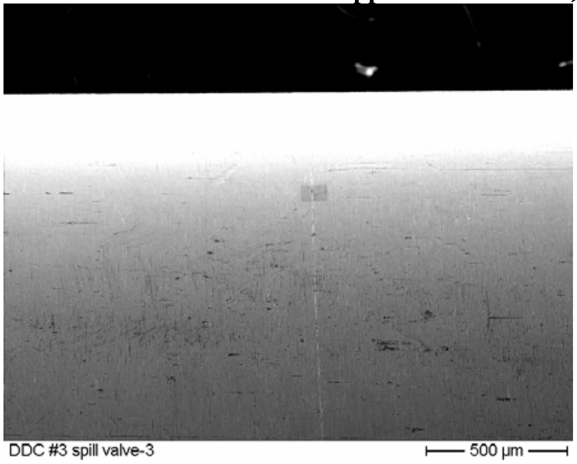

Figure 11. Higher Magnification of the "line" at the center-right of Figure 10.

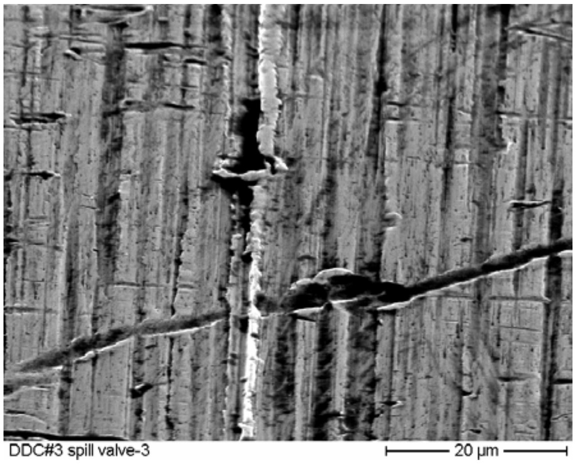

Figure 12. Higher magnification of the rectangular area "on the line" near the center of Figure 11. Although this valve visually "looked" the best of the four, it too had a part of its surface disturbed at some point in its life, but by abrasion, not by the type of adhesive wear that would be caused by insufficient fuel lubricity.

The overall lesson from the electron microscope images in Figures 7 through 12 may be that an electron microscope is able to "look" at surfaces with such great magnification (i.e. almost "too-close") that areas which "look bad" can be found on almost any part (and especially for parts that have been reused, possibly multiple times), even if the part has been performing its function in a completely normal manner.

The following figures provide additional references on the relative condition (based on visual appearance) of other used poppet control valves within other DDC engines used in this project. Figure 13 shows the four valves from the injectors that were removed from the engine of WMATA bus 2056, the subject of a companion report. These valves had functioned normally in bus 2056 running conventional ultra-low sulfur No. 1 diesel fuel, with a commercial lubricity improver, for over 200,000 miles. Then bus 2056 ran for almost 20,000 additional miles on Syntroleum S-2 fuel, also with a commercial lubricity improver, before an unrelated turbocharger failure, which then lead to a series of problems, partial-repairs, more problems, etc., as described in the companion report.

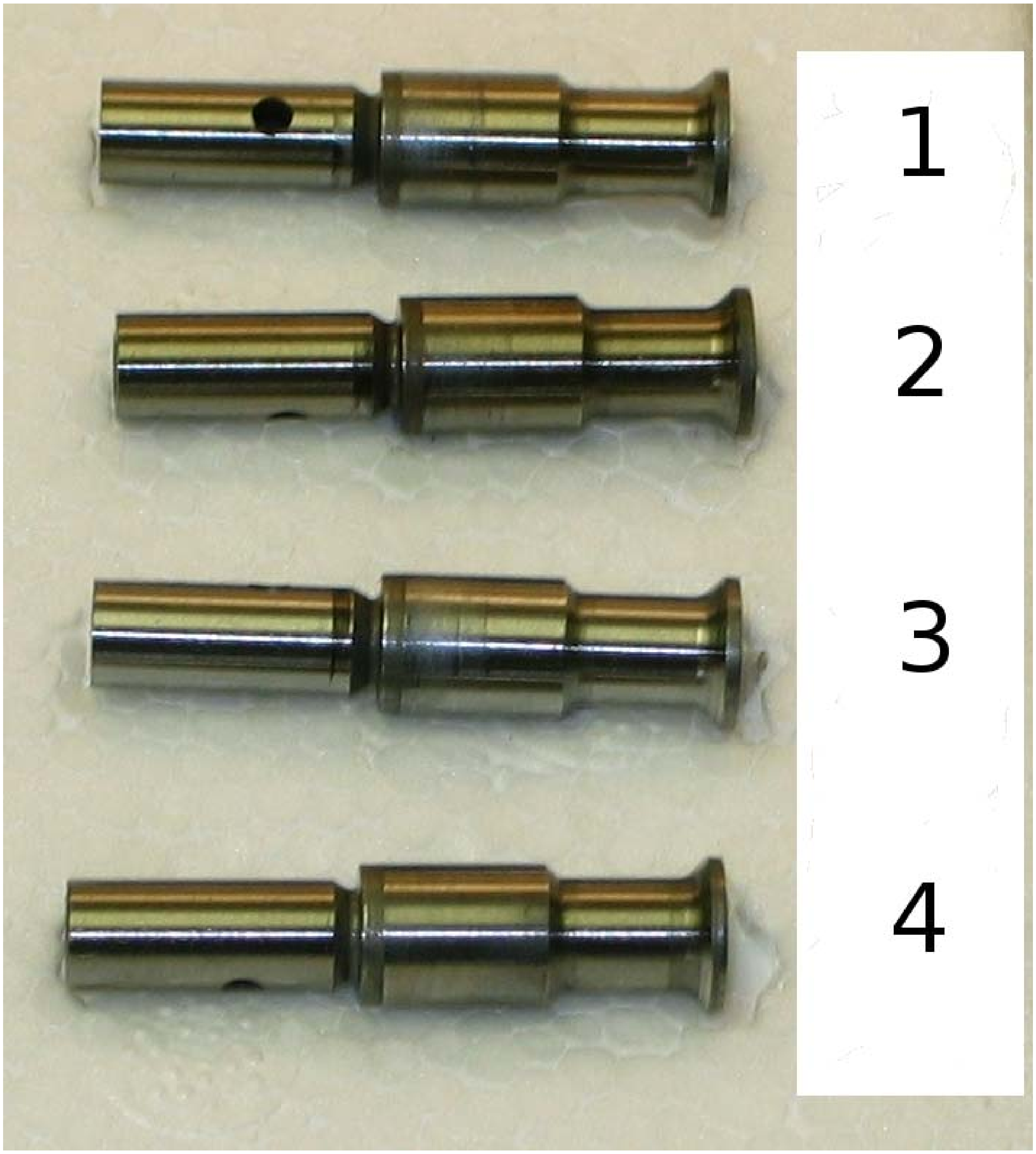

Figure 13. Poppet control valves from WMATA bus 2056 after running over 200,000 miles on ULSD1 and almost 20,000 miles on Syntroleum S-2, both with commercial lubricity improvers. Variability in appearance of the guide surfaces within the same engine is comparable to that shown in Figure 4.

Figures 14 through 16 show three of the four poppet control valves from the fuel injectors that were used in the DDC Series 50 diesel generator-set engine that evaluated S-1 and S-2 fuels, with commercial lubricity improver, at the University of Alaska Fairbanks (UAF), the subject of another companion report. UAF provided only 3 of the 4 fuel-injectors to ICRC to examine in follow-up studies of both fuel-injector nozzle-hole fouling (see companion report) and poppet control valve wear. The guide surfaces of these three poppet control valves from the same UAF engine show a variation in appearance that is similar to that shown in Figures 4 and 13.

Figure 14. UAF Poppet Control Valve 1.

Figure 15. UAF Poppet Control Valve 2.

Figure 16. UAF Poppet Control Valve 3.

Conclusions

All fuel systems of all diesel engines used in this overall F-T fuel evaluation project operated normally and none gave any indication of any performance problems attributable to fuel lubricity. At the end of the dynamometer-based fuel-system durability test of a Detroit Diesel Corporation Series 50 engine, its fuel-injectors (which had in fact been re-manufactured by DDC) were disassembled and inspected intensely. One surface of one poppet control valve (of four such valves in the engine) allegedly “looked” somewhat distressed. However, this particular poppet control valve had operated normally, was within specifications, and indeed would have been re-used and built into the re-manufactured fuel injector in the same condition at DDC’s fuel-injector re-manufacturing facility.

Based upon a thorough electron-microscope analysis of the poppet control valve (the primary subject of this report), analysis and comparison of other poppet control valves for reference, and from follow-up consultation with experienced engineers at DDC’s fuel-injector re-manufacturing facility (who consider fuel-injector plungers to be the component that would be most likely to first show signs of any insufficiency in fuel lubricity), ICRC concludes that:

1. There is no convincing evidence that any degradation attributable insufficiency in F-T fuel lubricity has occurred with any diesel engine fuel-system component during this entire project,
2. There is no convincing evidence that the alleged “unusual” appearance of the guide surface of the No. 4 cylinder poppet control valve examined in this report can reasonably be attributed to any insufficiency in the lubricity of the finished Syntroleum F-T diesel fuel evaluated, which incorporates commercially proven lubricity additive technology.

Analysis of Injector Deposits from Caterpillar and Detroit Diesel Engines Used in Fuel System Durability Testing at AVL Powertrain Engineering Laboratory

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DISCLAIMER

Abstract

AVL Powertrain Engineering conducted engine-dynamometer based fuel system durability testing with Ultra-Clean Diesel Fuel produced by Syntroleum Corporation via the Fischer-Tropsch process from natural gas. This testing program was designed to demonstrate that Ultra-Clean F-T diesel fuel with commercially available conventional diesel lubricity additive technology would protect diesel fuel systems from adverse wear under transit bus duty cycles. AVL successfully completed the durability testing program using a Caterpillar C-7 6-cylinder engine identical to that used in Denali National Park tourist buses and a DDC Series 50 four-cylinder diesel engine identical to that used in some WMATA transit buses in Washington, DC. During the Caterpillar C-7 engine testing program, a drop in power was noted. AVL analyzed the engine and determined that the power loss was due to partial to full plugging of some injector nozzle holes with deposits. The nature of these deposits could not be ascertained with equipment available at AVL Powertrain Engineering. Syntroleum Corporation analyzed the injectors using Scanning Electron Microscopy at the University of Tulsa and determined the nature of the deposits and their source. This report documents the results of the analysis of the injectors and recommends actions which are expected to prevent deposit formation from occurring when Ultra-Clean Fuel is used in modern diesel powered equipment.

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Analysis of Injector Deposits from Caterpillar and Detroit Diesel Engines Used in Fuel System Durability Testing at AVL Powertrain Engineering Laboratory

Supplemental Report

Reporting Period: September 1, 2006 – August 31, 2006

By
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John Cox
Syntroleum Corporation

Executive Summary

AVL Powertrain Engineering was contracted by ICRC to conduct fuel system durability testing of two diesel engines of the same type as would be used to demonstrate the benefits of Ultra-Clean Fischer-Tropsch synthetic diesel fuel in operating bus fleets. These engine-dynamometer based tests were to be conducted prior to field demonstrations of the Ultra-Clean Transportation Fuel in Washington Metropolitan Area Transit Authority (WMATA) transit buses and in tourist buses operated by Doyon-ARAMARK for Denali National Park. The WMATA bus engine was a Detroit Diesel Corporation (DDC) Series 50 four-cylinder engine and the Denali NP bus engine was a Caterpillar C-7 six-cylinder engine. AVL installed these engines in their dynamometer facility located in Ann Arbor, Michigan and conducted the testing program using the Chicago Transit Authority test cycle, as is described in a separate AVL report. This test cycle simulated urban bus usage under severe conditions typical of transit bus service. The test was run for 1500 hours with inspection of the fuel system at the end of the test program.

During the operation of the Caterpillar C-7 engine, a 20% power loss was noted as the end of the testing period approached. Analysis of the fuel system including flow testing of the injectors by AVL using a low-pressure test rig indicated that two of the six injectors were not flowing fuel. Visual and optical microscope analysis of the injectors by AVL indicated that fuel nozzle holes in the two injectors were plugged with deposits of unknown composition and origin. A sectioned nozzle showed that deposits did not form inside the injector, and that the injector sac area had no deposits. More sophisticated analytical techniques were needed to determine the composition of the deposits and begin to understand the source of the deposits.

Syntroleum Corporation was able to secure access to a scanning electron microscope with fully quantitative energy dispersive X-ray analysis at the University of Tulsa, Department of Geological Sciences. Injectors were analyzed where possible in their as-received condition and then sectioned using a low speed diamond saw to better fit into the SEM analysis chamber and/or expose internal areas of the injector for imaging.

The external surfaces of all injectors from both the Caterpillar and DDC engines showed the presence of metallic components consistent with the metals present in the engine oil. Deposits were only found on the outside of the injectors and not on internal areas including the injector sac region just inside the injector tip at the entrance to the fuel nozzle holes. Deposits were found to be encroaching into the fuel nozzle holes from the outside; but with no deposits on the inside, the fuel could not be the source of the deposits.
Since the deposits were composed of metals associated with engine oil additives and not metals associated with any fuel or fuel system component, it can only be concluded that the deposits were formed by combustion of engine oil in the combustion chamber and deposition of combustion products, metal oxides of zinc, calcium, phosphorus, sulfur and magnesium, on cooler section of the diesel fuel injector.

It is speculated that the deposits can accumulate because the Ultra-Clean Transportation fuel is a relatively poor solvent for polar compounds (compared to conventional petroleum-derived diesel fuel) as would be expected for the F-T fuel that is essentially 100% paraffinic and isoparaffinic. It is further speculated that addition of conventional dispersant additives to the F-T fuel will impart sufficient dispersancy performance to the fuel to prevent accumulation of the deposits with such-treated fuel. Testing of this hypothesis is currently underway in other diesel engines and will be the subject of future reports.

1.0 **Introduction**

Synthetic isoparaffinic diesel fuels derived from the Fischer-Tropsch process inherently contain no lubricity components that are found naturally in mildly processed conventional diesel fuels. This lack of lubricity will also be characteristic of highly hydroprocessed ultra-low sulfur diesel (ULSD) fuels that will be introduced in October, 2006 in the United States and other areas. Hydroprocessing removes lubricity-enhancing components from ULSD fuels derived from conventional sources, while these components do not exist in synthetic fuels such as those derived from the Fischer-Tropsch process. Both fuels will require supplemental lubricity improving additives to meet fuel system durability requirements.

Achieving acceptable lubricity in synthetic and highly hydroprocessed diesel fuels is not difficult as lubricity enhancing additives have been available for many years and are used in “Premium” diesel fuel as defined by the National Council on Weights and Measures. However, little data on the effectiveness of these additives in synthetic diesel fuels can be found in the literature. Therefore the NETL Fischer-Tropsch Fuel Production and Demonstration Program included demonstration of fuel system protection as one aspect of the Ultra-Clean Fuels demonstration program. For this program, part of the demonstration involved dynamometer testing of identical engines which would be used in the field demonstration part of this program. Since the F-T fuel being evaluated is justifiably referred to as “Ultra-Clean”, the possibility that deposits might form at some location in the fuel system was not even seriously considered in developing the overall project plan; the focus of the program was lubricity.

To simulate normal operational conditions for diesel engine use in buses, the two different types of engines which have been used in the Washington Metropolitan Area Transit Authority (WMATA) and Denali National Park buses were tested for 1500 hours on a chassis dynamometer operating under a Chicago Transit Authority durability driving cycle at AVL Powertrain Engineering Laboratory in Ann Arbor, Michigan. The results of this test are included in a separate report from AVL. The WMATA buses are powered by Detroit Diesel Corporation Series 50 engines and the Denali NP tourist buses are powered by Caterpillar C-7 engines. Detailed description of the engines and dynamometer test conditions are included in the above report.

During the fuel-system durability testing program, AVL noted that the Caterpillar C-7 engine experienced approximately a 20% power loss as the test progressed. This prompted inspection of the engine for the cause of this power loss. As discussed in the AVL report, several injectors in the Caterpillar 6 cylinder engine were found to be fouled by deposits and the fuel flow restricted or stopped completely by the deposits. AVL's inspection of these injector nozzles by optical microscopy is included in the AVL report. Their observations were not detailed enough to identify the cause of the nozzle fouling, only to show that it existed. This report describes a more detailed analysis of the injectors by Scanning Electron Microscopy (SEM) coupled with Energy Dispersive Spectroscopy (EDS) for qualitative identification of the composition of the deposits in the injector. Injectors were also cut open for inspection of interior portions of the fuel passages to be sure of the cause of the fouling.

2.0 Caterpillar and Detroit Diesel Fuel System Durability Testing Summary

2.1 AVL Fuel System Durability Testing Summary

Syntroleum provided AVL Powertrain Engineering Laboratory with 26,845 gallons of S-2 Ultra-Clean Diesel Fuel produced in Syntroleum's Catoosa Demonstration Facility for conducting fuel system durability testing in the same DDC Series 50 engine as used in the WMATA buses which were running on the same fuel in Washington, DC, and a Caterpillar C-7 engine identical to that used in Denali National Park tourist buses in Alaska.

The two engines were operated for a total of 1500 hours each on engine dynamometers following the Chicago Transit Authority

AVL provided the following conclusions from the durability testing program:

- The DDC Series 50 performed 1500 hours of Syntroleum fueled repetitive CTA cycles without incident. There was no indication of any fuel-system performance problem at the end of the test.

- The Caterpillar C7 performed 1500 hours of Syntroleum fueled repetitive CTA cycles. Engine peak power decreased approximately 20% over the 1500 hour duration.

- Fuel injectors were inspected by Jim McCandless of AVL who has several decades experience related to diesel fuel systems, injector design and practical field knowledge. The DDC injectors showed only slight polish to their internal spill valves. Some of the Caterpillar injector nozzle holes were severely fouled with deposit material to be determined. Jim's PowerPoint report on all injectors is included in Appendix. The fouled injectors were shipped to Robert Freerks of

> Syntroleum for electron microscope and other analysis of the deposits at the University of Tulsa. Results of the Syntroleum/Tulsa inspection are not included in this report.

Additional details of this durability demonstration can be found in the AVL topical report on this effort.

2.2 AVL Optical Analysis of Caterpillar Injector Deposits

AVL Powertrain Engineering Laboratory conducted an initial inspection of the injectors used in the Caterpillar and DDC engines during the durability testing program. Due to fouling of the Caterpillar injectors, a separate set of injectors was used for the subsequent emissions testing program.

Figure 2.1 is an optical microscope view of the Number 6 injector from the Caterpillar C-7 durability test engine. This injector's fuel spray holes appeared to be completely fouled with deposits and deposits covered much of the injector tip surface area.

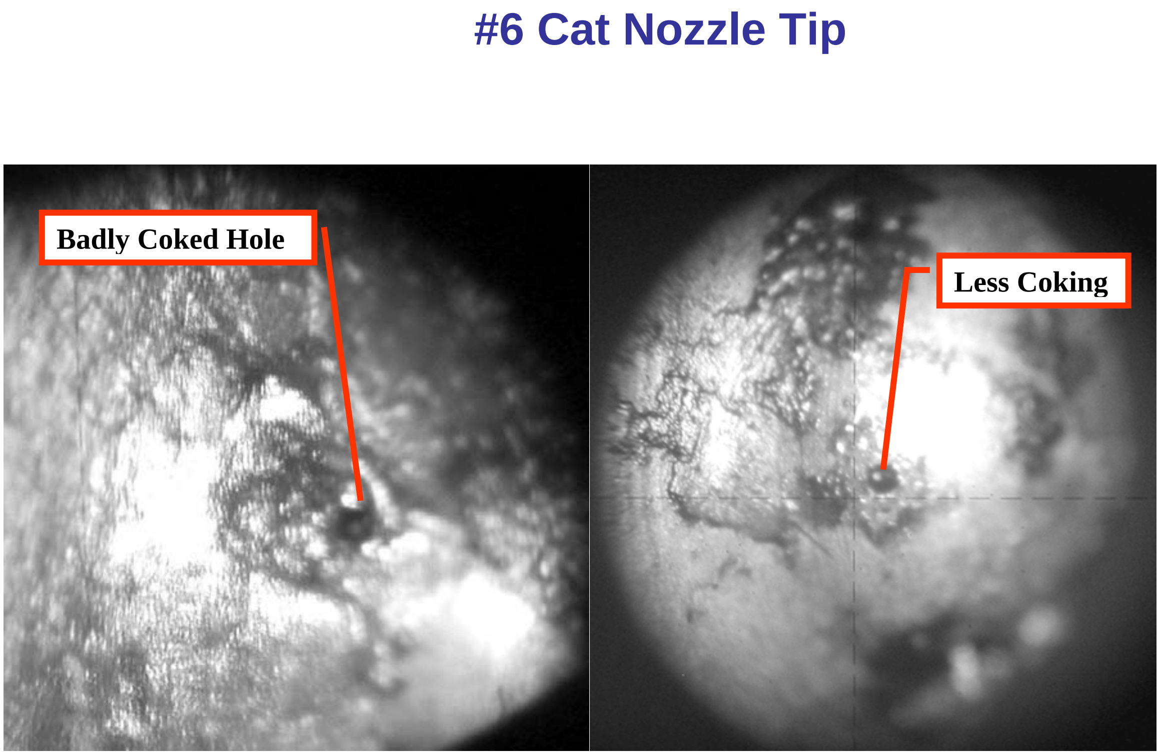
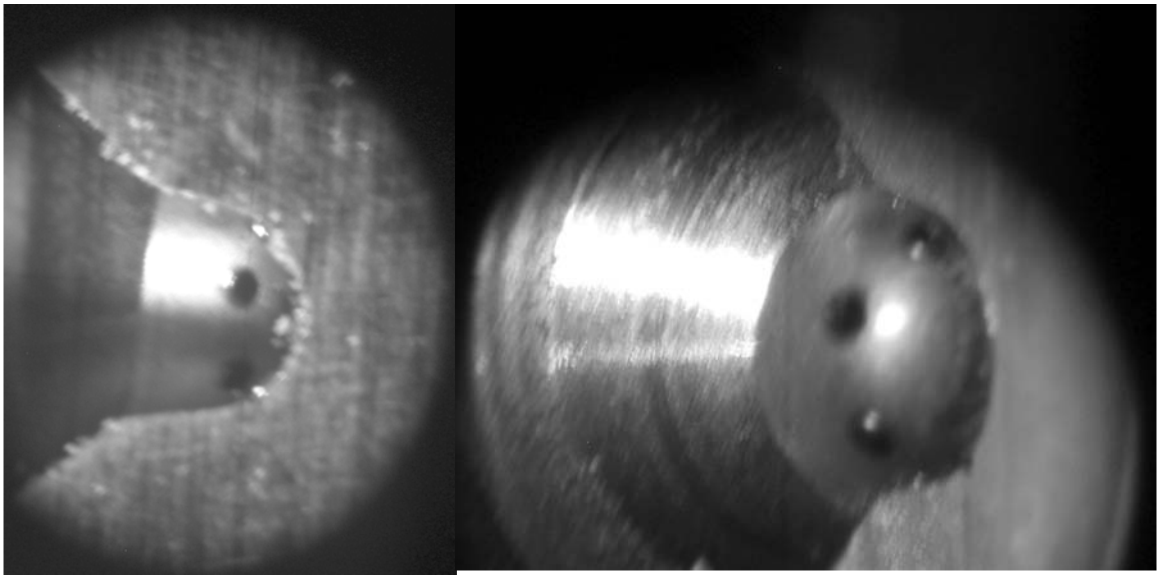


Figure 2.1. AVL optical microscope view of Caterpillar Injector #6 injector tip showing fuel spray hole fouled with deposits.

Injector #5 from the Caterpillar engine was sectioned by AVL to show the interior fuel sack area. If deposits originated from fuel degradation, this area should show deposits as the injector tip is the hottest point in the entire fuel distribution system. Figure 2 shows the optical microscope view of the #5 injector fuel sack area. No obvious deposits were seen in this image.

Cat Nozzle #5 Section



- **No Evidence of Deposits in Sac**
- **Minimal Seat Wear**
- **No Sign of Overheating**

Figure 2.2. AVL optical microscope view of Caterpillar Injector #5 injector sac after sectioning showing fuel spray hole entrance free of deposits.

AVL attempted to clean the deposits from Injectors # 1 and #6. The injectors were first flow tested and did not flow any fuel at 2000 psi using a relatively low pressure laboratory bench flow test apparatus. Cleaning of the injectors was attempted first by ultrasonic bath and solvent, but neither injector flowed after 2 hours of this treatment. Both injectors were then ultrasonic cleaned solvent for 4 hours and the deposits were physically removed from the injector tip external surface with a wire brush. The #1 injector then flowed 35 kg/hr @ 100 bar and the #6 injector flowed 34.5 kg/hr at 100 bar.

Plungers, intensifiers, and other internal parts of the fuel injectors were inspected and found to be free of deposits and showed minimal or no wear.

2.3 AVL Optical Analysis of DDC Injector Deposits

The DDC Series 50 4-cylinder diesel engine did not experience power loss during the 1500 hour fuel system durability testing program. However, deposits were found on the external surface of the injector tips. Figure 2.3 shows the optical microscope photograph of the #1 injector from the DDC Series 50 engine ran for 1500 hours on Syntroleum S-2 synthetic diesel fuel.

Nozzle Tip #1 (Macro)-Typical

- **Nothing Unusual Visible**

Figure 2.3. AVL optical microscope view of DDC Series 50 Injector #1 injector tip external surface showing minimal deposits.

The DDC Series 50 #1 injector was inspected further under the optical microscope and some deposits were found around the fuel injector spray holes. Figure 2.4 shows one of the nozzle holes of injector #1 with deposits forming around the hole area. This image is not conclusive and further expansion of the region is needed to more fully understand the extent and impact of the deposits forming on this and other injectors.

AVL Powertrain Engineering did not have access to equipment needed to view deposits in more detail or to determine the composition of these deposits.

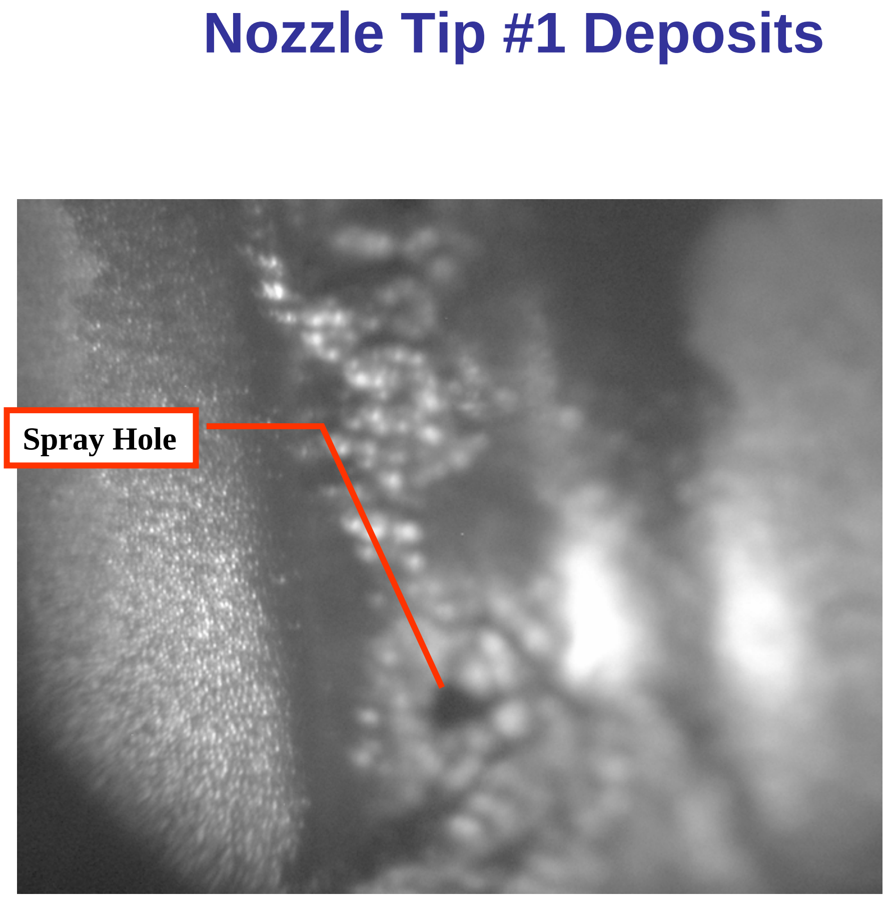


Figure 2.4. AVL optical microscope view of DDC Series 50 Injector #1 injector tip external surface showing fuel spray hole with deposits surrounding the hole area.

3.0 SEM Analysis of Injector Deposits

Several injectors from the Caterpillar C-7 and DDC Series 50 engines were sent to Syntroleum for analysis by Scanning Electron Microscopy/Energy Dispersive X-Ray Spectroscopy (SEM/EDS) using the instruments available at the University of Tulsa. Information on the capabilities of SEM/EDS is readily available and will not be discussed in this report. Remove on version

Injector tips were not prepared in any way for analysis under the electron microscope other than washing with a non-polar solvent to remove liquid hydrocarbons such as residual fuel and engine oil which may cause volatile hydrocarbons in the vacuum chamber of the SEM instrument.

3.1 SEM Analysis of Caterpillar C-7 Injector Deposits

The #3 Caterpillar injector, which had not been cleaned at AVL, was first viewed at Syntroleum under an optical microscope to give a general overview of the deposits formed during the durability demonstration run. Figure 3.1 shows the #3 injector at low magnification.

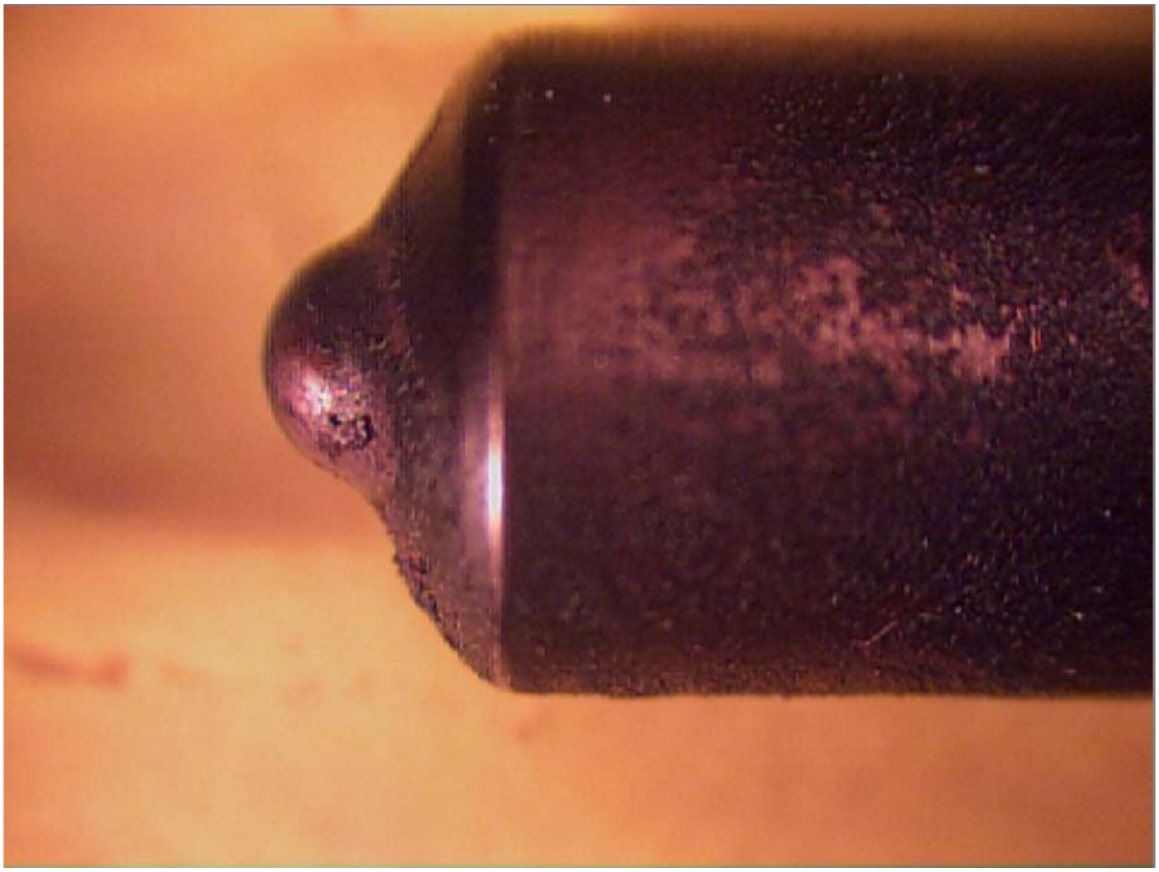


Figure 3.1. Optical microscope image of Caterpillar Injector #3 from AVL 1500 hour durability demonstration showing overall deposit formation in injector tip.

Under the electron microscopy, the Caterpillar #3 injector showed some deposits over the exterior surface of the injector tip. Figure 3.2 shows the Caterpillar #3 injector looking down on the injector tip. Much of the surface is free of deposits, but there are significant accumulations between the tip (which is located at the bottom center of the image) and the outside edge (which is located at the top of the image). In addition to the deposits away from the injector spray holes, deposits are found around and actually protruding into the.

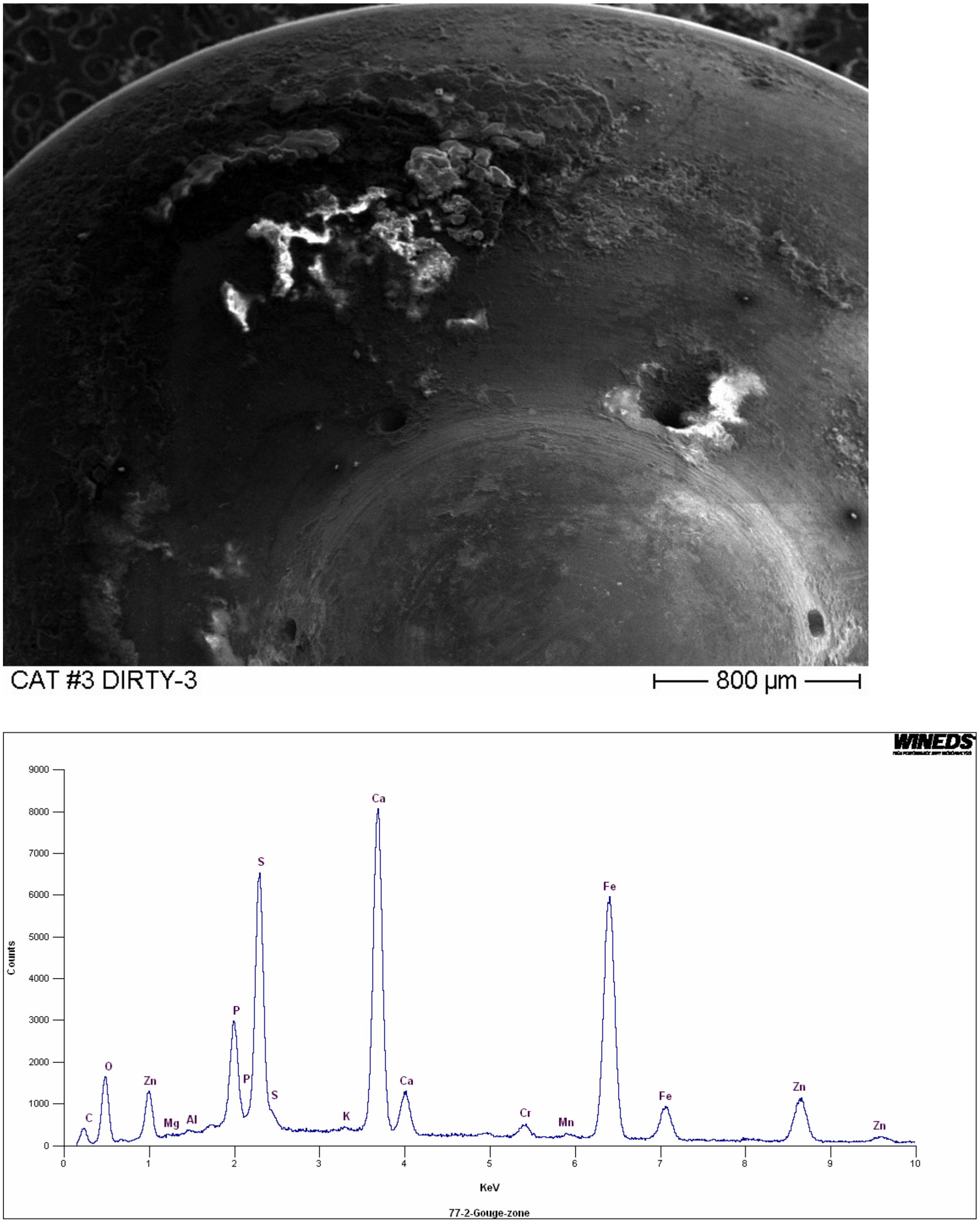


Figure 3.2. SEM/EDS image and spectrogram of Caterpillar injector #3 from the AVL 1500 hour durability run.

injector hole as seen just right of center of the image. This hole will be inspected in further detail. Energy Dispersive X-Ray Spectroscopy of the deposits showed very little carbon, but did show zinc (Zn), magnesium (Mg), phosphorus (P), calcium (Ca), along with iron (Fe) and chromium (Cr) which are associated with the base metal of the injector

Focusing in on the injector hole shows encroachment of deposits from the outside of the injector and reveals a more detailed view of the deposits. As seen in Figure 3.3, the deposits are forming around the injector hole and beginning to plug the hole from the outside.

As with the lower magnification view of the Caterpillar injector, Figure 3.4 EDS spectrogram shows the presence of Zn, P, S, Ca, Mg along with the base metals of the injector.

Caterpillar injector #3 was next sectioned across the injector tip to expose the injector sac area. A slow speed diamond saw lubricated with paraffinic hydrocarbon solvent was used to cut the injector to expose the sack area. This cutting method does not disturb existing deposits.

Figure 3.4 shows the sac area of Caterpillar injector #3. This view is from the inside of the injector showing the areas where needle seats, and the sac volume below. The sac volume provides room for the tip of the needle to extend into the nozzle tip without touching the nozzle tip beyond the seat. Fuel sealing occurs on the flank of the needle tip. The nozzle tip sealing surface is shown as the outside of the bowl shaped region which includes the nozzle holes. Note that the nozzle holes are not symmetrical in the sac area. This injector is designed to protrude into the combustion chamber at an angle with the nozzle holes machined so that they are symmetrical with the piston bowl during engine operation.

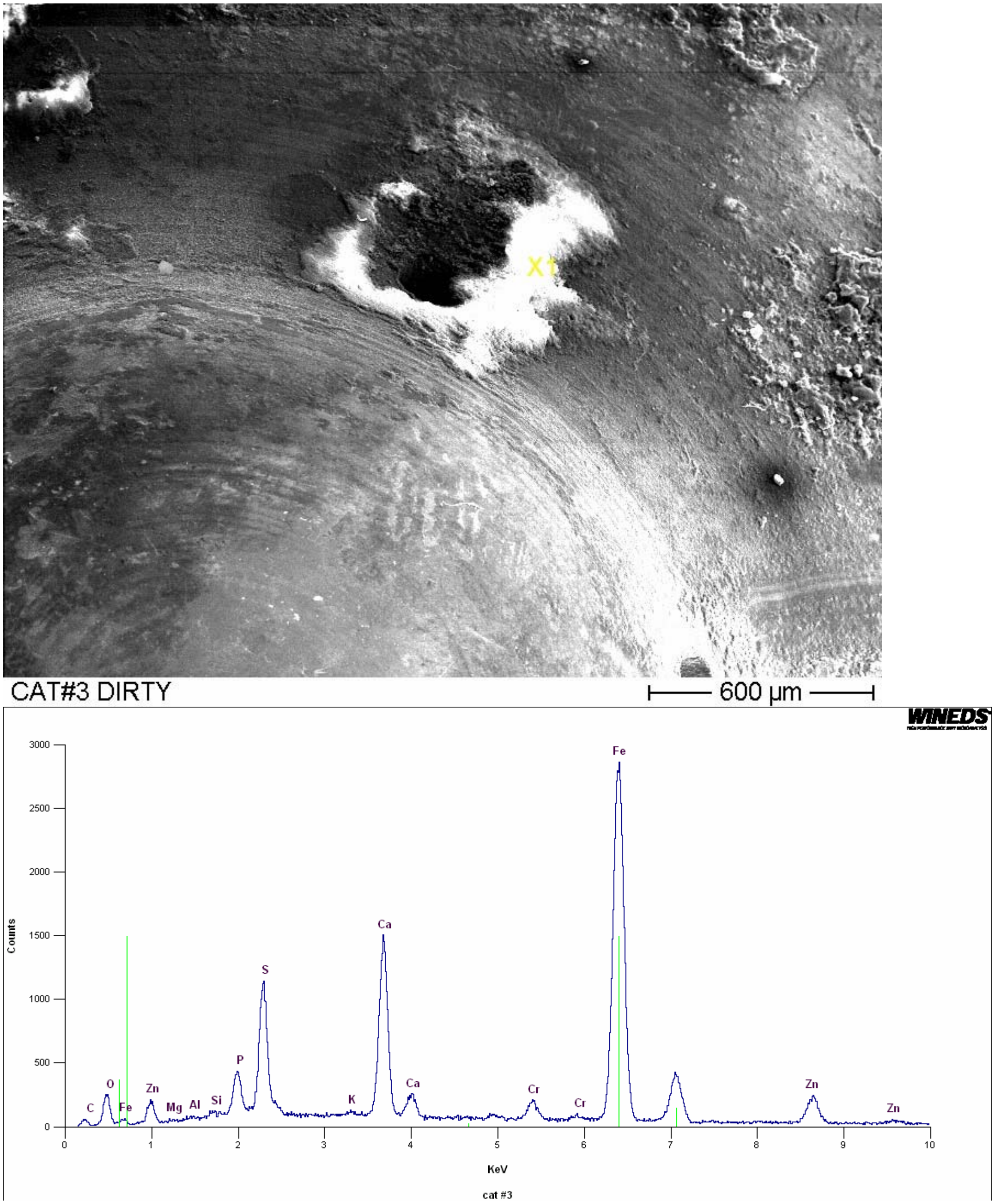


Figure 3.3. SEM/EDS image and spectrogram of Caterpillar injector #3 from the AVL 1500 hour durability run showing encroachment of deposits into one spray hole.

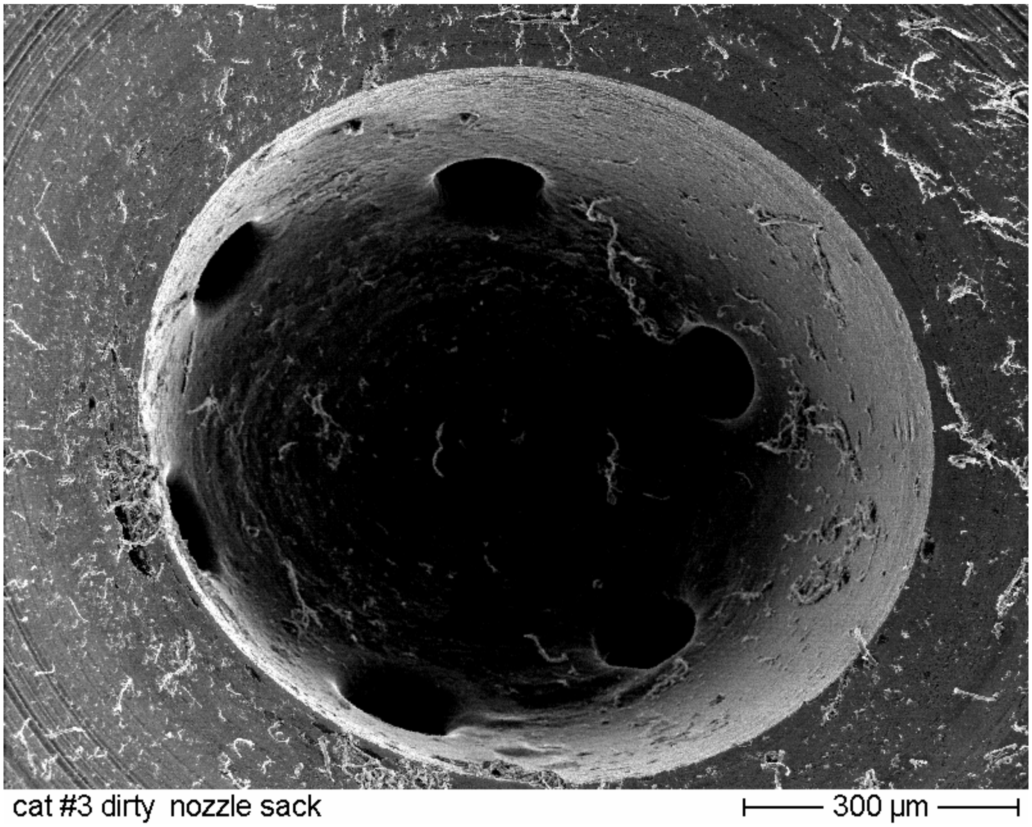


Figure 3.4. Caterpillar #3 Injector Tip sectioned to show sack area. Fine material are debris from the diamond saw. Note offset of injector holes.

Figure 3.5 shows the #6 injector from the Caterpillar C-7 engine which was cleaned by AVL. Note that wire brush marks are visible on the tip surface and that the injector hole still shows signs of deposits.

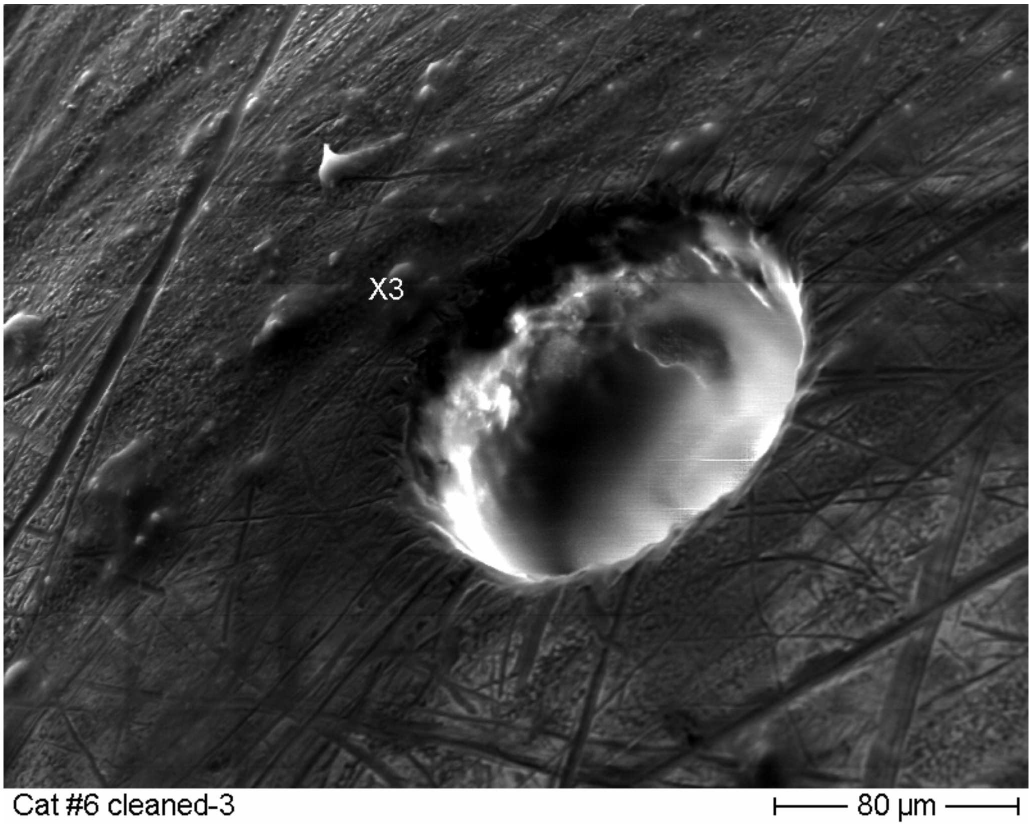


Figure 3.5. Caterpillar C-7 #6 Injector cleaned by AVL showing wire brush marks and residual injector deposits.

3.2 SEM Analysis of DDC Series 50 Injector Deposits

Several injectors from the Detroit Diesel Series 50 4-cylinder diesel engine used for 1500 hour fuel system durability testing at AVL Powertrain Engineering laboratory were analyzed by SEM/EDS at the University of Tulsa. These injectors were examined using the same techniques as for the Caterpillar injectors. All images were produced by the SEM/EDS at the University of Tulsa.

Figure 3.6 shows an overall view of the injector with deposits forming on the tip surface and around the fuel spray holes. Although deposits exist over all the injector surface, more are concentrated near the injector holes. ECS spectroscopy indicates that the major components of the deposits are Zn, Mg, P, S, and Ca, with very little carbon present in the deposits. This is the same result as for the Caterpillar deposits.

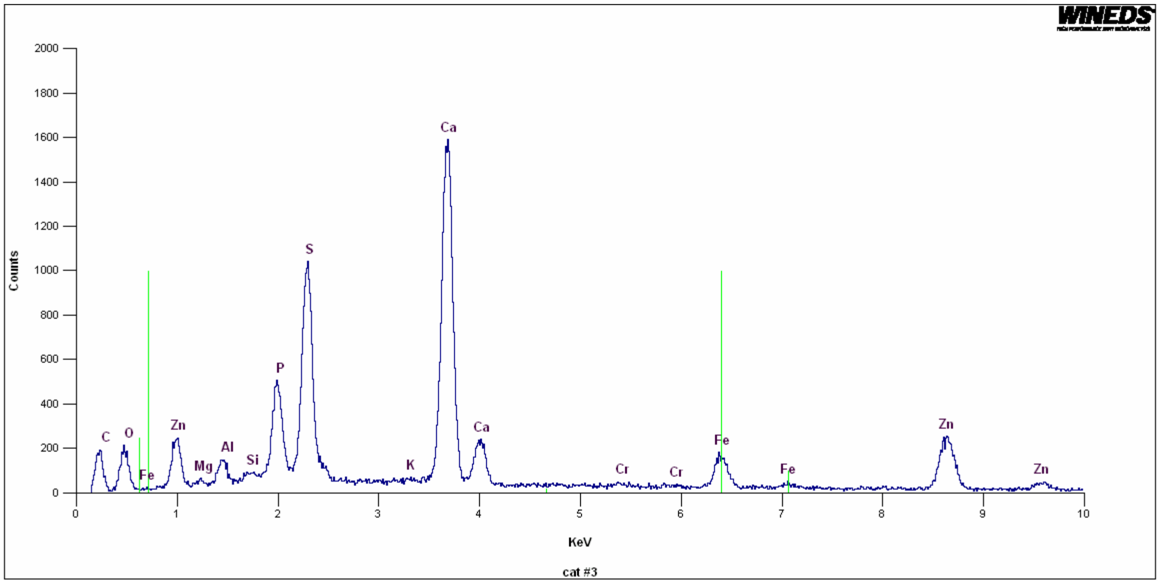


Figure 3.6. View of DDC Series 50 fuel injector #4 showing deposit formation on surface of injector tip (upper image) and EDS spectra of emissions from deposits showing presence of Zn, Mg, P, S, and Ca (lower image).

A view of one of the fuel injection holes is shown in Figure 3.7. Here the deposits are seen to be encroaching into the hole with a portion of the deposits overhanging over the hole. EDS analysis indicated the presence of Zn, Ca, P, S, and Mg as well is Fe from the base metal of the injector.

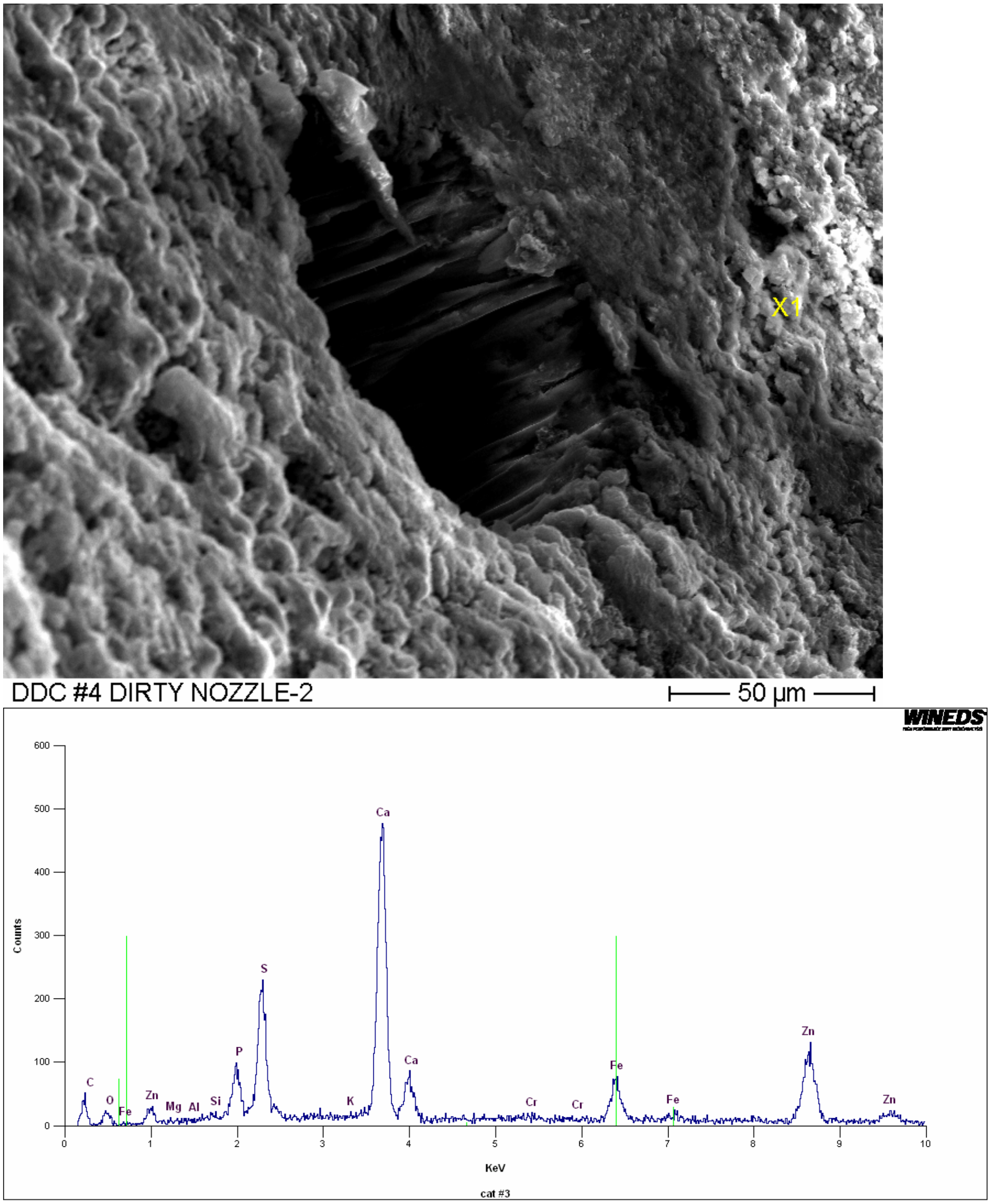


Figure 3.7. Magnified view of DDC Series 50 fuel injector #4 showing deposit formation occurring around and beginning to plug the spray hole of the injector tip. EDS spectra of emissions from deposits showing presence of Zn, Mg, P, S, and Ca.

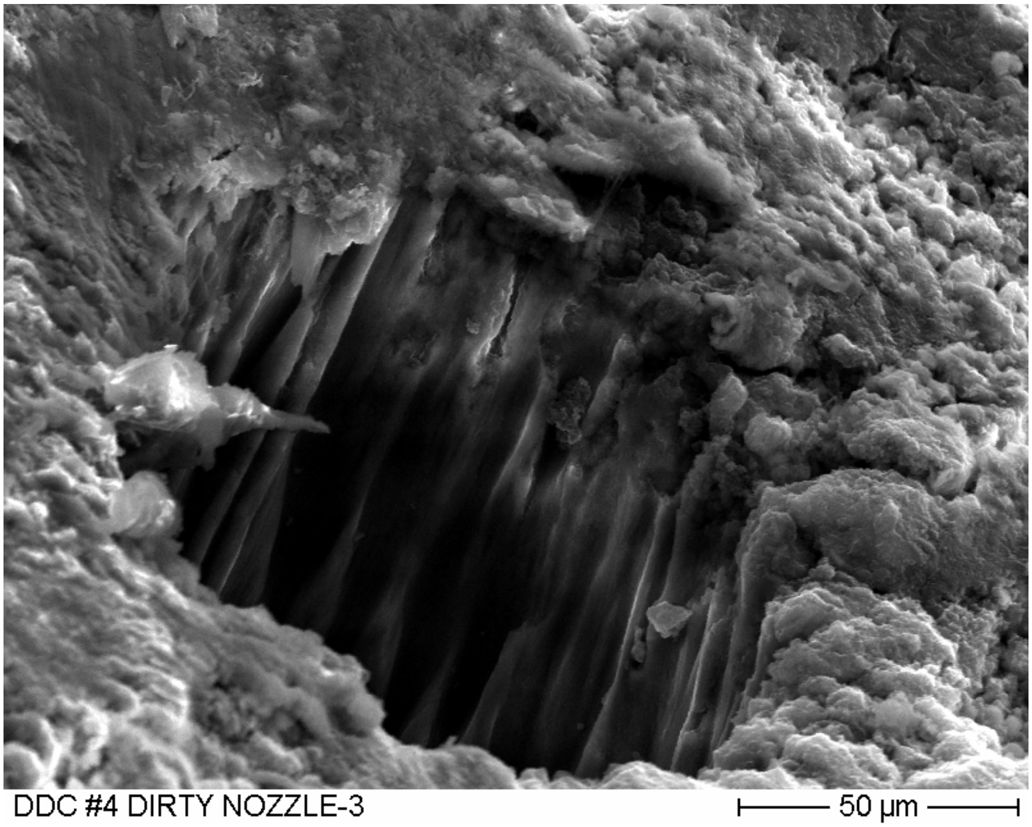


Figure 3.8. Close in view of deposits growing into DDC injector spray hole with overhanging deposit.

A close in view of the injector hole shown in Figure 3.8 gives a very good view of the deposits forming in and around the injector spray hole.

This injector was cut to expose the sac area behind the fuel spray holes to determine if any deposits formed in this area. Figure 3.9 shows the sac area after diamond saw sectioning of the injector tip. It is important to note that this area of the DDC injector, as well as the Caterpillar injector, show no deposits and are essentially bare metal.

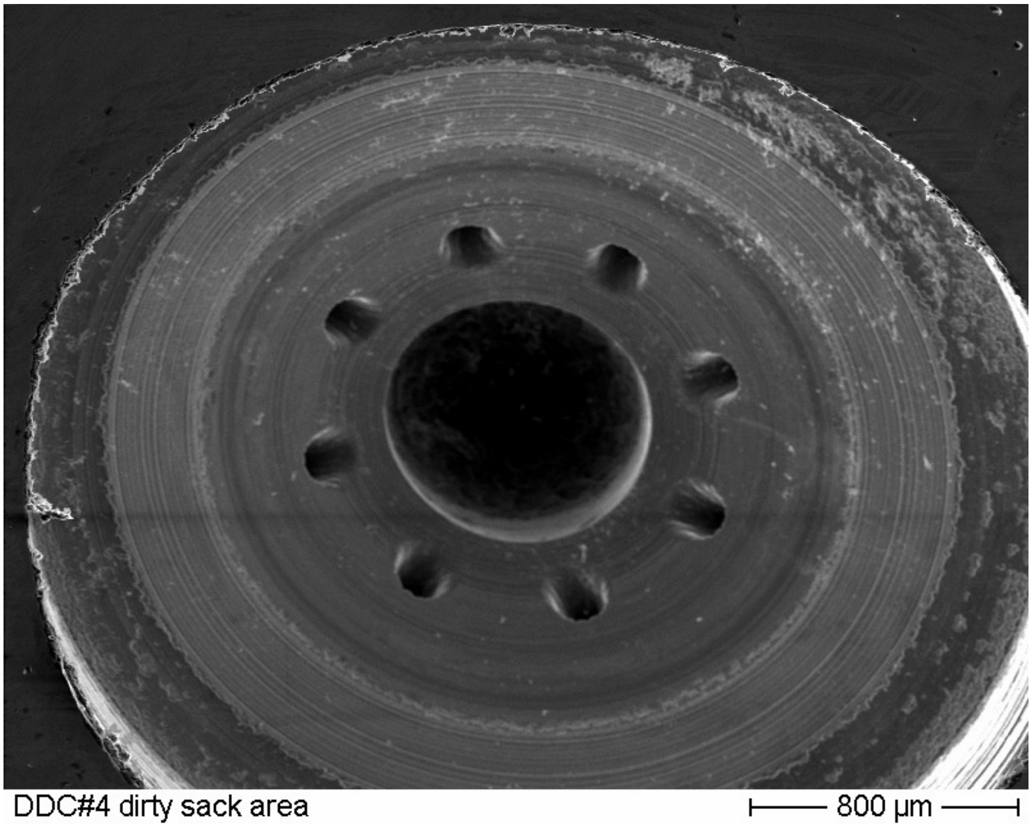


Figure 3.9. Inside view of DDC injector sack area and fuel injector spray holes showing no deposits. Note that the radius of the holes has been smoothed by abrasive slurry honing to improve entrance flow dynamics.

4.0 Analysis of Engine Oil Used During Durability Testing

AVL Powertrain Engineering used commercially available diesel engine oil for the 1500 hour fuel system durability demonstration. This oil was subjected to analysis for metallic additive components to determine if the metals in the lubricating oil were the same as the metals observed in the deposits found on the fuel injectors. Table 1 shows the major metals detected in the engine oil and also shows the concentration of metals often found in engine oil additive packages which were not found in this oil.

Table 4.1. ASTM D 5185 Determination of Additive Elements by Inductively Coupled Plasma Atomic Emissions Spectrometry (ICP-AES) analysis of engine oil used for fuel system durability testing by AVL Powertrain Engineering.

Element	Unit	Result
Boron	ppm	<1
Calcium	ppm	3,577
Copper	ppm	<1
Magnesium	ppm	19
Molybdenum	ppm	<1
Phosphorus	ppm	1217
Potassium	ppm	<5
Sodium	ppm	6
Zinc	ppm	1347

The above data indicates that only calcium, phosphorus and zinc are present in any substantial amount in the engine oil. Magnesium is a trace component only. Comparing the engine oil metals content with the EDS spectroscopic analysis of the deposits found on the fuel injector tips indicates that there is a strong correlation between the two analyses.

5.0 Conclusions From Analysis of Fuel Injectors and Injector Deposits

The ability to view the Caterpillar and DDC injectors under Scanning Electron Microscopy and analyze the composition of the deposits with Energy Dispersive X-Ray Spectroscopy has eliminated decomposition of the Ultra-Clean diesel fuel as the source of nozzle-hole deposits. The deposits were severe enough to plug some injector nozzle holes in the Caterpillar engine resulting in the power loss observed by AVL Powertrain Engineering Laboratory during the 1500 hour fuel system durability demonstration run. The SEM/EDS technique also identifies the source of the deposits as the non-combustible (ash) components of the lubricating oil with virtual certainty.

The visual and spectroscopic evidence obtained by SEM/EDS analysis of the Caterpillar and DDC injector nozzles indicated that additives found in the heavy duty diesel engine oil used to lubricate the crank case of the engine leaked past the piston rings (a normal situation in any diesel engine), burned along with the diesel fuel in the combustion chamber, and deposited on the injector tips and other cool areas of the combustion chamber. SEM images indicate that these deposits form around the injector spray holes and are most likely pushed into the holes as pressure rises during the combustion event within the cylinder. The total absence of deposits on the sack side of the injector hole clearly show that deposits did not start from the inside and move out to the exit of the holes.

6.0 Recommendations for Further Studies

The extent to which such oil-ash-drived injector nozzle-hole deposits may form and remain in place with conventional petroleum-derived diesel fuels is unknown. However, it can be safely assumed that if such deposits routinely caused enough injector nozzle-hole fouling to reduce diesel engine power output significantly, this would have been recognized in the field long ago.

Nevertheless, it would be worthwhile to assess the level of such deposits in diesel engines running on conventional diesel fuels as a baseline.

Conventional petroleum-derived diesel fuels contain significant aromatic fractions, which could influence such nozzle-hole deposition by either, or both, of the following mechanisms (and possibly by other mechanisms as well). First, aromatic hydrocarbons produce much more soot “early” in the combustion process than do the saturated hydrocarbons that make up ultra-clean F-T fuel. Much of the initial aromatic-derived soot that flows and mixes with the hot combustion gases subsequently “burns-out” later in the combustion process. However, the presence of a more persistent soot layer on combustion chamber surfaces, including the injector tip, may lessen the ability of oil-ash components to “bond” to these metal surfaces. Furthermore, the hot, high-velocity fuel that flows through the nozzle holes (as it is vaporizing rapidly) may be better able to “dissolve” and thus remove initial deposits or their precursors if the fuel contains aromatics.

Considering that the two engines used in this study represent completely different design philosophies yet still showed similar deposit formation tendencies indicates that ultra-clean transportation fuels may be prone to nozzle-hole deposit formation by additives found in lubricating engine oils. It is speculated that all saturated-hydrocarbon fuels may show similar tendencies as they are essentially the same chemical structure if prepared from Fischer-Tropsch hydrocarbons which do not initially contain aromatic components.

Considering that the diesel injector deposits can also be formed by decomposition of some (undesirable) components in conventional fuels, and that these deposits are usually adequately “dissolved” by dispersant (fuel detergent) additives, it is speculated that including a dispersant component in the Ultra-Clean fuel additive system may give the fuel sufficient dispersant properties to also keep these engine oil additive derived ash-components from depositing on and in the injector nozzle holes.

Acknowledgements

ICRC and Syntroleum Corporation gratefully acknowledge the assistance of Dr. Winton Cornell, Ph.D., Department of Geosciences, University of Tulsa for his help and input with conducting the Scanning Electron Microscope evaluation of diesel fuel injectors and their deposits.

Fleet Demonstrations of Ultra-Clean F-T Fuel

DOE Cooperative Agreement Number DE-FC26-01NT41099

Submitted By
Integrated Concepts Research Corporation

June 30, 2006

Disclaimer

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1.0 Abstract

The Washington D.C. Metropolitan Transit Authority (WMATA) Transit Bus Fleet Demonstration and the Denali National Park Demonstration of Syntroleum Fuel were conducted to help the general public and national leaders become more aware of the potential of ultra-clean Fischer-Tropsch (F-T) fuels, produced from domestic energy resources such as stranded natural gas, to contribute to the solution of two national problems simultaneously. The demonstration showed first that F-T fuels can displace imported petroleum in transportation applications which require liquid hydrocarbon fuels such as diesel fuel, and second, that F-T fuels can reduce emissions compared to conventional petroleum-derived diesel fuel.

The Denali National Park bus fleet demonstration began in May 2004, with one of the Syntroleum fueled Denali buses on hand for the 2004 Alaska Clean Energy Symposium in Anchorage Alaska. The 2004 Alaska Clean Energy Symposium featured Senator Lisa Murkowski (see Figure 1) and Congressman Don Young of Alaska as keynote speakers. The Denali National Park fleet demonstration continued through the summer of 2004. It was so successful that the Denali National Park personal requested to continue the evaluation of the Syntroleum Fuel into and through the winter of 2004-2005 in their snow removal vehicles (see Appendix 9.1 for the report on the Cold Weather F-T Fuel Demonstration).

Figure 1. Senator Lisa Murkowski and the Syntroleum fueled Denali Park bus, 2004 A.C.E.S. Symposium

The WMATA demonstration was kicked-off officially with a press-conference event on Capitol Hill on September 22, 2004 which was hosted by House Transportation Committee Chairman Don Young of Alaska and by Congressman John Sullivan of Oklahoma.

The actual initial F-T fueling and initial emission testing of the three F-T fuelled and three control buses at WMATA were completed by project-partner West Virginia University in late August of 2004 in preparation for the Capitol-Hill event. The demonstration program at WMATA continued for over six months, into May 2005.

In general, the program went smoothly with F-T fuel being praised at both locations by bus depot personnel and drivers for producing reduced smoke and odor emissions, (even in comparison to WMATA's normal fuel, which was low-emission ultra-low sulfur No. 1 diesel). However, near the end of the WMATA demonstration program, one of the buses running on F-T fuel experienced a turbo-charger failure, with subsequent problems that are detailed in a companion report. While the type of failure observed was fairly common for the type, age and mileage of equipment used, and is not believed to be fuel-related, a subsequent thorough investigation, detailed in a companion report, provides significant insight on some issues potentially related to ultra-clean fuels of the future, regardless of whether these fuels are derived from petroleum or other resources.

2.0 LIST OF GRAPHICAL MATERIALS

Figure 1. Senator Lisa Murkowski and the Syntroleum fueled Denali Park bus, 2004 A.C.E.S. Symposium

Figure 2. Denali Syntroleum Fueled Bus

Figure 3. WMATA Syntroleum Fueled Bus

Figure 4. Major hardware modules and software components of the Onboard System

Figure 5. Data Repository functional diagram

Figure 6. Hours of data collected on Denali buses

Figure 7. Total Distance (Crosshatched areas indicate S2)

Figure 8. Total Fuel Used (Crosshatched areas indicate S2)

Figure 9. Fuel Mileage in Miles per Gallon (Crosshatched areas indicate S2)

Figure 10. Hours of data collected on WMATA buses

Figure 11. WMATA S2 controlled refueling

Figure 12. Total Distance (Crosshatched areas indicate S2)

Figure 13. Total Fuel Used in Gallons (Crosshatched areas indicate S2)

Figure 14. Total Fuel Mileage in Miles per Gallon (Crosshatched areas indicate S2)

3.0 INTRODUCTION

The US currently imports approximately 13 million barrels per day of petroleum and petroleum products, the vast majority of which is ultimately used to fuel transportation. US domestic production of petroleum that can be used to produce transportation fuels (i.e. including only the “heaviest” pentanes-plus fraction, or about 15% of domestic natural gas liquids production) is less than 6 million barrels per day, meaning that the US now imports approximately 70% of the hydrocarbons that make up its liquid transportation fuels, gasoline, diesel and jet fuels. Petroleum imports increase US vulnerability to those who would cause harm, and cost the US economy $500 million per day, an amount that is likely to keep increasing.

Fischer-Tropsch (F-T) ultra-clean liquid-hydrocarbon fuels can be substituted directly for imported petroleum products in many transportation applications, and F-T fuels can be made from many domestic energy resources, including coal, biomass and stranded natural gas. F-T fuels have the additional advantage, as shown in this demonstration program, of potentially reducing emissions from diesel engines, compared to even the cleanest available conventional petroleum-derived diesel fuels.

This report focuses on two bus fleet tests of F-T Ultra Clean Liquid Hydrocarbon fuel at two separate and distinct locations: Denali National Park, Alaska and Washington D.C. Metropolitan Area Transit Authority (WMATA). These two test sites, and subsequently their fleets, (see Figure 2 and Figure 3), were chosen to evaluate the F-T Ultra Clean Liquid hydrocarbon fuel for several reasons, but primarily because they represent nearly opposite ends of several spectra, including: climate; topography; engine load factor; mean distance between stops and composition of normally used conventional diesel fuel. Although the locations were distinctly different, the managers of these fleets both share the same strong desire to participate in a program aimed at minimizing exhaust emissions, especially those emissions that are most apparent to riders, people in vehicles and by-standers. At the same time, both fleet managers appreciated the free (to them) supply of F-T Ultra Clean Liquid Hydrocarbon fuel, the subject of both fleet tests. This report and others in the Project Report Package will present the results of these two complementary fleet tests, including all raw data and analyses, miles driven and fuel economy obtained, and specific identification of the fuels and the additives used.

Figure 2. Denali Syntroleum Fueled Bus

Figure 3. WMATA Syntroleum Fueled Bus

4.0 EXECUTIVE SUMMARY

The purpose of the Denali National Park and WMATA Transit Bus Fleet Demonstrations of Syntroleum Fuel was to help the general public and national leaders become more aware of the potential of ultra-clean Fischer-Tropsch (F-T) fuels, produced from domestic energy resources such as stranded natural gas, to contribute to the solution of two national problems simultaneously. The demonstrations showed first that F-T fuels can displace imported petroleum in transportation applications that require liquid hydrocarbon fuels, such as diesel fuel, and second, that F-T fuels can reduce emissions compared to conventional petroleum-derived diesel fuel.

The Denali National Park bus fleet demonstration began in May 2004, with one of the Syntroleum fueled Denali buses on hand for the 2004 Alaska Clean Energy Symposium in Anchorage Alaska. The 2004 Alaska Clean Energy Symposium featured Senator Lisa Murkowski and Congressman Don Young of Alaska as keynote speakers. The Denali National Park fleet demonstration continued through the summer of 2004.

The WMATA demonstration was kicked-off officially with a press-conference on Capitol Hill on September 22, 2004 which was hosted by House Transportation Committee Chairman Don Young of Alaska and by Congressman John Sullivan of Oklahoma. The actual initial F-T fueling and initial emission testing of the three WMATA buses using Syntroleum fuel was completed by West Virginia University in late August of 2004 in preparation for the Capitol Hill event. The demonstration program continued for over six months, into May 2005. In general, the program went smoothly, with F-T fuel being praised at both locations by bus depot personnel and drivers for producing reduced smoke and odor emissions, (even in comparison to WMATA's normal fuel, which was low-emission ultra-low sulfur No. 1). However, near the end of the demonstration program, one of the WMATA buses running on F-T fuel experienced a turbo-charger failure, with subsequent problems that are detailed in a companion report. While the type of failure observed was fairly common for the type, age and mileage of equipment used, and is not believed to be fuel-related, a subsequent thorough investigation, detailed in a companion report, provides significant insight on some issues potentially related to ultra-clean fuels of the future, regardless of whether these fuels are derived from petroleum or other resources

5.0 EXPERIMENTAL

The field demonstration of the Syntroleum fuel involved operation and testing of a total of twelve vehicles, six WMATA buses and six Denali buses. Three of the buses at WMATA ran on WMATA's normal low-emission fuel, conventional petroleum-derived ultra-low sulfur No. 1 diesel fuel (ULSD1), and these buses were considered to be the control vehicles. Three WMATA buses ran on Syntroleum S-2 fuel, and these were the demonstration vehicles. Because of the large WMATA bus fleet, and complex logistics and fuel distribution systems, WMATA fuel distribution included three specialized fuel filler adapters. These adapters were fitted to the S-2 control test vehicles and one specialized mating nozzle fitted to the S-2 Fuel tank supply. This system was successfully used to maintain control of S-2 fuel used in the three WMATA test buses.

In Denali, three of the buses that ran on Denali's normal No. 1 diesel fuel, which is actually Jet-A fuel with its sulfur content reduced to no more than 500ppm (referred to by fuel suppliers as “low sulfur”). The Denali Jet-A is the Park's normal low-emission diesel fuel, and buses using it were considered to be the control vehicles. Three Denali buses ran on Syntroleum S-2 fuel, and these were the demonstration vehicles. Vehicle performance data for the buses was automatically collected, for statistical analysis and comparison, from all the vehicles involved and delivered to a central repository server. The data was filtered and exported to a comma separated file for use with Microsoft Excel.

5.1 Data Collection System

Performing vehicle data collection was automatic and unattended while the vehicle ignition was on. The unique ICRC developed data collection system was quickly adapted to both the WMATA and the Denali test environments and saved countless hours of tedious data collection. This section describes the data collection system in more detail. The system collected a set of parameters from the vehicle's electronic engine control unit (ECU), using a J1708 vehicle network architecture. The parameters were chosen from the SAEJ1587 spec. The engine data, location, and altitude of the vehicle, were collected. The location and altitude of the vehicle was collected with the same interval as the vehicle data, so they could be correlated.

The collected vehicle engine and location data was archived for later uploading to the server at the bus terminal or bus depot.

The collected information was uploaded to the repository server upon the vehicles return to the bus depot. The uploading process was also automatic and unattended.

The software provided secure and reliable storage for the information as well as providing data filtering features for generating export files.

5.2 Data Collection System Design

The system was comprised of two major components – the On-Board System and the Back Office Repository System. A wireless Network (802.11b) was used for communication between the on-board computers and the Repository Server.

5.3 The On-Board System

The On-Board System (OBS), diagramed in Figure 4, was responsible for collecting and uploading data from the vehicle bus and other devices.

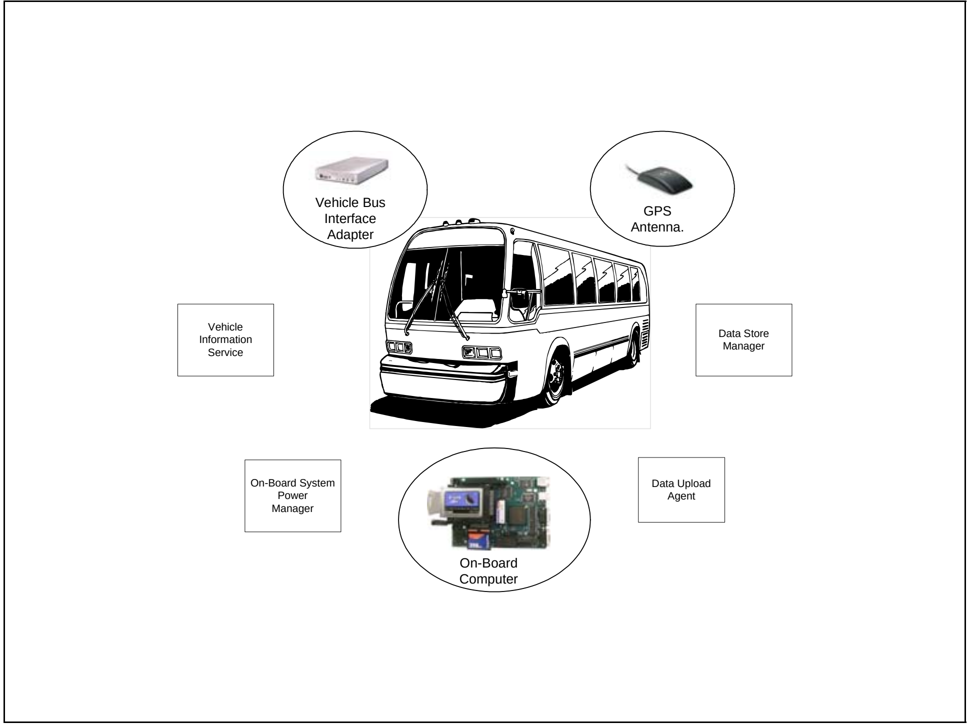

Figure 4. Major hardware modules and software components of the Onboard System

The circular items in the Figure are the hardware modules, and the rectangular items denote software modules.

5.3.1 GPS Antenna

A Global Positioning System (GPS) provided location, altitude, and date time information. The Date and Time value was used as a time stamp for the data stored. The altitude was an important factor affecting vehicle fuel economy.

GPS data was used to track vehicle distance traveled. Due to the variation of tire wear and pressure, the odometer reading from the ECU was merely an estimation of travel distance. The GPS, on the other hand, tracked actual vehicle movement. Therefore, GPS data was the preferred way of tracking a vehicle's driving distance.

The GPS antenna was mounted outside of the vehicle for optimal performance.

5.3.2 Vehicle Bus Interface Adapter

A vehicle bus interface adapter connected the vehicle data link to the On Board Unit via the computer's serial port. The adapter supported J1708 protocol and had a Linux driver.

5.3.3 On-Board Computer

The on-board computer, OBC, was equipped with two serial ports, one parallel port, and one 802.11b wireless network card.

The computer was able to withstand the harsh operating environment of a surface vehicle. Similarly, the enclosure of the computer was sealed to protect its electronic components from dust, gas, liquids, and magnetic field interference.

When the integrated PC card wireless network adapter was used, the computer was mounted in an open area for optimal radio frequency reception; otherwise, an external antenna was used.

Linux was used as the operating system for the on-board computer.

The OBC booted up automatically after the vehicle ignition was turned on. All software modules, described below, started automatically as well.

5.3.4 Vehicle Information Service

Vehicle Information Service was a software module responsible for collecting vehicle data from the vehicle network data link.

The incoming vehicle network messages were retrieved, parsed, and the latest information relating to the test was stored in the computer's memory.

5.3.5 Data Storage Management

This module recorded parameter values based on the time interval specified. Its operation was analogous to picture taking. A snapshot of the parameter values and positional data were taken and persisted to a non-volatile storage media.

GPS readings were taken, and Date and Time was used as the timestamp for data stored. The vehicle position was also recorded, along with engine data.

This operation was done at a constant time interval near once per second. Consequently, the frames comprised a vehicle's performance history.

If GPS information was not momentarily available, due to a building or other obstruction to satellites, the timestamp was marked as 0.00 to indicate N/A. When the location was acquired again, the timestamp was retrofitted to all records missing timestamps.

5.3.6 Data Upload Agent

This module was responsible for detecting the remote hosting server for data uploading. It attempted to connect to a server as soon as data in data storage was available for upload. Authentication was performed prior to the data uploading operation. A communication handshake was performed on the packet level to assure data integrity and completeness.

The uploaded records were removed from the on board unit (OBU) after they were successfully transferred.

5.3.7 On-Board System Power Manager

This module was responsible to maintain system power during data transfer, regardless of the ignition key status. The OBC was powered up when the ignition key was on, but the shutting down process was conditional depending on the state of upload progress. The OBC maintained its power and normal operational processing regardless of the ignition state, if the data upload operation was in process.

5.4 The Repository Server

This section provides an overview of the Repository Server.

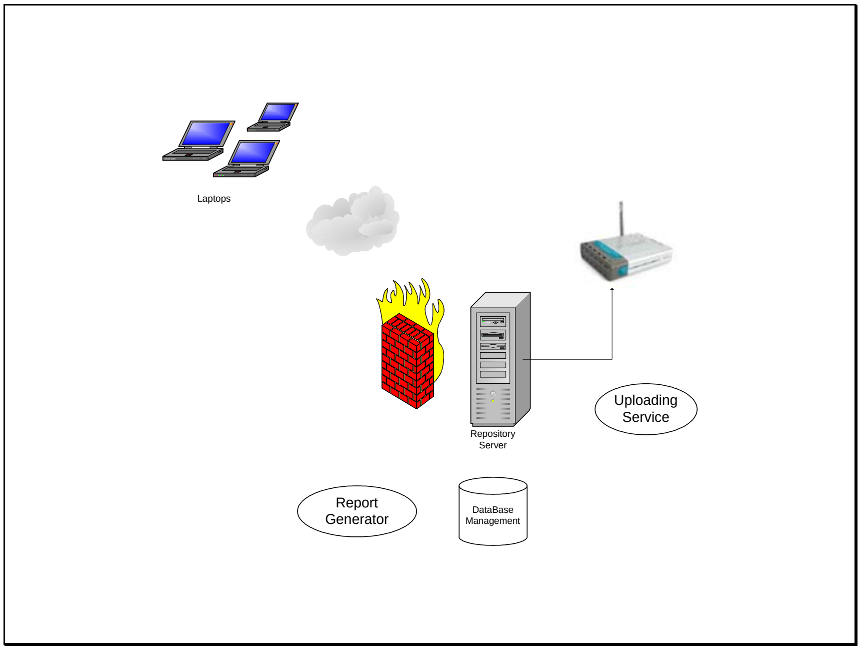

Figure 5. Data Repository functional diagram

The Repository Server (RS) was a web based server and was responsible for receiving data from the test vehicles, as well as for providing data access and exporting features to ICRC via the Internet.

The server was capable of receiving multiple wireless network connections from the test vehicles simultaneously. A wireless (802.11b) Access Point was used for communicating with the on-board computers on the test vehicles. Ideally, the Access Point was installed at a location that was accessible to all the test vehicles with a driving-by coverage of about 1-2 minutes. Refuel stations were used for the location of the wireless network antennas.

An external high power antenna was used to further increase the communication performance.

The server had sufficient computing power and storage capacity to receive, decipher, and store all vehicle parameter readings that were collected.

There were options for delivering the collected information to the user, depending on the network used:

- The RS as part of WMATA's or Denali's intranet. In this case, it could be accessed via the Internet. A web server, along with associated web pages, could be installed to allow web access. Users could access the vehicle data using a web browser. The web server could be capable of accepting multiple users' requests and provide responses that include accessing the database, performing data filtering, constructing page contents, and delivering the result via email.

- The RS as part of World Wide Web with a dedicated IP address. This could be accomplished by subscribing to either a cable or DSL line. It could provide the same functionality as the method described above.

- The RS using dial-up networking. In this case, the functionality of the RS could be distributed into two parts. The data collection function could reside at the bus fleet site. The repository and filtering functions could reside at the ICRC site. Communication between the two sites could be via telephone line. The collected vehicle data could be uploaded automatically to the remote server daily. The remote server would be responsible to provide Internet access.

The server was directly exposed to the Internet. A firewall and sophisticated authentication mechanism was used to eliminate the risk of data loss due to unwanted intrusion.

5.4.1 Database Management

A MySQL database management system was used to store data. Vehicle data was identified by its respective Vehicle Identification Number (VIN).

5.4.2 Upload Service

The upload service module was responsible for uploading information from vehicles. It allowed simultaneous upload from more than one vehicle. The uploaded data was then inserted into the database for processing.

5.5 Test Vehicles

The WMATA test vehicles were six similar buses running their normal routes during the course of the demonstration. The test buses and the control buses were given no special treatment by service or by the dispatch. This was to ensure that the fuel was tested in real world conditions. The WMATA buses all used a Detroit Diesel Series 50 power plant. One of the six test buses, bus 2056, experienced a problem, the documentation of which is contained in the report titled "Investigation of the Engine Problems of WMATA Bus 2056," Part 5 of the main report. There were 3296.56 hours of data collected on the six WMATA buses. The data was collected over the 7 months of operation, and all the raw data is available in separate backup documentation.

The Denali test also used six similar buses. These buses ran their normal routes during the course of the demonstration. The test buses and the control buses were given no special treatment by service or by the dispatch. The Denali buses all used a CAT C7 power plant. There were 814.04 hours of data collected on the Denali six buses. The data was collected over the 3 months of operation, and all the raw data is available in separate backup documentation.

6.0 RESULTS AND DISCUSSION

Bus fuel economy, fuel used and hours of data collected are discussed in this section for both the WMATA and Denali bus fleet tests. Additionally, information is presented on emission measurements and fuel-system durability/controlled emission testing. All the Fuel usage data is based on the information collected from each vehicle’s data bus. Only the actual data was used and all zero or N/A data was omitted. All graphs and tables reflect only information gathered on the data collection system.

6.1 Hours of data collected Denali

Below in Figure 6 are the hours of data collected. Due to the lack of accessibility of the vehicles in Denali some of the data was not collected. Due to equipment durability issues or the vehicle not getting close enough to the base antenna some data was not captured during the test. One of the issues encountered in Denali was due to the harsh driving conditions and rough roads the wireless cards were vibrating loose. This would cause a lack of communication on the buses that experienced this problem. The charts shown below are based upon only that data obtained during the test.

	Syntroleum Fuel			**Jet A Control Fuel**		
	Bus 533	Bus 534	Bus 537	Bus 531	Bus 532	Bus 536
July hrs of data	70.02	24.81	92.9	68.81	30.32	67.57
Aug hrs of data	3.23	0	89.44	138.05	60.1	91.36
Sept hrs of data	0	0	0	63.18	18.25	0
Grand total Hrs	**73.25**	**24.81**	**182.34**	**270.04**	**108.67**	**158.93**

Figure 6. Hours of data collected on Denali buses

6.2 Fuel Usage Denali

Figures 6 and 7 below represent the total distance covered and fuel used, by both the control fuel (Jet A diesel) Denali buses and the Syntroleum S-2 fueled Denali buses.

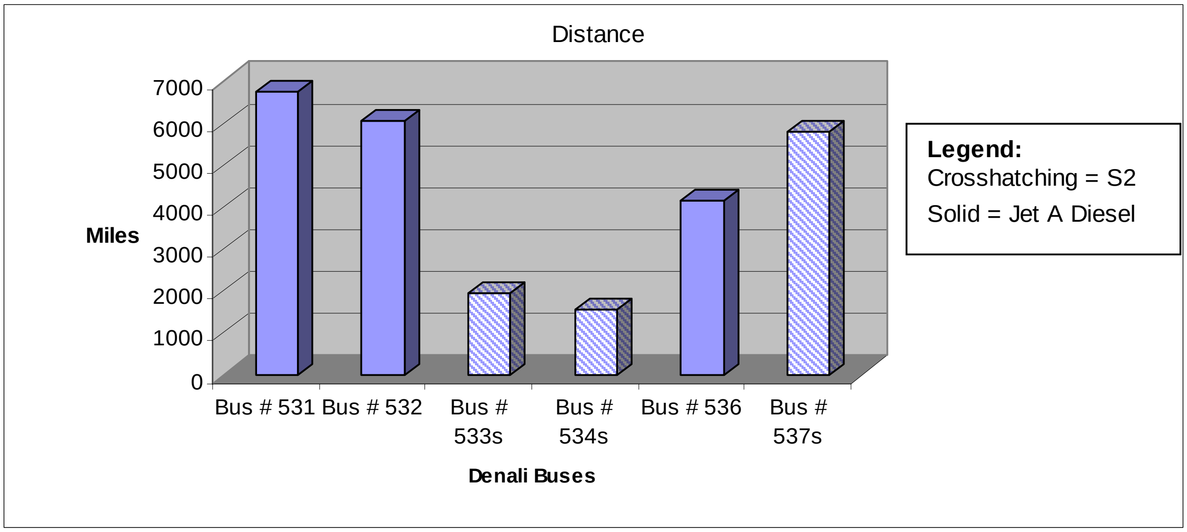

Figure 7. Distance (Crosshatched areas indicate S-2)

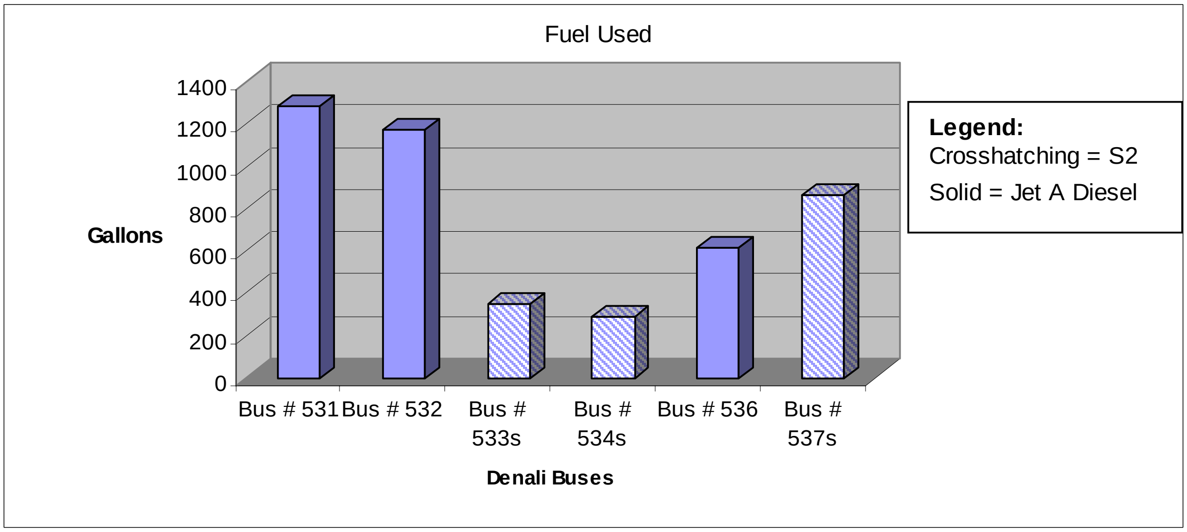

Figure 8. Fuel Used (Crosshatched areas indicate S-2)

A fuel consumption analysis was performed, in addition to bus fleet testing support provided at the Denali National Park, by personnel from the College of Engineering and Mines at the University of Alaska Fairbanks. This analysis can be seen in Appendix 9.2, “F-T Fuel Demonstration Report and Fuel Consumption Analysis”, dated July 2005, College of Engineering and Mines, University of Alaska Fairbanks.

6.3 Bus Fuel Economy Denali

Figure 8 presents the measured fuel economy of the buses run at Denali. Differences in fuel economy between the control fuel (Jet A diesel) Denali buses and the Syntroleum S2 fueled Denali buses were virtually negligible when bus operating conditions are taken into account. Specifically, buses 536 and 537, using Jet A and S-2 fuel respectively, were used exclusively during the summer of 2004 on the route within Denali National Park known as the Savage River Shuttle. This route starts near the entrance of the Park and runs to the Savage River Ranger Station and back. This route is the initial 15 miles into the Park, where the road is paved and has only moderate grades. The other buses traveled over the same road, but then they traveled much farther into the Park where the roads are generally not paved and the grades are much steeper.

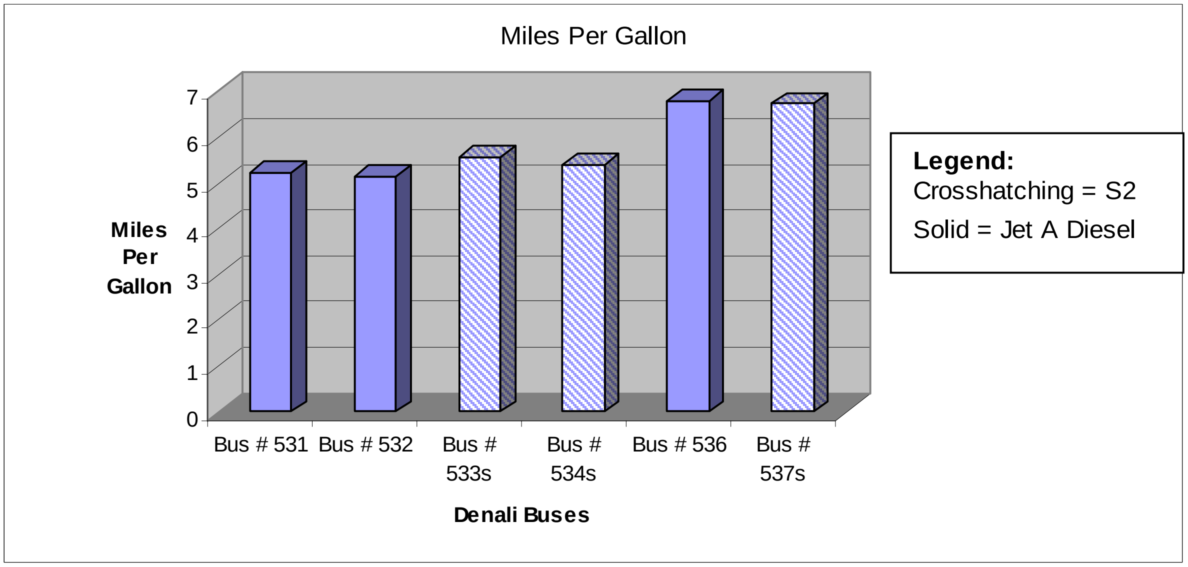

Figure 9. Fuel Economy in Miles Per Gallon (Crosshatched areas indicate S2)

6.4 Hours of data collected WMATA

Below are the hours of data collected. It should be noted that bus number 2056 had 0 hours for April and May. This was due to the turbocharger failure that was fully investigated and documented in the report titled “Investigation of the Engine Problems of WMATA Bus 2056,” Part 5 of the main report. Shown below in Figure 10 are the hours of data collected.

	Syntroleum Fueled Buses			**Ultra Low Sulfur Number 1 Diesel Control Fueled Buses**			
Month/Hours	Bus 2054	Bus 2055	Bus 2056	Bus 2092	Bus 2093	Bus 2094	Totals
November	23.11	5.55	105.48	35.82	195.24	28.20	393.40
December	52.29	24.84	28.17	50.88	90.53	125.55	372.26
January	130.27	103.69	95.50	39.02	37.14	148.57	765.66
February	325.17	55.21	72.75	60.01	22.94	44.85	580.92
March	415.05	116.83	108.83	30.94	0.00	41.24	712.88
April	101.86	121.69	0.00	103.92	60.59	62.99	451.05
May	56.13	55.65	0.00	55.90	32.08	32.09	231.85
Total Recorded Hours of Data Collected	**1103.88**	**483.45**	**410.74**	**376.49**	**438.52**	**483.49**	3296.56

Figure 10. Hours of data collected on WMATA buses

6.5 Fuel Usage WMATA

Figure 11 below shows the separate WMATA S2 refueling station using uniquely configured nozzles and orifices, used to control the distribution of S2 fuel to only the test buses running S2 fuel.

Figure 11. WMATA S2 controlled refueling

Figures 12 and 13 below represent the total distance covered and fuel used, by both the control fuel (ULSD1) WMATA buses and the Syntroleum S-2 fueled WMATA buses.

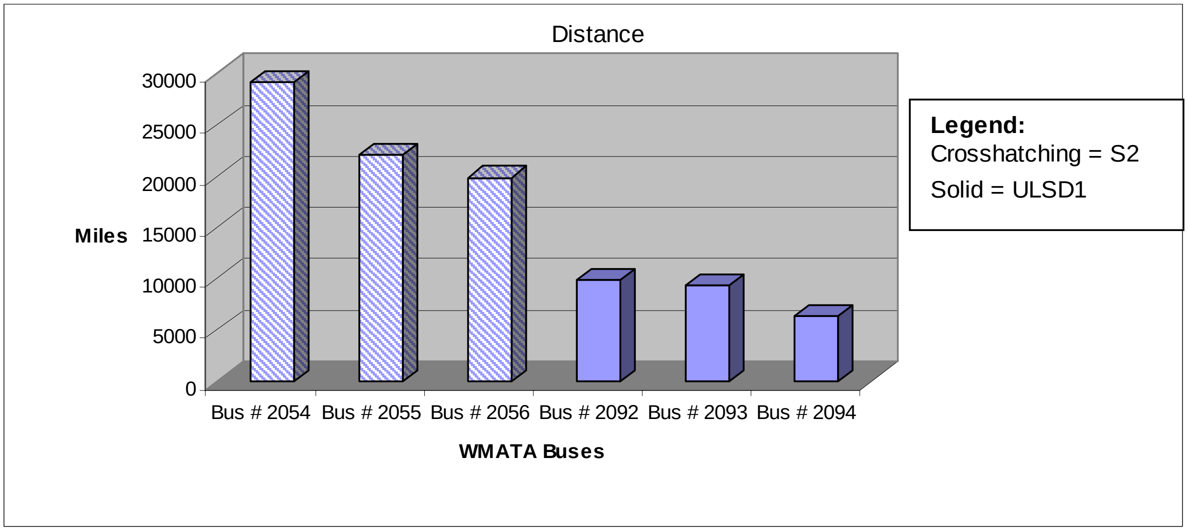

Figure 12. Distance (Crosshatched areas indicate S2)

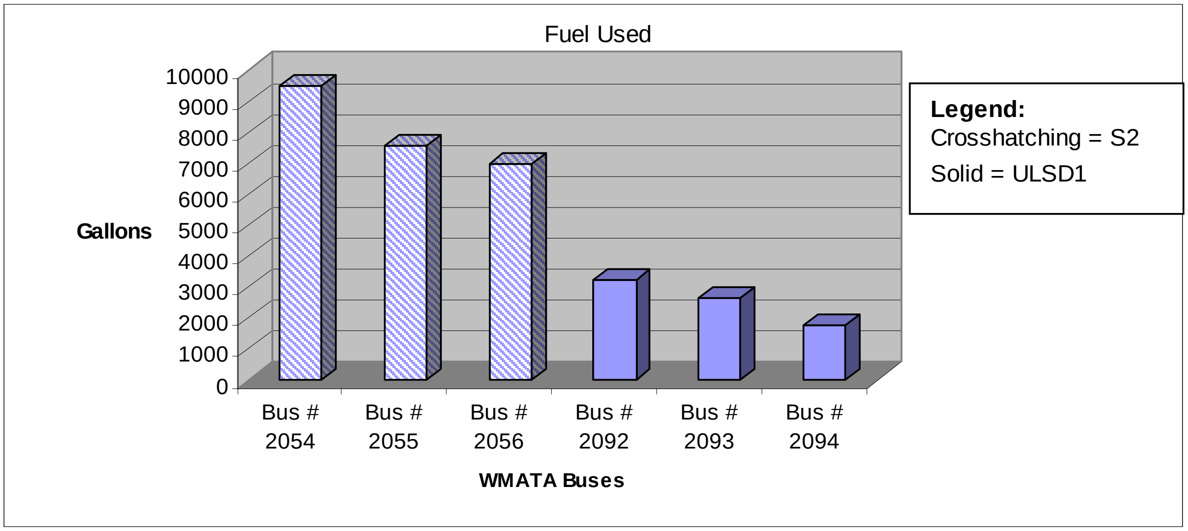

Figure 13. Fuel Used in Gallons (Crosshatched areas indicate S2)

6.6 Bus Fuel Economy WMATA

Figure 14 below presents the fuel economy of the buses that ran at the Washington D.C. Metropolitan Transit Authority (WMATA), both the control fuel (ULSD1) WMATA buses and the Syntroleum S-2 fueled WMATA buses. Here the fuel economy differences for the 2 fuels are not negligible, primarily because the density of the ULSD1 fuel (0.83 gm/ml) is significantly greater than that of both S-2 (0.77), and of the Jet A fuel (0.81) that was used as the control fuel at Denali National Park. However, the positive effect of increased density, or mass per unit volume, on increased fuel economy is mitigated somewhat by the higher energy per unit mass of S-2 fuel. Because of its higher hydrogen content, S-2 has approximately 3.3% and 2.4% higher energy per unit mass, respectively, than the ULSD1 and Jet A fuels. The higher energy content of S-2 moderates the net effect that the higher density fuels can exert on increasing fuel economy.

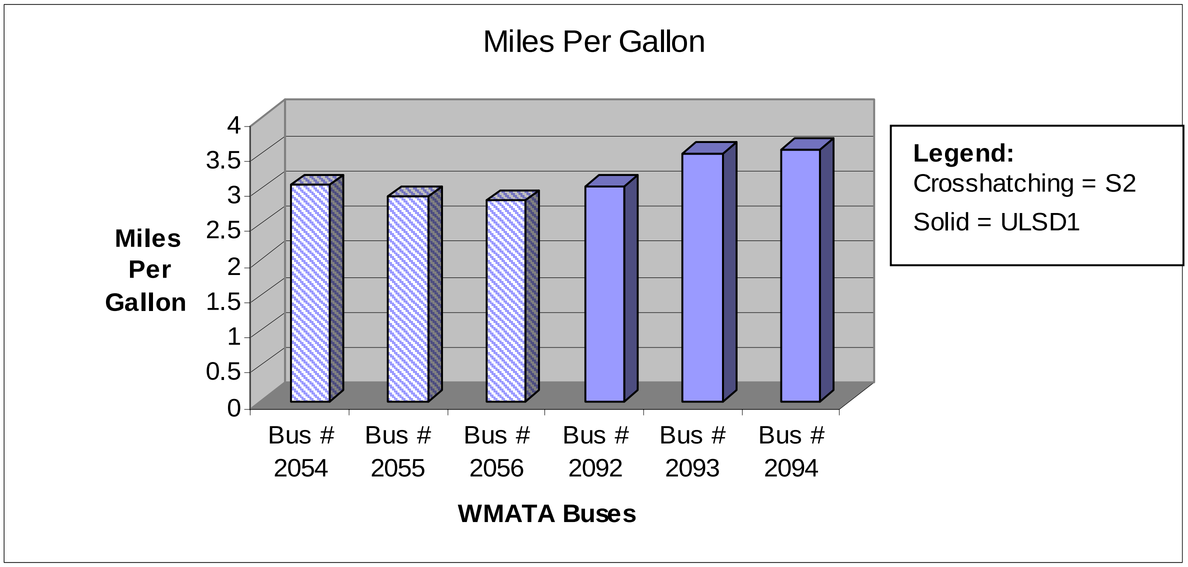

Figure 14. Fuel Economy in Miles Per Gallon (Crosshatched areas indicate S-2)

6.7 Emission Measurements

West Virginia University was selected to perform detailed emission measurements for both the WMATA and the Denali bus demonstration programs. A detailed emissions report on both WMATA and Denali testing can be seen in the report titled “WVU Report on Bus Emission Measurements for Both Fleets,” found in Part 6 of the main report.

The following paragraphs, gleaned from the above referenced report, summarize general emission testing results obtained. As detailed in the report, exhaust emission measurements were conducted on six 2000 model year transit buses operated at WMATA and powered by Detroit Diesel Corporation Series 50 engines and equipped with diesel oxidation catalysts. The measurements were made at WMATA. During the tests, three buses were operated on Syntroleum S-2 fuel and three buses were operated on ultra-low sulfur No. 1 (ULSD1) petroleum derived diesel fuel. Initial emissions were measured shortly after the buses were converted to Syntroleum S-2 fuel and then again 6 months later.

Similarly, emission measurements were also conducted on six 2004 model year Thomas buses equipped with new-technology 2004 model Caterpillar C7 ACERT engines and diesel oxidation catalysts at Denali National Park, Alaska. Three buses were operated on Syntroleum S-2 fuel (test buses) and three control buses were operated on the Denali fleet’s normal No. 1 diesel fuel which is actually Jet-A fuel. The Denali Park buses were tested on only one occasion. All emission changes were compared to the baseline petroleum diesel fuel used at each bus fleet.

Although more detailed information is available in West Virginia University's report, the three WMATA transit buses fueled with Syntroleum S-2 fuel demonstrated apparent emission reductions of between 16 and 22 percent for NOx and 35 percent for particulate matter (PM) compared to three sister buses running on ULSD1. HC and CO emissions from the WMATA buses were similar for both fuels with no significant differences noted between the Syntroleum S-2 and ultra-low sulfur fuel given high vehicle-to-vehicle variation.

On a single WMATA transit bus equipped with an Engelhard DPX passive catalyzed diesel particulate filter, emission measurements were also conducted back-to-back with both S-2 and ULSD1fuels. Separate tests were conducted with the DPX installed and with the OEM oxidation catalyst installed. Installation of a catalyzed particulate filter in conjunction with the Syntroleum S-2 fuel reduced PM emissions to less than 0.01 g/mile. HC and CO emissions were also reduced to "at or below" ambient levels by the catalytic action of the DPX filter.

The West Virginia University report similarly contains information showing the three Denali buses fueled with Syntroleum S-2 showed apparent emission reductions of 25 percent for PM, 81 percent for HC compared to three identical buses running on the "baseline" Jet-A fuel typically used as No. 1 diesel fuel at Denali National Park (discussed above). However, NOx emissions from these Denali buses, equipped with new-technology Caterpillar C-7 engines, which were calibrated for the "normal 40 to 45 Cetane" level of conventional fuels rather than for the much higher Cetane level of the Syntroleum fuel, showed an apparent increase of approximately 23 percent. As discussed in much more detail in the report, and in the Executive Summary for the Overall Project, the combination of extremely high Cetane fuel and a "normal" (i.e. not matched to the high Cetane level) calibration of the Caterpillar C-7 engine resulted in combustion beginning earlier in the cycle with higher in-cylinder temperatures than for a calibration better-matched to the fuel. During emission testing, fuel economy was computed from exhaust emission data using a carbon balance. The Syntroleum S-2 fuel did not cause significant changes in fuel economy in either bus fleet.

6.8 Fuel-System Durability/Controlled Emission Tests

AVL Powertrain Engineering, Inc was selected to perform an investigation of the durability of the fuel systems of two heavy-duty diesel transit-bus engines (WMATA and Denali) running 1500 hours each on Syntroleum Corporation's S-2 fuel. A 1500 hour durability test portion was followed with dynamometer controlled emission testing of each engine on each of three fuels; Syntroleum S-2, WMATA's low sulfur No. 1 diesel fuel and Denali National Park's "Jet A" fuel, discussed earlier. The two diesel engines tested included a Detroit Diesel Corporation (DDC) Series 50 provided by WMATA, and a new 2004 Caterpillar C-7 provided by Doyon/Aramark, owner and operator of the buses at Denali National Park in Alaska. All testing was performed at AVL Mechanical Development and Validation Facility, Ann Arbor, Michigan between June 2004 and May 2005. A detailed durability and controlled emissions report can be seen in the accompanying "AVL Report on Bus Engine Fuel-System Dynamometer Durability and Emissions Tests," found in Part 3 of the main report.

It should be noted that the dynamometer-laboratory emission measurements from the two engines were an add-on task to the fuel-system durability test programs, motivated primarily by data obtained when West Virginia University measured emissions “in the field” from six buses equipped with Caterpillar C-7 engines an Denali National Park. The purpose of the dynamometer-based emission measurements at AVL was to obtain direct comparisons of emissions, especially NOx, with each of the three fuels from the same two engines.

The dynamometer-based, direct-comparison emission measurement program was designed to determine, under well controlled laboratory conditions, whether or not S-2 fuel would cause an inherent increase in the NOx emissions from the Caterpillar C-7 engine over emission levels obtained from the same engine with identical Jet A fuel used as No.1 diesel fuel at Denali National Park, and further, to compare NOx emission results with the more conventional low-sulfur No.1 diesel fuel used by WMATA. Similarly, since the older technology DDC Series 50 engine was also available, gaseous emissions from it were also measured with the same three fuels to obtain yet another direct comparison of the effects of the three fuels on diesel NOx emissions.

7.0 CONCLUSIONS

The following conclusions are compiled from the work done by the team members who have performed this Project. Additional detailed information can be seen in accompanying reports or the appendices attached.

7.1 Emissions-(West Virginia University)

The use of Syntroleum S-2 diesel fuel produced reductions in NOx and PM emissions of Washington D.C. transit buses outfitted with DDC Series 50 engines.

The use of Syntroleum S-2 diesel fuel similarly produced reductions in PM, HC and CO emissions of tour buses operating in Denali National Park, Alaska and outfitted with Caterpillar C-7 ACERT engines.

Considering the variability between vehicles within the WMATA bus fleet, there appeared to be no substantial difference in HC and CO emissions between Syntroleum S-2 and the WMATA baseline ultra-low sulfur fuel.

The Denali National Park buses fueled with Syntroleum S-2 demonstrated reductions of 81% in HC and 68% in CO, compared to the control buses fueled on low sulfur Jet A fuel.

As a part of both the Denali and WMATA emission measurement tasks, carbon-balance fuel economy determinations showed no significant differences with Syntroleum S-2 and petroleum-derived diesel fuels.

7.2 Emissions-(AVL Powertrain Engineering

Syntroleum fuel decreased NOx 12% (DDC) and 19% (CAT) from the reference WMATA ULSD1 fuel.

Syntroleum fuel decreased PM 42% (CAT only) from the reference WMATA ULSD1 fuel.

7.3 Fuel-System Durability-(AVL Powertrain Engineering)

The fuel-system durability testing evaluated two medium duty diesel engines, fueled on Syntroleum S-2 fuel, for fuel system wear and performance over 1500 hours of Chicago Transit Authority (CTA) cycle testing.

The DDC Series 50 engine performed 1500 hours of Syntroleum S-2 fueled repetitive CTA cycles without incident.

The Caterpillar C-7 engine performed 1500 hours of Syntroleum S-2 fueled repetitive CTA cycles. Like the DDC Series 50, the CAT fuel system experienced no lubricity related issues, but CAT engine peak power experienced a 20% decrease over the 1500 hour test duration.

The Caterpillar C-7 fuel-injector nozzle-orifices were inspected and found to be fouled with deposit material. The deposit material was later determined through electron microscope inspection and analysis to have originated from non-combustibles in the engine oil, not from the Syntroleum S-2 fuel.

7.4 Final

From initial fuel/bus fleet testing, it appears that ultra-clean F-T diesel fuel, made from domestic energy resources, can be successfully substituted for conventional diesel fuel:

- Emissions can generally be reduced to levels below those obtained even with low-emission conventional diesel fuels.
- Fuel economy is essentially the same as for other low-emission diesel fuels.

Further investigation is necessary to investigate and quantify the effects of:

- Modern, complex diesel engine fuel control systems and their methods of handling alternative/higher-cetane advanced fuels.
- Fuel additive packages to improve the dispersant characteristics of hydrogen-saturated fuels and thus eliminate potential fuel-injector nozzle-orifice fouling that can originate from non-combustibles in the engine lubricating-oil additive package.

8.0 LIST OF ACRONYMS AND ABBREVIATIONS

CO	Carbon Monoxide
ECU	Electronic Control Unit
F-T	Fischer-Tropsch
GPS	Global Positioning System
HC	Hydrocarbon
NOx	Oxides of Nitrogen
OBC	On-Board Computer
OBS	On-Board System
PM	Particulate Matter
RS	Repository Server
ULSD1	Ultra Low Sulfur Diesel No.1
VIN	Vehicle Identification Number
WMATA	Washington D.C. Metropolitan Area Transit Authority

9.0 Appendices

Appendix 9.1. Report on a Cold Weather Performance Study of Syntroleum Fuels at Denali National Park

Winter 2004 – 2005

Prepared for:
Mike Pestrikoff
Project Engineer, Integrated Concepts & Research Corporation
Fischer-Tropsch Process Fuels, Cold Weather Performance Study

By:
Bill Friesen
Fleet Manager, Denali National Park & Preserve, Alaska

May 10, 2005

To: Mike Pestrikoff

ICRC Project Engineer

Fischer-Tropsch Process Fuels, Cold Weather Performance Study

From: Bill Friesen

Fleet Manager

Denali National Park & Preserve, Alaska

Re: Report on a Cold Weather Performance Study of Syntroleum Fuels at Denali National Park, Winter 2004 – 2005.

Mike, thank you for the opportunity to participate in your alternative fuels testing program. It was a privilege to play a small role within your meaningful work pertaining to alternative fuels, and I trust our efforts will be of some value towards those ends. The following report details the comparisons of our study objectives and our experiences while using the Syntroleum fuels that you had provided to us for our cold weather testing over the course of the past winter.

Initial Study Proposal: In the early fall of 2004 a study was proposed by ICRC to conduct a field test of 4,000 gallons of Syntroleum fuel, an alternative to diesel fuel derived from natural gas using the Fisher-Tropsh gas to liquids process. This study proposal was suggested during the closeout of the successful summertime test of this fuel using fleet buses owned and managed by the Denali National Park Concession Doyon Ltd. / ARAMARK Joint Venture. As a follow-up to that successful test, a study was proposed to test the cold weather performance of this fuel. Vehicles designated were a truck and selected heavy equipment owned by the National Park Service and engaged in snow removal work through the winter of 2004 – 2005 at Denali National Park, Alaska. If the study was successful, and fuel remained available, the scope of the study would expand in early spring to include the heavy equipment used during spring road opening along the park road.

Historical Conditions Prior to the Study:

Roadway and Equipment: The majority of the Denali National Park road system closes due to snowfall, usually within the month of October each year. Only 3 miles of paved road connecting the park headquarters and Alaska Route 3 remain open throughout the winter. The heavy equipment and truck assigned to snow removal duties through the winter are:

1 – 1998 Ford L9000 snow plow truck,

1 – 2004 Caterpillar 140H motor grader and

1 – 1990 Case W14 front end loader.

Periodically a Caterpillar 972 and 950 front end loader and a Caterpillar 12G grader provide support during heavy snowfalls or heavy ice buildup. We use bio-based hydraulic oil in all of our heavy equipment after their warranty periods. A temperature cutoff of minus 20F is observed with our winter equipment in deference to the limits of these oils and to avoid excessive strain on cold soaked steel components.

Fuels: We switch from summer grade diesel (#2), to purchasing winter grade (#1) diesel fuel in early August each year. Our experiences have shown us that there is enough fuel turnover in our bulk tanks between early August and late September (our final fuel purchase for the winter), to provide us with a fuel that resists gelling at temps lower than -45F. We add a lubricity enhancer to all winter grade bulk fuel deliveries. Our bulk fuels are supplied from in-state refineries and sold to federal facilities using contracts managed through the Defense Logistics Agency. Typical sulfur content of these fuels is: <5,000 PPM for Diesel Fuel #2 (+10F), and <1,000 PPM for Diesel Fuel #1.

Conditions: Typical winter conditions found in our park are snow cover from late September to early May, snow depth averages of 3 - 4 feet and winter temperatures between +10F and -60F.

Experiences within the Study Period: Initial bulk delivery of 4,000 gallons of Syntroleum occurred in October 4, 2004. The fuel was delivered to an above ground 8,000 gallon tank located at the JV / ARA bus parking area. The equipment involved in our study would pick up their fuel from that location.

The winter of 2004 – 2005 provided snowfall accumulations of 6.37 feet at headquarters, and a temperature range of +51F to –33F at our weather station, with other local spots registering to -50F. A total of 51 days registered below zero readings this winter at headquarters. Working conditions required reliable performance at full load and on grades up to a 12% incline. A total of 290 hours of equipment use was logged, and a total of 1,740 gallons of Syntroleum was consumed during the period from October 7, 2004 to March 18, 2005.

The Syntroleum fuel performed in a 100% reliable manner, within all equipment using it. No reduction in power was observed under any conditions encountered. Engine performance at start, idle, partial and full load conditions were all observed with no problems noted at any point during the study.

- The fuel experienced temperatures down to at least –33F while in equipment fuel tanks. This equipment was then brought back into operation immediately once ambient temperatures warmed to -20F. At no occasion did this fuel offer any indication of problems due to extreme temperatures.
- During fuel handing, it was observed that Syntroleum is a much “clearer” fuel, lacking in color. It consistently presented a clear sample during random “clean / clear / bright” tests. Odor was light and non-offensive. Small spills evaporated quickly with no oil residue left afterward.

Exhaust emissions had fewer visible particulates in equipment involved in this study. Comparably, a grey exhaust plume is typical to diesel engines operated in temperatures 0F or lower, with the cloud growing in density as the temperature drops. The equipment using Syntroleum showed anywhere from a “zero” to “barely visible” exhaust signature in temperatures down to -20F. Employees aware of our study commented on the absence of a visible exhaust plume. Exhaust odor followed the volume of visible plume, with only trace exhaust odor being detected while following behind equipment operating in temperatures -10F or colder. Above this temperature it was difficult to detect any exhaust odor while following behind equipment using this fuel.

- No fuel filter change outs were necessary, though we anticipated some clogging during the change over to this fuel. No fuel related repairs were necessary to any equipment using this fuel during the study.
- The success of the winter study led us to expand the test to include all equipment involved in the park’s spring road opening efforts. While road opening work is ongoing, we have not experienced any fuel related difficulties in any equipment involved in this expanded portion of the study.

Other observations:

Operator comments were numerous, and all consistent. “Very clean exhaust, it’s amazing to not be leaving an exhaust trail everywhere I go.” “I don’t notice any lack in power, it feels like this fuel has every bit as much pick up as our usual diesel, maybe a bit more.” “The 972 typically has a slight lope at idle, but while burning the Syntroleum it went away and idled smoothly for the first time.” “I wound up spilling a small amount of Syntroleum onto the side of the fuel tank and by the time I had gotten down to retrieve a rag for cleanup and then returned the fuel had evaporated! Even while trying to clean up where the fuel had been spilled didn’t result in picking up much oily residue. This is a really clean fuel.”

At -30F a space heater mistakenly was fueled with a container holding a summer grade diesel, which rapidly gelled and stalled the heater. During the repair, Syntroleum was used as the replacement fuel and the unit restarted. It continued to run outdoors non-stop with no other gelling complaints. This unit ran using Syntroleum through the coldest temperatures recorded at Denali this winter.

Conclusions: Our experiences have been consistently positive with this fuel. We would gladly replace our currently available Diesel Fuels with Syntroleum if the price and availability were comparable to our choices currently offered within the DLA fuel contract regimen.

Thank you for the opportunity to field test your fuel within our winter environment.

Respectfully,

Bill Friesen, Fleet Manager

Denali National Park, Alaska

Cc: Dutch Scholten

Elwood Lynn

Paul Anderson

Tim Hudson

Lowell Burgett, ARAMARK

Winter Use Records, October 10 through March 18

Equipment Description	Total Hours of Use	Total Days Used	Total Gallons Consumed	Average GPH
2004, Caterpillar 140H motor grader	162	19	633.1	3.908
1998, Ford L9000 plow truck	46	7	167.0	3.630
2001, Caterpillar 972 loader	59	12	835.6	14.16
1990, Case W14 loader	23	5	105.0	4.565
Totals of equipment use	290	33	1,740.7	6.559

Spring Road Opening Records, March 19 though April 12

Equipment Description	Total Days Used	Total Gallons Consumed
2002, Caterpillar D7 XR bulldozer	18	866
1987, Caterpillar 966 C loader	5	169
1996, Rolba 280 rotary snowblower	5	192
1993, Caterpillar 12 G motor grader	14	340
2001, Ingersol-Rand 30 kW genset	19	297
2001, Caterpillar 972 loader	10	366
Totals of equipment use	71	2,230

Appendix 9.2:

Bus Fleet Testing Support at Denali National Park

DOE Cooperative Agreement Number DE-FC26-01NT41099

Principal Investigators:

Sukumar Bandopadhyay, Ph.D., P.E.
Professor of Mining Engineering

Rajive Ganguli, Ph.D., P.E.
Associate Professor of Mining Engineering

College of Engineering and Mines
University of Alaska-Fairbanks

November 23, 2004

Introduction

Two types of fuel economy data (miles per gallon or mpg) were provided to the University of Alaska Fairbanks (see Appendix):

- CAT Electronic Technician records (ETR) that were collected by engine instrumentation
- Manual fuel usage logs

Additionally, the data included handwritten comments (not attached) from Aramark purportedly from drivers on overall bus performance. The drivers think that the "Synthetic fuel buses by far outweigh in performance and power.. those that run on diesel". Some other adjectives used in describing the S2 buses are "smoother", "quieter", "faster" and "more power".

The fuel economy analysis in this report did not use the manual fuel logs since some entries in every log (each bus had a separate log) did not contain the actual quantities of fuel that were filled. Instead, these entries simply indicated that the tank was completely filled.

A summary of the ETR is given in Table 1 below. No data was available for bus #532. Buses 531, 532 and 536 used the regular fuel, while 533, 534 and 537 used the Syntroleum S2 fuel. Note that the ETR data reflected fuel consumption of periods prior to the tests as well. This is because all the buses had a few thousand miles from being driven up to Alaska from the lower 48. Therefore, Table 1 is not an accurate indicator of the fuel consumption during the summer tests.

Table 1: Overall Fuel Economy (OFE) and Driving Fuel Economy (DFE) data of the buses.

Bus No	OFE (mpg)	DFE (mpg)	Fuel
531	5.41	5.44	R
536	6.46	6.54	R
532			R
533	5.85	5.89	S2
534	5.76	5.81	S2
537	6.51	6.61	S2

Table 2 lists the route pairings of the buses. For example, buses 531 and 533 were on the same route, covering a distance of 135 miles.

Table 2. Route pairings for the buses.

R Fuel	**S2-Fuel**	Approx. miles for Route
531	533	135
532	534	135
536	537	200

Analyses

A paired t-test was conducted on the buses (DFE data) with pairings as shown in Table 2. However, since there was no fuel economy data on 532, the t-test only had two pairs. The results (output from Excel[©]) are given in Table 3 below.

Table 3. Paired two sample t test for means of DFE

	Reg. Fuel	*S2 Fuel*
Mean	5.99	6.25
Variance	0.605	0.2592
Observations	2	2
Pearson Correlation	1	
Hypothesized Mean Difference	0	
df	1	
t Stat	-1.36842	
P(T<=t) one-tail	0.200879	
t Critical one-tail	6.313749	
P(T<=t) two-tail	0.401758	
t Critical two-tail	12.70615	

From the test, it is apparent that there is no difference in the mean fuel consumption since the t stat (-1.37) is well below the critical two tail t (12.7). It should be pointed out that when the sample size is small, it becomes very challenging to prove that two groups have different means since the t critical is typically high. For the sake of a quick interpretation, t-critical can be thought of as the required distance (in terms of the standard deviations of the groups) between the means of the two groups. In this case (sample size 2), the two means have to be 12.7 standard deviations apart for them to be deemed different. As sample size increase, t critical reduces.

[©] Microsoft Corp.

The engine oil samples from the buses were subjected to spectrochemical analysis to obtain additional information on engine performance. The results are summarized in Table 4 below (see Appendix for raw data). Dusty roads are apparent from the high levels of Si in oil from most of the buses. Bus #532 was also noted to have had excessive blowby since it was received.

Table 4. Oil analysis report

Bus #	Oil Analysis Report	Fuel Type
531	High: Si	Regular
532	High: Si, Cu	
536	OK	
533	OK	S2
534	High: Si	
537	High: Si	

The oil analysis report does not provide any insight into the fuel consumption behavior of the buses.

Conclusion

The following can be concluded based on the above analyses.

- The fuel economy of the buses on the two different fuel types is statistically similar. The lack of data on fuel economy is one reason for the similarity of the means. Note that in the two bus pairs, S2 buses had better fuel economy than the buses on regular fuel.
- Oil analysis does not provide any insight into the fuel consumption of buses

Better overall performance of S2 buses (in comparison to regular diesel buses) is also indicated from the bus driver comments.

Recommendation

For the fuel test results to be meaningful, it is strongly recommended that more tests be conducted. Increasing the sample size will allow differences in fuel consumption to be conclusively proven. Currently, despite both S2 pairs showing better mileage than regular buses, the two groups are statistically similar. Besides, better fuel economy data needs to be collected since the current data is not entirely representative of the summer tests. Accurate data could further highlight differences in fuel economy.

Cat Electronic Technician 2004A
Trip Segment - Fleet

10/18/2004 8:02 AM

531

* go to manual log for starting mileage

C7 Truck (KAL23694)

Parameter	**Value**
Vehicle ID	48982
Engine Serial Number	KAL23694
ECM Serial Number	34336364IE
Personality Module Part Number	2517442-00
Personality Module Release Date	MAR04
Personality Module Code	29
ECM Date/Time	1/1/2036+

Description	**Value**	**Unit**
Time	681:20	hours
Driving Time	650:47	hours
Distance	15195.1	Miles
Fuel	2811.0	Gal
Overall Fuel Economy	5.41	MPG
Driving Fuel Economy	5.44	MPG
Idle Time	30:32	hours
Idle Fuel	17.4	Gal
% Idle Time	4	%
PTO Time	0:00	hours
PTO Fuel	0.0	Gal
% PTO Time	0	%
Avg Load Factor	Invalid Data	%
Avg Vehicle Speed	22.3	MPH
Avg Driving Speed	23.3	MPH
Max Vehicle Speed	77	MPH
Max Engine Speed	2718	RPM
Start Time	0:00	hours
End Time	681:21	hours
Start Odometer	0.0	Miles
End Odometer	15195.1	Miles

Cat Electronic Technician 2004A
Trip Segment - Fleet

#533

10/12/2004 2:22 PM

C7 Truck (KAL24396)

Parameter	Value
Vehicle ID	48984
Engine Serial Number	KAL24396
ECM Serial Number	34736360IE
Personality Module Part Number	2517442-00
Personality Module Release Date	MAR04
Personality Module Code	29
ECM Date/Time	1/1/2036+

Description	Value	Unit
Time	594:24	hours
Driving Time	566:12	hours
Distance	13897.0	Miles
Fuel	2374.8	Gal
Overall Fuel Economy	5.85	MPG
Driving Fuel Economy	5.89	MPG
Idle Time	28:12	hours
Idle Fuel	14.8	Gal
% Idle Time	5	%
PTO Time	0:00	hours
PTO Fuel	0.0	Gal
% PTO Time	0	%
Avg Load Factor	Invalid Data	%
Avg Vehicle Speed Current driver trip	23.4	MPH
Avg Driving Speed Not lugging under	24.5 1200 RPM	MPH
Max Vehicle Speed	73	MPH
Max Engine Speed	2813	RPM
Start Time	0:00	hours
End Time	594:23	hours

534

Cat Electronic Technician 2004A
Trip Segment - Fleet

10/13/2004 9:58 AM

C7 Truck (KAL24760)

Parameter	**Value**
Vehicle ID	48985
Engine Serial Number	KAL24760
ECM Serial Number	35236146IE
Personality Module Part Number	2517442-00
Personality Module Release Date	MAR04
Personality Module Code	29
ECM Date/Time	1/1/2036+

Description	**Value**	**Unit**
Time	488:32	hours
Driving Time	455:35	hours
Distance	11349.7	Miles
Fuel	1971.0	Gal
Overall Fuel Economy	5.76	MPG
Driving Fuel Economy	5.81	MPG
Idle Time	32:57	hours
Idle Fuel	18.9	Gal
% Idle Time	7	%
PTO Time	0:00	hours
PTO Fuel	0.0	Gal
% PTO Time	0	%
Avg Load Factor	Invalid Data	%
Avg Vehicle Speed	23.2	MPH
Avg Driving Speed	24.9	MPH
Max Vehicle Speed	74	MPH
Max Engine Speed	2820	RPM
Start Time	0:00	hours
End Time	488:33	hours
Start Odometer	0.0	Miles
End Odometer	11349.7	Miles

Cat Electronic Technician 2004A
Trip Segment - Fleet

536

10/14/2004 12:56 PM

C7 Truck (KAL24268)

Parameter	**Value**
Vehicle ID	48987
Engine Serial Number	KAL24268
ECM Serial Number	35436438IE
Personality Module Part Number	2517442-00
Personality Module Release Date	MAR04
Personality Module Code	29
ECM Date/Time	10/14/2004 3:00:03 PM

Description	**Value**	**Unit**
Time	664:57	hours
Driving Time	611:32	hours
Distance	14852.5	Miles
Fuel	2299.1	Gal
Overall Fuel Economy	6.46	MPG
Driving Fuel Economy	6.54	MPG
Idle Time	49:57	hours
Idle Fuel	27.0	Gal
% Idle Time	8	%
PTO Time	3:27	hours
PTO Fuel	2.0	Gal
% PTO Time	1	%
Avg Load Factor	Invalid Data	%
Avg Vehicle Speed	22.3	MPH
Avg Driving Speed	24.3	MPH
Max Vehicle Speed	72	MPH
Max Engine Speed	2763	RPM
Start Time	0:00	hours
End Time	664:57	hours
Start Odometer	0.0	Miles
End Odometer	14852.5	Miles

Cat Electronic Technician 2004A
Trip Segment - Fleet

537

10/13/2004 9:35 AM

C7 Truck (KAL24425)

Parameter	**Value**
Vehicle ID	48988
Engine Serial Number	KAL24425
ECM Serial Number	34536131IE
Personality Module Part Number	2517442-00
Personality Module Release Date	MAR04
Personality Module Code	29
ECM Date/Time	1/1/2036+

Description	**Value**	**Unit**
Time	708:47	hours
Driving Time	639:38	hours
Distance	15541.3	Miles
Fuel	2387.1	Gal
Overall Fuel Economy	6.51	MPG
Driving Fuel Economy	6.61	MPG
Idle Time	67:30	hours
Idle Fuel	36.4	Gal
% Idle Time	10	%
PTO Time	1:38	hours
PTO Fuel	0.9	Gal
% PTO Time	0	%
Avg Load Factor	Invalid Data	%
Avg Vehicle Speed	21.9	MPH
Avg Driving Speed	24.3	MPH
Max Vehicle Speed	73	MPH
Max Engine Speed	2789	RPM
Start Time	0:00	hours
End Time	708:48	hours
Start Odometer	0.0	Miles
End Odometer	15541.3	Miles

20 gal a day

5124
3624
1500 miles

Fuel Log

1500 gal month

Bus # 537a

		Fuel				Fuel		
	Date	Mileage	Gallons	Fuelers Intl	Date	Mileage	Gallons	Fuelers Intl
	7-6	3624	22	JT				
# 216	7-7	4052	15	JJ				
215	7-9	4265	19	JJ				
	7-10	4480	26	JJ				
204	7-11	4698	25	DD				
	7-12	4903	29					
227	7-14	5124	25	JV				

22
6)133
12
13

133
22
155 gallons

1500

15gal day

Fuel Log

Bus # 533

	Fuel				Fuel		
Date	Mileage	Gallons	Fuelers Intl	Date	Mileage	Gallons	Fuelers Intl
5/24/04		55					
5/25/04		25					
5/30/04		30					
6/24/04	4713	40	JM				
6-27	4983	Full	BB				
6-29	5262	Full	[illegible]				
7-2	5521	Full	[illegible]				
7/3	5731	19	VK				
7/5	6060	full	AY				
7/8	6465	22	CP				

15 gal day 1723 ~~286~~ 195

Fuel Log

Bus # 532

Date	Fuel Mileage	Gallons	Fuelers Intl	Date	Fuel Mileage	Gallons	Fuelers Intl
6-24-04	3,136	58	JM				
6-25-04	3,137	Full	JP				
6-27	3271	Full 28	BB				
6-29	3405	Full	JJ				
7-1	3540	Full 20					
7-2	3674	19	CR				
7-3	3808	23	CR				
7/4	3942	20	KK				
7/5	4077	25	JJ				
7/8	4346	22	JJ				
7/10	4481	Full 10	JVM				
7-11	4615	Full 10	BB				
7-12	4750	28	MVH				
7-13	4859	Full 10	JJ				

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4943 NW FRONT AVENUE
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(800) 770-4128 FAX (503) 286-1562

CUSTOMER NO.: 2001902
UNIT NO.: 537A
DESCRIPTION: ENGINE
END USER: WILLIAM WARD
ARAMARK DPR
END USER LOCATION: DENALI PARK, AK 99755

MAKE:
MODEL
OIL BRAND:
OIL TYPE:
SERIAL NO.:
FUEL TYPE:

NO. COPIES 2

SAMPLE DATA			SPECTROCHEMICAL ANALYSIS (ppm)																				PHYSICAL PROPERTIES					
LAB#	SAMPLE DATE RECEIPT DATE	TIME ON OIL TIME ON UNIT	IRON	CHROMIUM	LEAD	COPPER	TIN	ALUMINUM	NICKEL	SILVER	SILICON	BORON	SODIUM	MAGNESIUM	CALCIUM	BARIUM	PHOSPHORUS	ZINC	MOLYBDENUM	TITANIUM	VANADIUM	POTASSIUM	FUEL (%VOL)	VIS @ 40 C cSt	VIS @ 100 C cSt	WATER (%VOL)	SOOT/SOLIDS (%WT)	GLYCOL
57228 ABNORMAL	08/18/2004 08/31/2004	11577	38	2	1	10	0	7	0	0	30 A	32	14	307	2807	0	1276	1360	0	0	0	0	<1	N/A	12.46	0	0.2	NEG

LAB#	ADDITIONAL TESTS		
	F-SOOT	TBN	SAE
57228	0.2	7.6	30

GRAPHICAL ANALYSIS

No History to Graph

Key	
A: Abnormal	C: Critical

LAB#	ANALYSIS RECOMMENDATIONS
57228	SILICON LEVEL IS HIGH - RECOMMEND CHECK AIR INTAKE SYSTEM. NOTE: OTHER TEST RESULTS ARE ACCEPTABLE. NO ABNORMAL WEAR DETECTED.

ANALYST-TAE

JEFF MULHOLLAND
INLET PETROLEUM
ANCHORAGE, AK 99501

WILLIAM WARD
ARAMARK DPR
P O BOX 87
DENALI PARK ROAD
DENALI PARK, AK 99755

THE FOLLOWING INFORMATION HAS BEEN PROVIDED TO ASSIST IN THE INTERPRETATION OF YOUR OIL ANALYSIS.

WEAR ELEMENTS

These metals indicate wear on particular components of an individual unit. The particles of these metals will indicate a wear problem on the microscopic level before the problem can be detected by conventional means. The existence of a wear problem is determined not only by absolute values of metals, but more importantly a relative increase or trend in one or more of these metals.

WEAR METAL SOURCES

Iron	Cylinders, gears, rings, crankshafts, liners, bearings, housings, rust.
Chromium	Rings, roller/taper bearing, rods, platings.
Lead	Bearing overlays, additive in gear oil and gasoline.
Copper	Bushings, bearings, thrust-washers, friction plates, copper heat exchangers, and oil additive.
Tin	Bearings, bushings, pistons platings.
Aluminum	Pistons, bearings, pumps, blowers, rotors, thrust-washers.
Nickel	Valves.
Silver	Bearings, bushings, platings.
Manganese	Trace elements in liners and rings, additive in gasoline.
Titanium	Trace element.
Vanadium	Trace element.

CONTAMINANTS

These elements can be an indication of contamination from outside the system. The source and amount of contamination can be determined by comparison to a previous, non-contaminated sample of the same unit. Specific tests for some contaminants can supplement the analysis.

CONTAMINANT SOURCES

Silicon	Element used to determine the level of airborne dirt and abrasives in the oil (sometimes used as an anti-foam agent).
Boron	Present in most permanent anti-freeze systems (sometimes used as an oil additive).
Sodium	Present in most permanent anti-freeze systems (sometimes used as an oil additive).
Potassium	Present in most permanent anti-freeze systems.

WATER BY KARL FISCHER

Reports percent water (ASTM D-1744 or D-6304).

GLYCOL

A specific test for the presence of Glycol (Anti-Freeze) in an oil (ASTM D-2982).

PARTICLE COUNT

Determines the level of cleanliness in hydraulic fluids.

ADDITIVES

These elements are blended into the oil in different forms and quantities by the manufacturer. The additive package in an oil will vary depending on the type of oil.

ADDITIVE SOURCES

Magnesium	Dispersent/Detergent additive.
Calcium	Dispersent/Detergent additive.
Barium	Dispersent/Detergent additive.
Phosphorus	Anti-Wear additive.
Zinc	Anti-Wear additive.
Molybdenum	Anti-Wear additive.

FUEL DILUTION

Unburned fuel in the oil may signal fuel system leaks or incomplete combustion.

FUEL SOOT

A result of blow-by. High levels may indicate combustion problems or overextended drain intervals.

TOTAL BASE NUMBER

Measures the level of alkalinity in an oil. A decreasing total base number signals the need to change oil (ASTM D-4739).

VISCOSITY

The kinematic viscosity (ASTM D-445) determined at 40° C and/or 100° C is a measure of the flow rate of an oil in relation to time. This data is used to assign an SAE grade to an oil.

LubeWatch Test Descriptions	Test Method
Chlorine	X-Ray Florescence
Fat (%)	FTIR
Fuel Dilution	ASTM D-3524
Fuel Dilution	Fuel Dilution Meter
Fuel Soot	FTIR
Glycol	ASTM D-2982
Nitration	FTIR
Oxidation	FTIR
Particle Count	ASTM D-4438-85
RBOT	ASTM D-2272
Spectrochemical Analysis	Arc Emission
Sulfur	ASTM D-1552
Total Acid Number	ASTM D-664
Total Acid Number	ASTM D-974
Total Base Number	ASTM D-4739
Viscosity @ 40° C or 100° C	ASTM D-445
Water by Karl Fischer	ASTM D-1744
Water by Karl Fischer	ASTM D-6304
Water Separability	ASTM D-1401

SAE Viscosity Grades For Engine Oils
SAE J300 FEB 91

Viscosity, cSt at 100°		SAE Viscosity Grade
Min.	Max.	
3.8	-	0W
3.8	-	5W
4.1	-	10W
5.6	-	15W
5.6	-	20W
9.3	-	25W
5.6	<9.3	20
9.3	<12.5	30
12.5	<16.3	40
16.3	<21.9	50
21.9	<26.1	60

REPORT SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN APPROVAL OF THE LABORATORY.

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(800) LUBE-808

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CUSTOMER NO.: 2001902
UNIT NO.: 531
DESCRIPTION: ENGINE
END USER: WILLIAM WARD
ARAMARK DPR
END USER LOCATION: DENALI PARK, AK 99755

MAKE:
MODEL
OIL BRAND:
OIL TYPE:
SERIAL NO.:
FUEL TYPE:

NO. COPIES 2

SAMPLE DATA / SPECTROCHEMICAL ANALYSIS (ppm) / PHYSICAL PROPERTIES

LAB#	SAMPLE DATE RECEIPT DATE	TIME ON OIL TIME ON UNIT	IRON	CHROMIUM	LEAD	COPPER	TIN	ALUMINUM	NICKEL	SILVER	SILICON	BORON	SODIUM	MAGNESIUM	CALCIUM	BARIUM	PHOSPHORUS	ZINC	MOLYBDENUM	TITANIUM	VANADIUM	POTASSIUM	FUEL (%VOL)	VIS @ 40 C cSt	VIS @ 100 C cSt	WATER (%VOL)	SOOT/SOLIDS (%WT)	GLYCOL
57229 ABNORMAL	08/18/2004 08/31/2004	11998	37	3	5	13	0	6	0	0	26 A	33	15	249	2605	0	1212	1300	0	0	0	0	<1	N/A	13.00	0	0.2	NEG

ADDITIONAL TESTS

LAB#	F-SOOT	TBN	SAE
57229	0.2	6.3	40

GRAPHICAL ANALYSIS

No History to Graph

Key
A: Abnormal *C:* Critical

ANALYSIS RECOMMENDATIONS

LAB#	
57229	SILICON LEVEL IS HIGH - RECOMMEND CHECK AIR INTAKE SYSTEM. NOTE: OTHER TEST RESULTS ARE ACCEPTABLE. NO ABNORMAL WEAR DETECTED.

ANALYST-TAE

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P O BOX 87
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CUSTOMER NO.: 2001902
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MAKE:
MODEL
OIL BRAND:
OIL TYPE:
SERIAL NO.:
FUEL TYPE:

NO. COPIES 2

SAMPLE DATA / SPECTROCHEMICAL ANALYSIS (ppm) / PHYSICAL PROPERTIES

LAB#	SAMPLE DATE RECEIPT DATE	TIME ON OIL TIME ON UNIT	IRON	CHROMIUM	LEAD	COPPER	TIN	ALUMINUM	NICKEL	SILVER	SILICON	BORON	SODIUM	MAGNESIUM	CALCIUM	BARIUM	PHOSPHORUS	ZINC	MOLYBDENUM	TITANIUM	VANADIUM	POTASSIUM	FUEL (%VOL)	VIS @ 40 C cSt	VIS @ 100 C cSt	WATER (%VOL)	SOOT/SOLIDS (%WT)	GLYCOL
57227 ABNORMAL	08/18/2004 08/31/2004	10907	53	4	5	239 A	0	8	0	1	32 A	32	16	262	2676	0	1212	1277	0	0	0	0	<1	N/A	12.77	0	0.3	NEG

This unit has had excessive blowby
Since we recieved it

ADDITIONAL TESTS

LAB#	F-SOOT	TBN	SAE
57227	0.3	5.6	40

GRAPHICAL ANALYSIS

No History to Graph

Key
A: Abnormal C: Critical

ANALYSIS RECOMMENDATIONS

LAB#	
57227	SILICON LEVEL IS HIGH - RECOMMEND CHECK AIR INTAKE SYSTEM. NOTE: COPPER LEVEL APPEARS TO BE HIGH. COPPER SOURCES: BEARING/BUSHINGS, CAM WEAR, OIL COOLER. NOTE: OTHER TEST RESULTS ARE ACCEPTABLE. RECOMMEND CHANGE LUBE OIL AND LUBE OIL FILTER, IF NOT ALREADY DONE. RECOMMEND RESAMPLE TO CHECK WEAR TREND.

ANALYST-TAE

JEFF MULHOLLAND
INLET PETROLEUM
ANCHORAGE, AK 99501

WILLIAM WARD
ARAMARK DPR
P O BOX 87
DENALI PARK ROAD
DENALI PARK, AK 99755

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(800) 770-4128 FAX (503) 286-1562

CUSTOMER NO.: 2001902
UNIT NO.: 533
DESCRIPTION: ENGINE
END USER: WILLIAM WARD
ARAMARK DPR
END USER LOCATION: DENALI PARK, AK 99755

MAKE:
MODEL
OIL BRAND:
OIL TYPE:
SERIAL NO.:
FUEL TYPE:

NO. COPIES 2

SAMPLE DATA			SPECTROCHEMICAL ANALYSIS (ppm)																			PHYSICAL PROPERTIES					
LAB#	SAMPLE DATE RECEIPT DATE	TIME ON OIL TIME ON UNIT	IRON	CHROMIUM	LEAD	COPPER	TIN	ALUMINUM	NICKEL	SILVER	SILICON	BORON	SODIUM	MAGNESIUM	CALCIUM	BARIUM	PHOSPHORUS	ZINC	MOLYBDENUM	TITANIUM	VANADIUM	POTASSIUM	FUEL (%VOL)	VIS @ 40 C cSt	VIS @ 100 C cSt	WATER (%VOL)	SOOT/SOLIDS (%WT)	GLYCOL
57553 NORMAL	08/18/2004 09/01/2004	11352	29	2	1	8	0	6	0	0	22	34	15	257	2942	0	1332	1591	0	0	0	0	<1	N/A	12.37	0	0.1	NEG

LAB# ADDITIONAL TESTS

LAB#	F-SOOT	TBN	SAE
57553	0.1	7.3	30

GRAPHICAL ANALYSIS

No History to Graph

Key	
A: Abnormal	C: Critical

LAB# ANALYSIS RECOMMENDATIONS

57553 RESULTS OF TEST PERFORMED INDICATE NO CORRECTIVE ACTION REQUIRED. INCLUDE COMPONENT INFORMATION. MAKE/MODEL, OIL TYPE, MILES, ETC.

ANALYST-G2

JEFF MULHOLLAND
INLET PETROLEUM
ANCHORAGE, AK 99501

WILLIAM WARD
ARAMARK DPR
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DENALI PARK ROAD
DENALI PARK, AK 99755

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PORTLAND, OR 97210
(800) 770-4128 FAX (503) 286-1562

CUSTOMER NO.: 2001902
UNIT NO.: 534
DESCRIPTION: ENGINE
END USER: WILLIAM WARD
ARAMARK DPR
END USER LOCATION: DENALI PARK, AK 99755

MAKE:
MODEL
OIL BRAND:
OIL TYPE:
SERIAL NO.:
FUEL TYPE:

NO. COPIES 2

SAMPLE DATA			SPECTROCHEMICAL ANALYSIS (ppm)																		PHYSICAL PROPERTIES						
LAB#	SAMPLE DATE RECEIPT DATE	TIME ON OIL TIME ON UNIT	IRON	CHROMIUM	LEAD	COPPER	TIN	ALUMINUM	NICKEL	SILVER	SILICON	BORON	SODIUM	MAGNESIUM	CALCIUM	BARIUM	PHOSPHORUS	ZINC	MOLYBDENUM	TITANIUM	VANADIUM	POTASSIUM	FUEL (%VOL)	VIS @ 40 C cSt	VIS @ 100 C cSt	WATER (%VOL)	SOOT/SOLIDS (%WT)	GLYCOL
57226	08/18/2004	8795	46	4	1	13	0	8	0	0	32	33	15	283	2732	0	1261	1323	1	0	0	0	<1	N/A	12.45	0	0.2	NEG
ABNORMAL	08/31/2004										A																	

LAB#	F-SOOT	TBN	SAE
57226	0.2	7.0	30

ADDITIONAL TESTS

GRAPHICAL ANALYSIS

No History to Graph

Key	
A: Abnormal	C: Critical

JEFF MULHOLLAND
INLET PETROLEUM
ANCHORAGE, AK 99501

ANALYSIS RECOMMENDATIONS

LAB#	
57226	SILICON LEVEL IS HIGH - RECOMMEND CHECK AIR INTAKE SYSTEM. NOTE: OTHER TEST RESULTS ARE ACCEPTABLE. NO ABNORMAL WEAR DETECTED.

ANALYST: TAE

WILLIAM WARD
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(800) 770-4128 FAX (503) 286-1562

CUSTOMER NO.: 2001902
UNIT NO.: 536
DESCRIPTION: ENGINE
END USER: WILLIAM WARD
ARAMARK DPR
END USER LOCATION: DENALI PARK, AK 99755

MAKE:
MODEL
OIL BRAND:
OIL TYPE:
SERIAL NO.:
FUEL TYPE:

NO. COPIES 2

SAMPLE DATA / SPECTROCHEMICAL ANALYSIS (ppm) / PHYSICAL PROPERTIES

LAB#	SAMPLE DATE RECEIPT DATE	TIME ON OIL TIME ON UNIT	IRON	CHROMIUM	LEAD	COPPER	TIN	ALUMINUM	NICKEL	SILVER	SILICON	BORON	SODIUM	MAGNESIUM	CALCIUM	BARIUM	PHOSPHORUS	ZINC	MOLYBDENUM	TITANIUM	VANADIUM	POTASSIUM	FUEL (%VOL)	VIS @ 40 C cSt	VIS @ 100 C cSt	WATER (%VOL)	SOOT/SOLIDS (%WT)	GLYCOL
57230 NORMAL	08/18/2004 08/31/2004	11051	14	1	0	1	0	4	0	0	10	58	12	272	2641	0	1270	1302	0	0	0	0	<1	N/A	14.46	0	0.1	NEG

ADDITIONAL TESTS

LAB#	F-SOOT	TBN	SAE
57230	0.1	8.9	40

GRAPHICAL ANALYSIS

No History to Graph

Key
A: Abnormal C: Critical

ANALYSIS RECOMMENDATIONS

LAB#	
57230	RESULTS OF TEST PERFORMED INDICATE NO CORRECTIVE ACTION REQUIRED.

ANALYST-TAE

JEFF MULHOLLAND
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Investigation of the Engine Problems of WMATA Bus 2056

Final Report

Reporting Period: July 2001 – June 2006

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Report Issued
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DISCLAIMER

ABSTRACT

This report documents the circumstances and events that led to Washington Metropolitan Area Transit Authority (WMATA) Bus 2056 needing engine repair service during the late phases of its demonstration of ultra-clean Fischer-Tropsch (F-T) diesel fuel within the WMATA bus fleet. Since the purpose of the demonstration was to evaluate the compatibility of the F-T fuel with the bus and engine fuel systems, this report focuses on analysis of the condition of all the engine's fuel injectors after running about six months on F-T fuel.

The initial round of engine service/diagnosis was not thorough enough to find all the problems in the engine that needed repair at that time. Therefore, the bus was returned to transit service when it was not in road-worthy condition. This situation led to operational problems on the road, additional engine diagnosis, an engine teardown, and further analysis of engine components, all of which are covered in this report.

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EXECUTIVE SUMMARY

During the Washington Metropolitan Area Transit Authority (WMATA) bus field demonstrations of Syntroleum ultra-clean Fischer-Tropsch (F-T) diesel fuel Bus 2056 experienced a failure of its turbocharger, a component of the engine that had been recalled by the manufacturer at the US Environmental Protection Agency's behest. After replacement of the turbocharger the engine was still not running properly, so all four fuel injectors were removed and inspected. One injector, in cylinder No. 4, had a broken tip, so all four injectors were replaced. The bus was then returned to service without any further testing or diagnosis to verify that it was in road-worthy condition. Subsequent problems ensued on the road, and a compression check showed that cylinder No. 4 had no compression. Teardown of the engine revealed a burned exhaust valve in cylinder No. 4.

ICRC analyzed the series of events surrounding and leading up to the engine problems of Bus 2056, as well as the replaced parts themselves, particularly the fuel injection nozzles. The failure of the turbocharger's oil seal introduced oil into the engine's intake manifold. This oil likely contributed to the failure of cylinder number 4's fuel injector tip; although it is possible that the failure of the fuel injector, which is by no means a rare occurrence for these engines in the WMATA fleet, may have been unrelated. Regardless of the cause, the broken nozzle tip resulted in a concentrated and undispersed jet of fuel being directed at one of the cylinder No. 4 exhaust valves that eventually burned through the valve. The broken fuel injector was replaced, but with the valve burned–through, the cylinder no longer had enough compression to ignite and burn the diesel fuel when the bus was put back in service. This unburned fuel was pumped out of cylinder No. 4 and down the exhaust system where it collected in the diesel oxidation catalyst. Once the catalyst became hot, the collected fuel burned within the exhaust system of the bus.

To investigate the condition of Bus 2056's three used, but unbroken, fuel injectors, the injectors were sent to Southwest Research Institute for flow testing. Southwest Research Institute compared the fuel flow rates from the three "good" injectors and one new baseline injector. They found that one used injector had a 20% reduction in flow, and the others showed no degradation of their flow rates. Syntroleum examined all four of Bus 2056's injector-nozzles (including the broken-tip injector from cylinder No. 4) using a Scanning Electron Microscope (SEM) at the University of Tulsa. Syntroleum found that deposits, with a composition consistent with the non-combustible (i.e. ash) components of the engine oil additive package had accumulated and partially restricted some of the nozzle holes in some of the injectors, a condition that was discovered in some nozzle holes of injectors run in dynamometer-based fuel-system durability tests as part of this project. It is possible that such deposits could have lead to an increase in pressure within the nozzle sac, which may have contributed to the nozzle-tip failure in cylinder No. 4.

The injector nozzle-hole deposit phenomenon, and the indirect role that fuel properties and/or dispersant fuel additives may play in reducing or promoting the tendency for such deposits to accumulate in the nozzle holes of some engines, is the subject of follow-on work.

INTRODUCTION

During the WMATA bus field demonstration of Syntroleum ultra-clean Fischer-Tropsch (F-T) diesel fuel, Bus 2056 in the WMATA fleet experienced a turbocharger failure at 227,480 odometer miles. At 227,480 miles Bus 2056 had been operating on Ultra-Clean F-T fuel for six months and 19,859 miles. The turbocharger was replaced, and during service a fuel injector tip was found to be broken off. The problem with the fuel injector prompted the replacement of all four injectors. Following the fuel injector replacement, Bus 2056 was returned to service without any additional testing or diagnosis to verify that the bus was in road-worthy condition.

It was realized almost immediately that the engine had additional problems that had not been diagnosed during the just-finished service. A cylinder compression-check revealed that cylinder No. 4 had no compression. The engine was scheduled for teardown, which ultimately revealed that cylinder No. 4 had a burned exhaust valve. A complete analysis of the engine's problems was performed, and is described in this report.

REPLACEMENT OF THE TURBOCHARGER AND INJECTORS

Turbocharger failures are certainly not uncommon on WMATA's Detroit Diesel Series 50 bus engines. The WMATA division responsible for this ultra-clean F-T fuel demonstration has 49 buses with the DDC Series 50 engines. All of the buses have had their turbochargers replaced at least once, and 30 of the 49 have had their turbochargers replaced a second time as of the time of this incident with Bus 2056.

Detroit Diesel Series 50 four-cylinder engines apparently have a very high turbocharger failure rate in overall transit bus service. Detroit Diesel Corporation (DDC) issued a recall notice for Series 50 bus engine turbochargers and particulate filters from the 2001 through 2004 model years (http://www.epa.gov/otaq/cert/eng-recall/ddc1.htm). The current (2006) DDC website http://www.detroitdiesel.com/markets/on-highway/motorcoach/index.asp no longer lists the Series 50 engine as available for installation in new transit-bus or motorcoach service. Two Mercedes Benz engines, the MBE4000 and the MBE900 are now listed on the DDC website for motorcoach service in the lower power ranges than the DDC Series 60 six-cylinder engine, which is still available.

Bus 2056 was sent to a Detroit Diesel authorized repair facility for replacement of the turbocharger, under warranty according to WMATA's engineering contact for this project. Replacement of the turbocharger did not correct all of the problems being experienced by the engine. Therefore, all 4 injectors were removed for inspection. The injector in cylinder No. 4 was found to have a broken tip. The broken tip is shown in Figures 1 through 3. It is believed, as will be discussed, that the turbocharger failure may have contributed to this injector failure.

Injector failures are also fairly common in these engines. Of the 49 buses referred to above, 10 of those have also had injector failures this year, similar to the failure of cylinder No. 4 injector on Bus 2056. All four of the injectors in Bus 2056 were replaced. The injectors removed, which had run 19,859 miles on Syntroleum fuel during the demonstration, were subsequently obtained from the DDC service facility, but the cylinder numbers they had been used in, other than the broken injector from cylinder No. 4, could no longer be determined. These injectors were retained by ICRC for further analysis, as will be described.

Figure 1: Broken injector tip

Figure 2: Broken injector tip

Figure 3: Broken injector tip, showing nozzle sac, and nozzle needle

With the discovery of the broken fuel injector tip a decision was made to replace all four injectors. After this service, Bus 2056 was returned to WMATA, apparently without a cylinder compression-check being done. It is speculated that when the bus was returned to service with no compression in the No. 4 cylinder, the injected fuel was not burned. The unburned fuel from cylinder No. 4 passed through the exhaust valve, into the exhaust system and into the diesel oxidation catalyst. The collecting fuel in the catalyst and the heating of the exhaust system resulted in the fire. Bus 2056 was removed from the line and the engine was scheduled for teardown and rebuild. The teardown revealed that the exhaust valve in cylinder No. 4 had been subjected to an essentially uncontrolled, concentrated "jet" of poorly dispersed fuel from the broken injector tip. This fuel-jet acted like a flame-cutting torch, and it cut or melted a large hole in the valve head. This caused cylinder No. 4 to have no compression, which was apparently not recognized by the service personnel at the service facility.

ENGINE TEARDOWN

The engine of Bus 2056 was torn down to determine the problems and conditions leading to the exhaust system fire. The teardown was preformed at the WMATA rebuild shop by a certified diesel mechanic. During the teardown a large amount of oil was found throughout the intake manifold and the entire induction system, as shown in Figures 4 and 5. This oil is believed to be crankcase oil that entered the induction system when the turbocharger and its oil seal failed.

Figure 4: One of the port-connections of the intake manifold with crankcase oil from the turbocharger failure

Figure 5: Air Inlet of the intake manifold with crankcase oil from the turbocharger failure

The cylinder head was removed and it was obvious that one of the exhaust valves of No. 4 cylinder had a large hole burned in the valve. The burned valve is shown in Figures 6 through 8. The broken nozzle tip had blasted the virtually un-dispersed fuel-jet directly toward the (now-burned) valve. The fuel-jet acted as a torch and cut a hole in the valve.

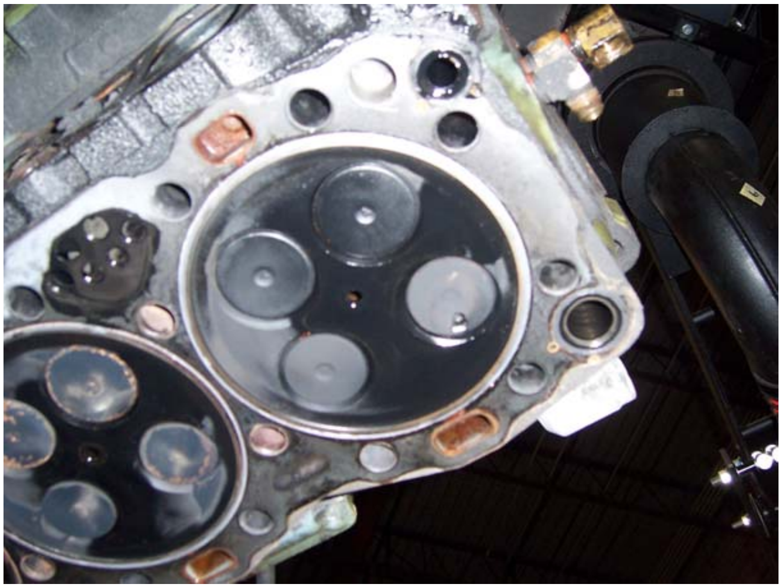

Figure 6: Burned exhaust valve in cylinder No. 4

Figure 7: Burned exhaust valve

Figure 8: Burned exhaust valve

After the turbocharger and injectors were replaced, the bus was put back in service. The hole in the valve caused the lack of compression in the cylinder. Without compression the cylinder was not able to fire. However, fuel continued to be injected into cylinder No. 4. All of the unburned fuel was then pushed out through the exhaust valves and into the exhaust system. The unburned fuel collected in the oxidation catalyst. Once the catalyst heated up, the unburned fuel ignited.

The injectors that were in the engine at the time of teardown were all in perfect condition (Figure 9). These injectors had just been replaced by the DDC service facility at 227,480 miles when the turbocharger was replaced.

Figure 9: Almost-new injectors in the engine when it was torn down

INJECTOR FLOW TESTS

The three still-functional injectors from Bus 2056 that had run 19,859 miles on Syntroleum S-2 fuel during the demonstration were sent to Southwest Research Institute® (SwRI®) for flow tests on S-2 fuel to determine whether their nozzle-holes were partially fouled. The test report from SwRI is included in the Appendix. The key finding from these tests was that one of the three still-functional injectors had its flowrate reduced by about 20% compared to a new, never-used injector (from the DDC parts supply system) which was tested to provide a baseline flowrate. The other two used injectors had measured flowrates 3% and 4% higher than that of the new baseline injector, indicating no significant fouling.

SCANNING ELECTRON MICROSCOPE (SEM) ANALYSIS OF INJECTOR NOZZLES

After flow-testing of the 3 used (and 1 new reference) injectors, all four nozzles that had run on F-T fuel, including the cylinder No. 4 broken-tip nozzle (along with the new reference injector nozzle), were sent to Syntroleum for SEM analysis at the University of Tulsa, in the laboratory of Dr. Winton Cornell, Ph.D., Department of Geosciences; ECM analyses were conducted primarily by John Cox and Bob Freerks of Syntroleum..

RESULTS AND DISCUSSION

The failure of the turbocharger and the turbo oil seal on Bus 2056 at 227,480 miles appear to be relatively “common” events unrelated to fuel. Although turbos and their seals apparently fail fairly frequently on this type engine, a much greater than normal amount of engine oil does get into the engine combustion chambers as a result. And while injection nozzle failures are apparently also fairly common for this type engine, the excess oil could have had some influence on the ensuing injector tip failure under either (or both) of two scenarios.

First, the oil entering the cylinder through the induction system is relatively cool, and if drops or globs of oil hit the hot injector-nozzle tip they could have increased thermal stress on the nozzle tip, thus accelerating fatigue and the type of cracking that occurred on the cylinder No. 4 nozzle.

Second, as discussed in the Executive Summary of the report on the overall project, nozzle-hole fouling caused by deposits originating from the non-combustible (ash) components of the engine oil were recognized late in the project as a potential area of concern. As will be shown, there is evidence of some such deposits within the nozzle holes of the cylinder No. 4 injector. Fuel pressure inside the nozzle tip, which is intended to be extremely high (~15,000 psi) for good fuel atomization, etc., could have been increased to some extent, possibly contributing to earlier nozzle-tip fatigue failure. It should be noted that oil-derived nozzle-hole deposits have been much less of an issue in the DDC Series 50 engines, and indeed in all other engines used in this project, than in one particular Caterpillar C-7 engine run in the dynamometer-based fuel-system durability test.

SEM RESULTS FOR THE BROKEN NOZZLE TIP FROM CYLINDER NUMBER 4

Figures 10 through 12 are SEM images of the broken nozzle tip at greater magnification than Figures 1 through 3. Figures 10 through 12 show that the nozzle tip broke in the “plane” of two of the nozzle holes (which would have acted as stress concentrations), “splitting” these two nozzle holes open.

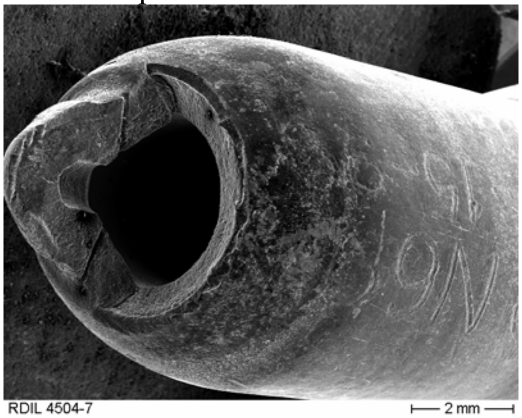

Figure 10: Broken tip of cylinder No. 4 nozzle

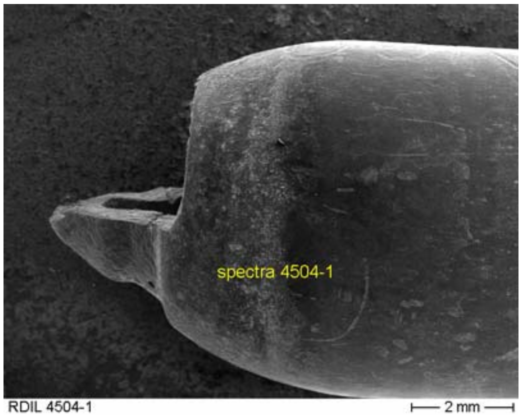

Figure 11: Broken tip of cylinder No. 4 nozzle

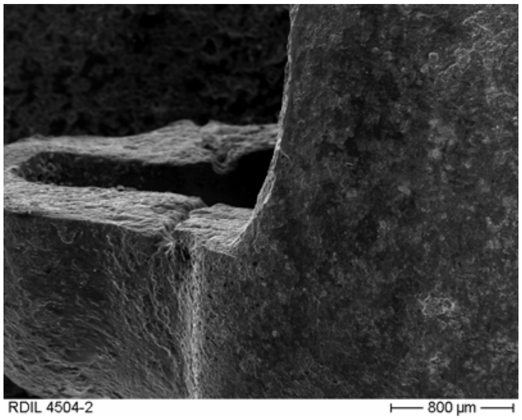

Figure 12: Broken tip of cylinder No. 4 nozzle

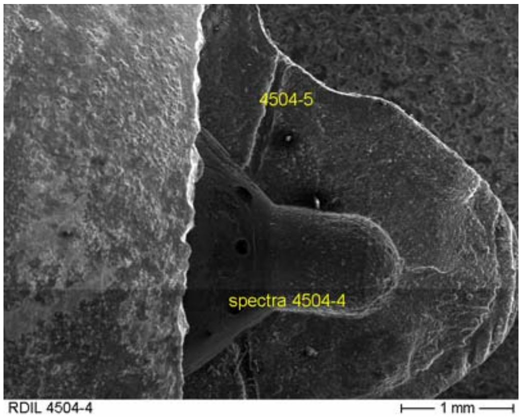

Figure 13: Broken tip of cylinder No. 4 nozzle

Although continued engine operation was attempted for a short period of time after the nozzle tip had broken off, and thus with fuel gushing uncontrolled from the broken nozzle, this nozzle with 2 split-open holes presents a unique opportunity to assess nozzle-hole deposit formation. Figure13 shows the approximate locations where SEM spectra were obtained to determine the composition of the surface material in those locations. Figure 14 shows one of these spectra, the one obtained in the nozzle sac area. The surface material in the sac area is predominantly iron, with only a slight amount of other elements present. By contrast, Figures 15 and 16 show that the deposit at the outlet of the "split-open" nozzle hole is consistent with the non-combustible (ash) material in the lubricating oil additive package.

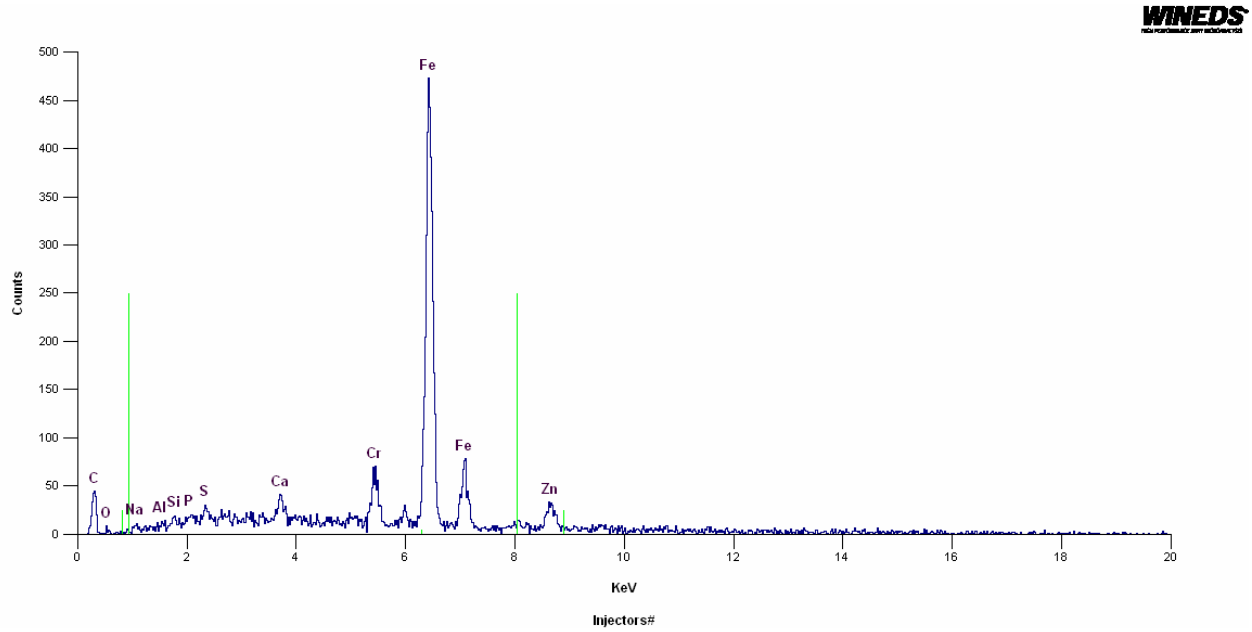

Figure 14: Spectra 4504-4. The composition of surface material in the sac area of the broken-tip nozzle is predominantly iron (i.e. minimal deposits are present)

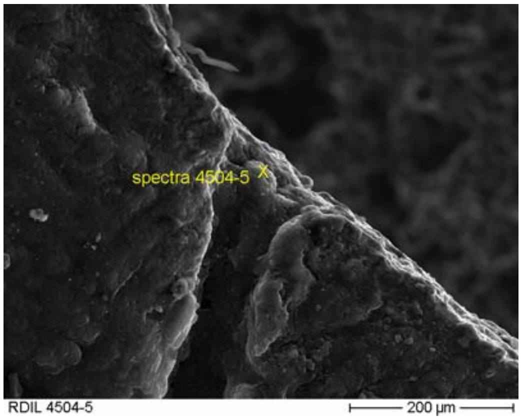

Figure 15: Deposit at the outlet of a nozzle hole in the broken-tip nozzle

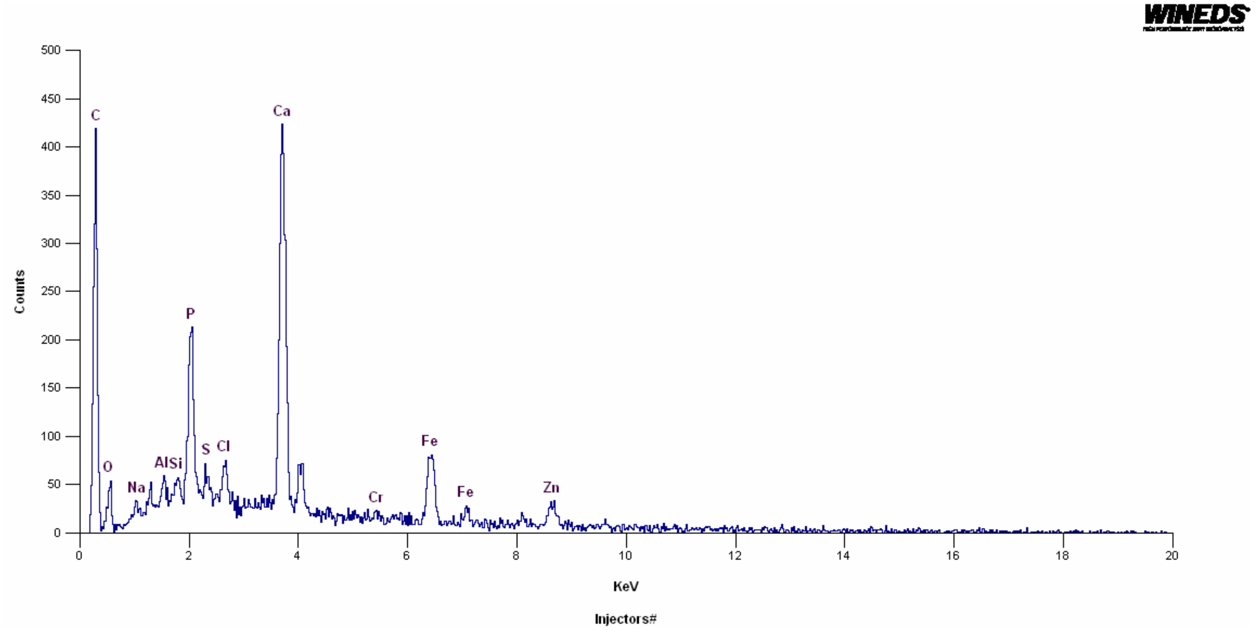

Figure 16: Spectra 4504-5. The composition of the deposit at the outlet of the nozzle hole in Figure 15 is consistent with the non-combustible (ash) material in the engine oil additive package

These results show that the deposits formed in the nozzle-holes of the engine in a bus operating in the field are similar to the deposits observed in the dynamometer-test engines. However, the results do not show that the deposits caused or contributed to the injector tip failure.

SEM RESULTS FOR THE OTHER NOZZLES

The other nozzles examined were a new reference nozzle purchased (as part of a "new" fuel injector assembly) from the DDC parts supply system and never run in an engine, and the remaining 3 nozzles that had run 19,859 miles on S-2 fuel in Bus 2056. Figure 17 shows one of the deposit-free holes in the new nozzle.

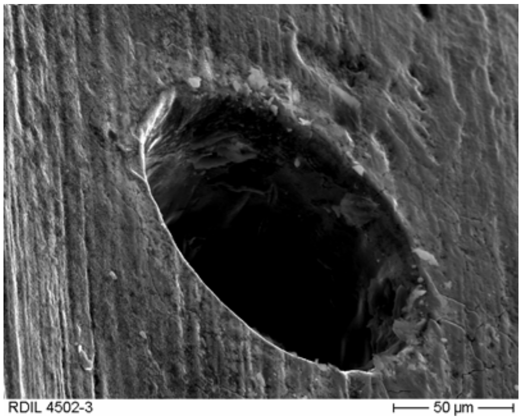

Figure 17: Hole of never-run (in an engine) new reference nozzle

The Figures 18 and 19 show representative holes from the two used nozzles that had measured flow rates 103% and 104%, respectively, of the new reference nozzle. Although these holes have quite different levels of deposits around them, their open flow areas are not much, if at all, affected by deposits.

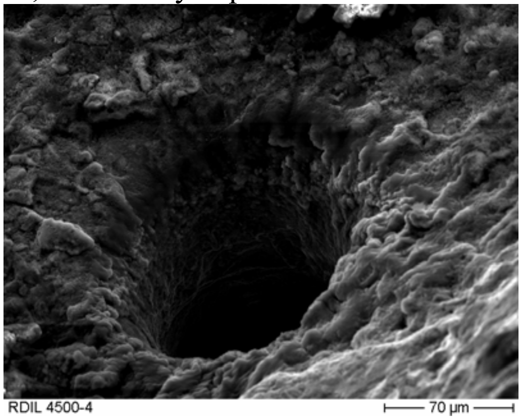

Figure 18: Hole of used nozzle with 103% flowrate of new reference nozzle

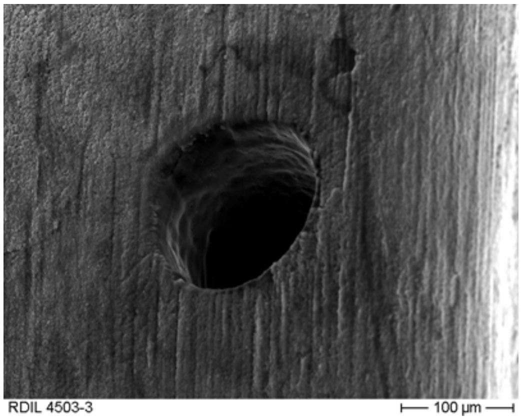

Figure 19: Hole of used nozzle with 104% flowrate of new reference nozzle

Figure 20 shows, at relatively high magnification, one hole of the Bus 2056 used nozzle that had a measured flowrate of 80% of the new reference nozzle, indicating a nozzle flow reduction of 20%. Figure 21 shows the composition of the deposit in the upper right of Figure 20, which is encroaching into the nozzle hole. This deposit is made up of the same materials as the non-combustible (ash) components of the engine oil additive package.

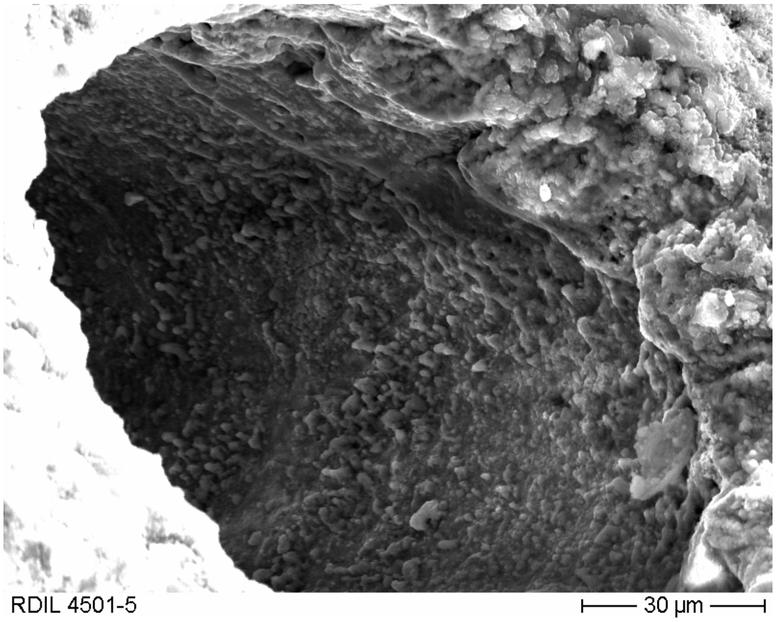

Figure 20: Hole of used nozzle with 80% of the flowrate of the new reference nozzle

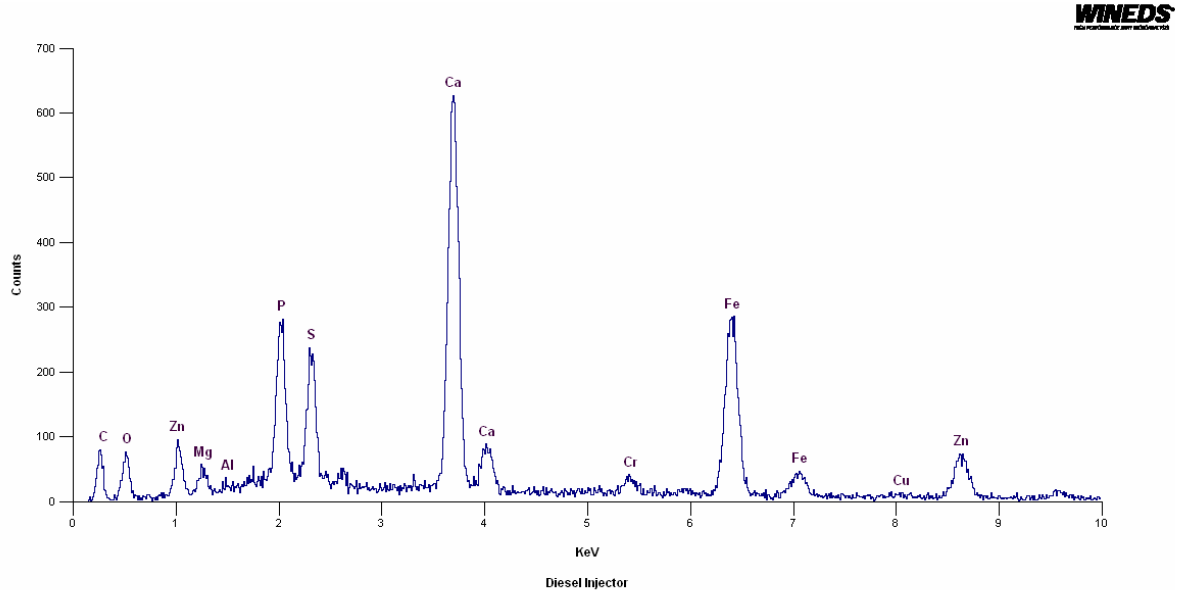

Figure 21: The composition of the deposit at the outlet of the nozzle hole in Figure 20 is consistent with the non-combustible (ash) material in the engine oil additive package

CONCLUSIONS

The turbocharger, plus a fuel-injector and exhaust-valve in the same cylinder, which needed replacement at 227,480 odometer miles on WMATA Bus 2056, constitute an unremarkable or commonplace event in light of the overall experience of the WMATA bus fleet with DDC Series 50 engines.

Some fuel-injector nozzle holes in the engine of Bus 2056 had engine-oil-ash derived deposits in and around their outlet ends, but not enough deposits to prevent or greatly restrict injected fuel from flowing. As was also observed with the dynamometer-tested DDC Series 50 engine in this project, the level of these deposits varied from essentially none to moderate accumulation, from cylinder to cylinder and from hole to hole of a given cylinder's injection nozzle.

The on-road operational problems that occurred after the turbocharger and fuel injectors were replaced were caused by insufficient follow-up testing and diagnosis. Had the service personnel re-tested the vehicle after the repair, they would have noticed that the number 4 cylinder was not producing any power. Under further investigation the burned exhaust valve would have been found. If the valve had been replaced before the bus went back to WMATA, there would have been no subsequent failure.

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December 7, 2005

VIA E-Mail to jwasylyk@icrcsolutions.com

John P. Wasylyk
Advanced Vehicle Technologies
Integrated Concepts & Research Corporation (ICRC)
41150 Technology Park Drive, Suite 101
Sterling Heights, MI 48314

Subject: Southwest Research Institute® (SwRI®) Final Report, Project 11824.01.300, "Injector Functionality Study"

Dear John:

Southwest Research Institute has finished flow performance evaluation for four DDC injectors for you. Evaluation test for these injectors was conducted using the injector test rig shown in the figure 1. Injector set-up is shown in Figure 2.

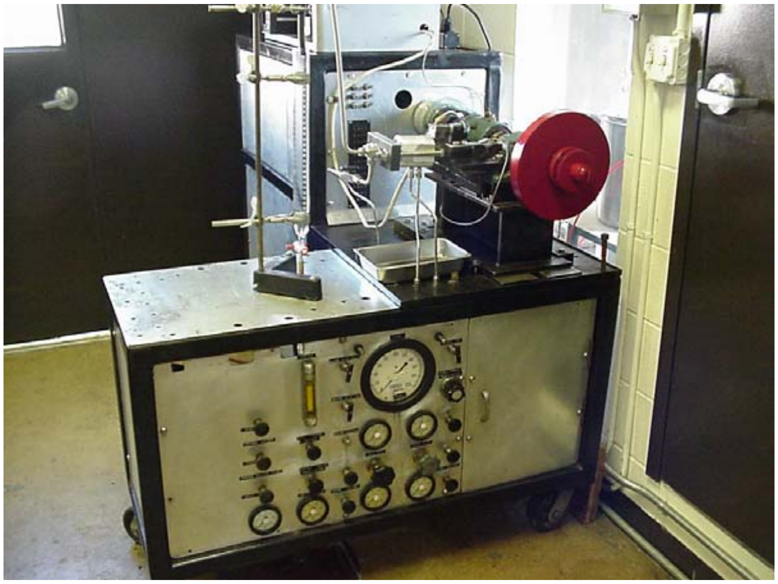

Figure 1. Injector Test Stand

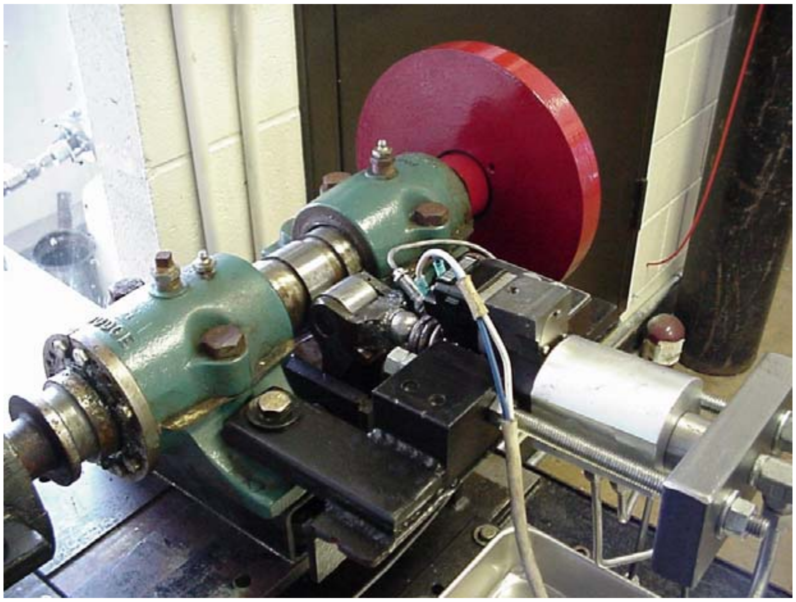

Figure 2. Injector Set-Up

Injector flow performance tests were conducted with series 60 cam shaft speed set at 1000 rpm and fuel temperature maintained between 96 to 100 degree of Fahrenheit. Test fuel used in the performance test was S-2 Synthetic Diesel Fuel, provided by Syntroleum Corporation.

After each injector was properly mounted onto the test rig, flow performance test began. When 200cc injected effluence fuel was collected or an equivalent time duration had elapsed, a test run was terminated. Injection volume per stroke was then calculated by dividing the volume of fuel collected with the total number of injection events which is registered via an electronic counter. For each test article four test runs were conducted to obtain the average and other associated statistics.

Test results for the four injectors supplied are as follows:

Injector Test Runs	**Injector Performance (cc/stroke)**			
	D1	**D2**	**D3(New)**	**D 4**
Run 1	0.458	0.349	0.435	0.460
Run 2	0.474	0.365	0.447	0.461
Run 3	0.437	0.348	0.439	0.455
Run 4	0.451	0.351	0.439	0.461
Average	0.455	0.353	0.440	0.459
Standard Deviation	0.0154	0.0079	0.0050	0.0029

Reviewing these results, we may reach the following conclusions and comments:

a. Each tested injector is very consistent in its four runs of flow performance indicated by the corresponding standard deviation value.
b. Two used injectors have higher injection rates than the baseline (D3) and one is significantly lower (D2).
c. Higher than baseline injection rate could be caused by erosion or corrosion to the injector spray holes.
d. Lower than baseline injection rate usually caused by partially plugged spray holes or by malfunctioned electronic valve armature that was contaminated and could not properly seal off the fuel when such an action is needed before and during the injection period.
e. Further investigation is needed to pin point the root cause.

SwRI has been very pleased to be in service for you. If you have any questions or need further information, please do not hesitate to contact me at (210) 522-6962. For your convenience, our fax number is (210) 522-5720. SwRI is pleased to have been of service to you and we look forward to working with you again in the future.

Sincerely:

Dr. Xiaojian Tao, Manager
Fuel Systems & Contamination Research
Vehicle Systems Research Department

Approved by:

Gary Stecklein, Director
Vehicle Systems Research Department
Engine and Vehicle Research Division

West Virginia University

THE NATIONAL RESEARCH
CENTER FOR ALTERNATIVE FUELS
ENGINES AND EMISSIONS

Project Number: DE-FC26-01NT41099

Report on Exhaust Emission Analyses

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EXECUTIVE SUMMARY

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) is the sponsor of an Ultra-Clean Fuels Production and Demonstration Program with Integrated Concepts and Research Corporation (ICRC) as the prime contractor and West Virginia University as a principal subcontractor. Under this demonstration program Syntroleum Corporation has built a small footprint plant to demonstrate Fischer-Tropsch (F-T) technology and produce ultra-clean diesel fuel from natural gas. The F-T fuel was demonstrated in a select number of urban transit buses operated by the Washington DC Metropolitan Transit Authority (WMATA) and in tour buses operated by Doyon/Aramark in Denali National Park, Alaska.

Exhaust emissions measurements were conducted on six 2000 model year transit buses equipped with 1999 model Detroit Diesel Corporation Series 50 engines and diesel oxidation catalysts at WMATA. Three buses were operated on Syntroleum S-2 gas-to-liquid fuel and three were operated on ultra-low sulfur No. 1 (ULSD1) petroleum derived diesel fuel. Emissions were measured shortly after the test buses were converted to Syntroleum S-2 fuel and then repeated 6 months later. Emissions measurements were also conducted on six 2004 model year Thomas buses equipped with new-technology 2004 model Caterpillar C7 ACERT engines and diesel oxidation catalysts at Denali National Park, Alaska. Three "test" buses were operated on Syntroleum S-2 fuel and three "control" buses were operated on the Denali fleet's normal No. 1 diesel fuel which is actually Jet A fuel. (This road-legal Jet-A fuel is sometimes referred to by fuel suppliers as "low-sulfur" because to be used as road-diesel fuel its sulfur content must be no more than 500 ppm, considerably lower than the maximum limit of 3000 ppm that would be acceptable for aviation use of Jet-A fuel.) Ultra-low sulfur fuel is not economically available in Alaska. The Denali Park buses were only tested on one occasion. All emissions changes are compared to the baseline petroleum diesel fuel typically used at each bus fleet.

Three WMATA transit buses fueled with Syntroleum S-2 fuel demonstrated apparent emission reductions of between 16 and 22% for NO_X and 35% for PM compared to three sister buses running on ULSD1. HC and CO emissions from the WMATA buses were low for both fuels with no significant differences noted between the Syntroleum S-2 and ultra-low sulfur fuel given vehicle-to-vehicle variation. Emissions measurements were also conducted back-to-back with both S-2 and ULSD1 fuels on a single WMATA transit bus equipped with an Engelhard DPX^{TM} passive catalyzed diesel particulate filter. Tests were conducted with the DPX installed and with the OEM oxidation catalyst installed. Installation of a catalyzed particulate filter in conjunction with the Syntroleum S-2 fuel reduced PM emissions to less than 0.01 g/mile. HC and CO emissions were also reduced to at or below ambient levels by the catalytic action of the DPX filter.

Three Denali Park buses fueled with Syntroleum S-2 showed apparent emission reductions of 25% for PM, 81% for HC and 68% for CO compared to three identical buses running on the "baseline" Jet-A fuel typically used as No. 1 diesel fuel at Denali Park. However, NOx emissions from these Denali buses, equipped with new-technology Caterpillar C-7 engines which were calibrated for the "normal 40 to 45 Cetane" level of conventional fuels rather than for the much higher Cetane level of the Syntroleum fuel, showed an apparent increase of approximately 23%. As discussed in more detail the report, the combination of extremely high Cetane fuel and a "normal" (i.e. not matched to the high Cetane level) calibration of the Caterpillar C-7 engine apparently resulted in combustion beginning earlier in the cycle with higher in-cylinder temperatures than for a calibration better-matched to the fuel, similar to an increase in injection timing advance in an old-technology diesel engine. During the emissions testing, fuel economy was computed from exhaust emissions data using a carbon balance. The Syntroleum S-2 fuel did not result in significant changes in fuel economy in either bus fleet.

Use or Syntroleum S-2 synthetic diesel fuel produced from natural gas produced reductions in NO_X and PM emissions of transit buses equipped with DDC Series 50 engines operating in Washington DC and reductions in PM, HC and CO emissions of tour buses equipped with Caterpillar C7 ACERT engines in Denali Park, Alaska. Although gas-to-liquid fuels, such as Syntroleum S-2 fuel have the potential to produce modest reductions in regulated emissions, the near-zero sulfur content of these fuels may prove most beneficial by enabling advance sulfur sensitive emission control devices on newer technology engines.

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1.0 INTRODUCTION

The Fischer-Tropsch (F-T) process was invented in Germany in the 1920's and has been used in South Africa to produce gasoline and diesel fuel from coal for several decades. Recently, interest has grown in the production of GTL fuels. Two principal objectives underlie this interest; emissions reductions and energy security. The F-T process can allow liquid compression ignition fuels to be made from domestic energy sources such as coal, biomass, and natural gas, thereby reducing petroleum imports while simultaneously reducing harmful emissions. Through recent advances, F-T production facilities have become more economical as well as relatively portable. Production facilities can be positioned close to energy resources that might not otherwise be suitable for use because the gas is too far away from the end user. Alaska, for example, has a huge non-petroleum energy reserves, but much of it is in remote locations. In the near future, zero-sulfur, zero-aromatic, high-cetane synthetic diesel fuel could be produced locally in Alaska, and at many other locations around the U.S. and the rest of the world using non-petroleum energy resources.

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) was the sponsor of an Ultra-Clean Fuels Production and Demonstration Program with Integrated Concepts and Research Corporation (ICRC) as the prime contractor and West Virginia University as a principal subcontractor. The goal of the program was to pioneer a new generation of ultra-clean transportation fuels to significantly reduce tailpipe emissions from cars, trucks, and other heavy vehicles. Under this demonstration program Syntroleum Corporation has built a small footprint plant to demonstrate Fischer-Tropsch (F-T) technology and produce ultra-clean diesel fuel from natural gas. The fuel was produced in Tulsa Oklahoma at a gas-to-liquids demonstration facility built by the Syntroleum Corporation and Marathon Oil Company with funding, in part provided by U.S. DOE and NETL. The ultra-clean GTL fuel was manufactured using Syntroleum's proprietary gas-to-liquids technology called *The Syntroleum Process*®.

The Syntroleum S-2 fuel was demonstrated in a select number of urban transit buses operated in revenue service by the Washington DC Metropolitan Transit Authority (WMATA) in Washington DC and in tour buses operated by Doyon/Aramark in Denali National Park, Alaska. Performance, exhaust emissions, and fuel economy of the buses operated on Syntroleum S-2 fuel were evaluated at each location and compared with identically equipped sister buses operated on petroleum-derived diesel fuels. Operational, maintenance, and fuel economy data were collected at each site by ICRC. The West Virginia University, Center for Alternative Fuels, Engines and Emissions, as a subcontractor to ICRC, measured the exhaust emissions from three (3) test buses at WMATA and three (3) test buses at Denali National Park and compare the performance and emissions to that of three (3) identical technology "control" buses at each site that were fueled with each fleet's standard petroleum-derived diesel fuel.

1.1 Project Overview

The overarching goal of the Ultra-Clean Transportation Fuels Production and Demonstration Program was to pioneer a new generation of gas-to-liquid fuels to significantly reduce tailpipe emissions from buses, trucks, and other heavy vehicles and to demonstrate this fuel in bus fleets operated in Washington DC and Denali Park, Alaska. The emissions testing component of the project was divided into four phases.

- In Phase 1, a single WMATA public transit bus was tested with and without a catalyzed diesel particulate filter to demonstrate the compatibility of Syntroleum S-2 fuel with catalyzed diesel particulate filters.
- In Phase 2, six tour buses equipped with 2004 model year Caterpillar C7 ACERT engines and diesel oxidation catalysts were tested in Denali National Park, Alaska; 3 buses fueled with Syntroleum S-2 fuel and 3 control buses fueled with the low sulfur Jet A diesel fuel utilized by Denali National Park.
- In Phase 3, six public transit buses equipped with 2000 model year DDC Series 50 engines and oxidation catalysts were tested in Washington DC; 3 buses fueled with Syntroleum S-2 fuel and 3 fueled with ultra-low sulfur type 1 diesel fuel.

- In Phase 4 three out of the six WMATA buses were re-tested to evaluate the performance and emissions after the vehicles have been operating on Syntroleum S-2 fuel for a period of six months.

1.2 Organization of the Report

The final repot format is divided into 5 main sections as discussed below:

- Section 2.0 provides a literature review of previous studies conducted on the F-T fuels.
- In Section 3.0 a detailed discussion of the types of fuels, which were used in this project, is presented.
- Section 4.0 presents a thorough explanation of the driving cycle used and the testing equipment.
- In Section 5.0 a comprehensive discussion of the test results is presented.

2.0 PRIOR GAS-TO-LIQUID FUEL STUDIES

Properties of compression ignition fuels are known to affect diesel engine emissions. Bio-diesel blends have been found most often to reduce PM while raising NO_X slightly [1, 2, 3]. In contrast, prior studies of Fischer-Tropsch GTL fuels have shown a reduction of both PM and NO_X. GTL fuel has superior properties to crude oil derived diesel fuel. The hydrogen/carbon ratio is greater than conventional diesel fuel. It is believed that the high H/C ratio in GTL fuel is a consequence of the near zero aromatics content. The very low sulfur content is one more characteristic of the GTL fuel. Typical GTL fuel contains about 0.5 ppm of sulfur which in turn results in significant PM reductions. In addition, the near zero sulfur content of the GTL fuel will enable sulfur sensitive emission control devices to be used in modern technology engines. The GTL fuels have cetane numbers of 74 or higher which are much higher than conventional diesel fuels. The higher cetane number has been reported to produce NO_X reductions in some studies while other studies report no effect on NO_X emissions [10].

Schaberg *et al*. [4] examined a range of Fischer-Tropsch fuels and presented their emissions benefits over petroleum diesel. The study examined seven diesel fuels, two typical crude oil derived diesel fuels, namely, CARB diesel fuel and 2-D diesel fuel; two variations of the Sasol Slurry Phase Distillate (SSPD) fuel which is made by employing the Fischer-Tropsch synthesis, and three blends of SSPD and 2-D fuels with varying amounts of SSPD fuel. The researchers used a 1991, four stroke, heavy-duty emission level diesel engine and used a transient emissions test cycle.

The regulated emissions of the SSPD fuels were lower when compared to CARB and 2-D fuels. Since both variations of the SSPD fuel produced nearly identical results, the authors stated a single set of these results. HC were lower by 49% and 15% when compared to 2-D and CARB fuels, respectively. The reductions in CO were 33% compared to 2-D fuel and 23% compared to CARB fuel. SSPD fuels produced reductions in NO_X by 27% compared to 2-D fuel and 15% reduction when compared to CARB fuel. A 21% reduction of SSPD fuels PM emissions was measured compared to both 2-D and CARB fuels, however, the volatile organic fraction (VOF) of PM was significant. Relative to 2-D fuel the VOF of PM was less by 34% and it was less by 29% relative to CARB fuel.

The three fuel blends of SSPD and 2-D fuels produced reductions in regulated emissions. These blends showed a proportion of the reduction percentage to the amount of SSPD fuel in the blend. Blend B1, which was 30% SSPD and 70% 2-D, has the least reduction percentage among the three blends. Whereas B3, which is 80% SSPD and 20% 2-D, had the highest reductions among these three blends. B1 NO_X reduction was 14% and B3 NO_X reduction was 29% when both of these blends were compared to 2-D. B2 blend was an intermediate blend which showed transitional results as the amount of SSPD fuel in the blend was increased [4].

These data were echoed in a wider review of alternative compression ignition fuels by Clark *et al*. [5]. The study utilized a Navistar T444E (V8, 7.3 liter) engine which was installed on an engine dynamometer. Transient emissions measurements were collected by employing the Federal Heavy Duty Engine Transient Test Procedure (FTP). A variety of fuels were used including a federal low sulfur pump diesel, California pump diesel, Malaysian Fischer-Tropsch fuel containing very low sulfur and aromatics content, several blends of soy-derived biodiesels, a Moss Gas fuel (MG) which is a Fischer-Tropsch fuel containing very low sulfur and 10% aromatics, and the same MG fuel with 10% isobutanol by volume.

The reduction in NO_X and PM were evident from the data collected for the two types of Fischer-Tropsch fuels when compared to 49-state diesel fuel. These results are in agreement with the results obtained by Schaberg *et al*. [4]. The Malaysian F-T fuel showed a reduction of 14% and 13% in NO_X and PM, respectively. The MG fuel reductions were 6.5% and 15% in NO_X and PM, respectively. The biodiesel failed to reduce NO_X emissions, but it was reliable in reducing PM emissions. The NO_X emissions were 4% higher when compared to 49-state diesel fuel. On the other hand, PM reductions were about 42%. The data presented simultaneous reductions in NO_X and PM for the Fischer-Tropsch fuels whereas the biodiesel had a NO_X-PM tradeoff. [5]

In a separate paper, Clark *et al*. [6] also reported benefits of two Fischer-Tropsch fuels, one contained 0.1% aromatics and the other contained 10% aromatics. A Malaysian Fischer-Tropsch fuel was compared to California #2 diesel fuel by analyzing emissions from over the road Class 8 tractors equipped with Caterpillar 3176 engines. The 5-Mile route was employed by using a chassis dynamometer. The study also examined and compared the emissions produced by Detroit Diesel 6V-92 powered transit buses, three of them equipped with catalytic aftertreatment devices and rebuilt engines, and three without these modifications. Two types of fuels were used in these buses, namely, a Fischer-Tropsch fuel containing 10% aromatics and a 49-state # 2 diesel fuel.

The emissions results showed marked reductions in NO_X and PM from the Malaysian F-T fuel when compared to the California #2 diesel fuel. The NO_X levels were reduced by an average of 12% and the PM levels were reduced by 25%. For the other part of the investigative study the F-T fuel showed benefits over the 49-state diesel fuel. NO_X were lower by 8% and PM reductions were 31% for the buses with catalytic converters and rebuilt engines. NO_X and PM were reduced by 5% and 20%, respectively, for the three buses without the aftertreatment devices [6].

Although Fischer-Tropsch fuels offer modest improvements in emissions on their own, they also enable the use of exhaust aftertreatment devices because they contain very low levels of sulfur. In this way particulate matter filters may be used without fear of deterioration and without production of appreciable sulfate from sulfur in the fuel. The benefits of particulate matter filters have been demonstrated previously in studies using ultra-low sulfur petroleum diesel fuel [7, 8, 9].

Prior research suggests that the combination of Fischer-Tropsch fuel and exhaust filtration will yield substantial reductions in PM and measurable reductions in NO_X. The National Renewable Energy Laboratory and West Virginia University conducted an operability and emissions study on a fleet of six 2001 International Class 6 trucks using GTL fuel and catalyzed diesel particulate filters (CDPF) in Southern California [10]. The fleet was divided into 2 groups, the baseline and the test groups. Three baseline vehicles were running on CARB specification diesel fuel without any emission control devices installed. The other three vehicles were running on GTL fuel with CCRT™ diesel particulate filter installed. Prior to commencing the study the GTL fuel was tested for fuel-engine and elastomer compatibility and the results met or exceeded the specifications of ASTM D975. WVU conducted the emissions testing using the City Suburban Heavy Vehicle Route (CSHVR) and New York City Bus (NYCB) cycles.

The three trucks operating on GTL fuel were tested twice, with the CDPF and without it to determine the benefits of using such devices along with GTL fuel. On the CSHVR cycle, NO_X and PM were reduced 8% and 33%, respectively, for the trucks without the CDPF and 14% and 99%, respectively, for the trucks operating with the CDPF devices, when compared to CARB specification diesel fuel. The NO_X and PM reductions were 16% and 23%, respectively, for the trucks without the catalyzed filters, and 20% and 97%, respectively, for the CDPF equipped trucks on the NYCB cycle. Noticeable reductions in NO_X and PM emissions were due to the very low aromatics content of the GTL fuel which was less than 1% [10].

3.0 TEST FUELS

Three different fuels were used in the course of completing this project. The Syntroleum S-2 GTL fuel was tested in buses at both Washington Metropolitan Transit Authority and Denali National Park. However, two different baseline fuels were used by the two test fleets. WMATA utilized ultra-low sulfur type 1 diesel fuel in their diesel bus fleet. Due to the logistics involved in shipping diesel fuel to Alaska, it is not economically feasible to use ultra-low sulfur diesel fuel at Denali National Park. The Doyon/Aramark Denali Park bus fleet utilized low sulfur (~300 ppm) Jet A fuel.

3.1 Syntroleum S-2 Gas-to-Liquid Fuel

Syntroleum S-2 is a synthetic diesel fuel produced from natural gas with most of the positive benefits of petroleum based diesel fuel. The basic GTL chemistry was developed in 1923, when two scientists, Franz Fischer and Hans Tropsch, demonstrated the catalytic conversion of carbon monoxide and hydrogen (synthesis gas) into synthetic hydrocarbons. The technology was first applied in Germany during World War II and in more recent years in South Africa [11]. Syntroleum S-2 is produced by a proprietary gas-to-liquids technology called *The Syntroleum Process®* shown schematically in Figure 1. The Syntroleum S-2 fuel for this project was produced in Tulsa Oklahoma at a small footprint gas-to-liquids demonstration facility built by the Syntroleum Corporation and Marathon Oil Company (Figure 2). The plant consists of three primary components: an autothermal reformer that changes the natural gas into synthesis gas; a Fischer-Tropsch unit that converts the synthesis gas into synthetic crude oil; and a refining unit that upgrades the synthetic crude to finished synthetic diesel.

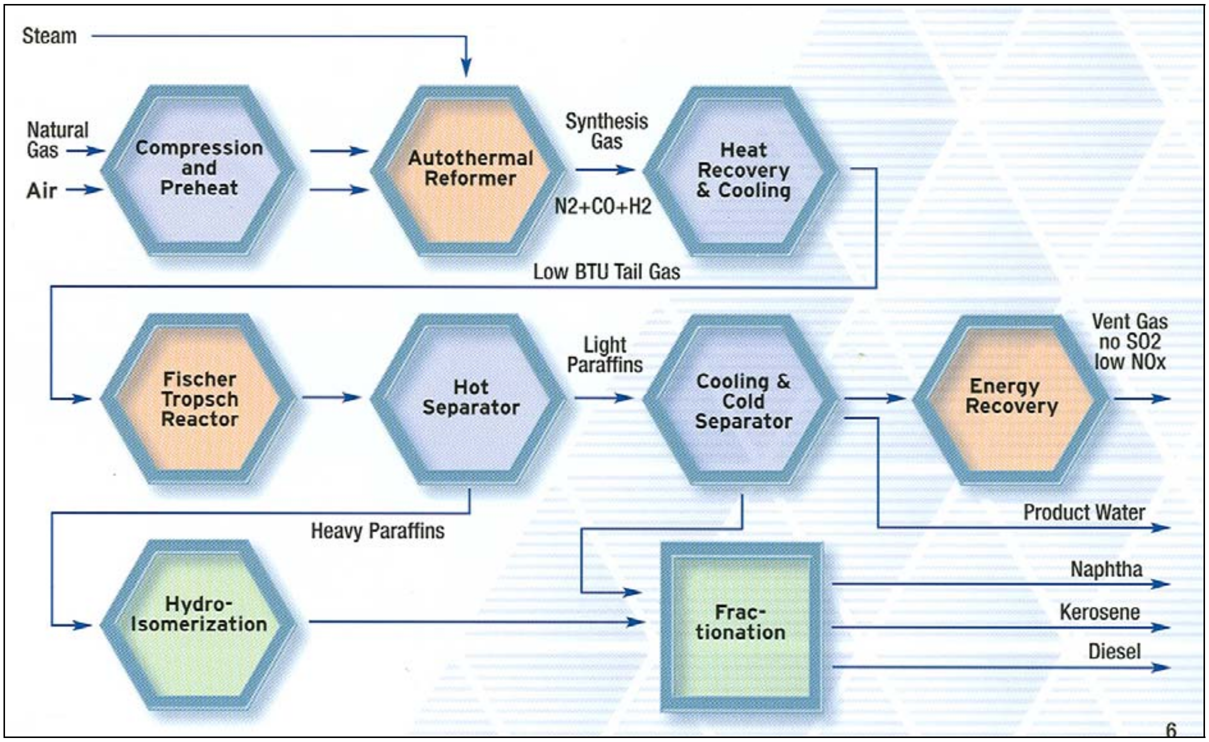

Figure 1: Simplified Syntroleum Process [11]

Figure 2: Syntroleum Pilot Plant in Tulsa Oklahoma [11]

Syntroleum S-2 is a paraffinic, high-cetane distillate fuel with extremely low levels of sulfur, olefins, metals, aromatics and alcohols. It is 99%+ saturates (i.e. the fuel consists of hydrocarbon molecules that are saturated with hydrogen). Properties of the Syntroleum S-2 fuel determined by analysis of samples collected at WMATA are listed in Table 1. Several key fuel specifications which contribute to the superior characteristics of Syntroleum S-2 fuel are discussed below.

In the United States, a minimum cetane number of 40 is specified for diesel fuels. The Syntroleum S-2 fuel had a cetane number of 74, due to its high paraffin content and near absence of aromatics. The higher the cetane number, the more readily the fuel will ignite and the shorter the ignition-delay period. Some studies have shown that increasing cetane number leads to decreased NO_X emissions while others have shown no effect. The effect of cetane number on NO_X emissions appears to be less prominent on newer technology engines with more advanced fuel injection strategies [10, 13, 14, 15].

The density of GTL fuels is typically lower than conventional diesel fuels [16]. The density of Syntroleum S-2 is about 0.77g/ml compared to a range of .80 to .84 g/ml for typical U.S. diesel fuels. Reductions in fuel density of 5% have been shown to reduce PM emissions by up to 20% in older technology engines [12].

The sulfur content of diesel fuel can be reduced by hydrodesulfurization. However, this increases the cost of producing the diesel fuel and lowers the over all yields [12]. Presently U.S. regulations limit sulfur content of on-road diesel fuel to 500 ppm. Recent legislation will require a reduction in sulfur content to 15 ppm by September 2006. The U.S. EPA estimates that reducing the sulfur content of petroleum-derived diesel fuel will result in price increase of approximately 4.5 to 5 cents per gallon. Reducing the sulfur content of diesel fuel typically reduces PM emissions but with diminishing returns as sulfur content becomes very low [10, 14]. To comply with environmental regulations, engine manufacturers may rely on aftertreatment emissions control devices. Many of the leading aftertreatment technologies, including lean NO_X, catalyzed diesel particulate filters (DPF), and diesel oxidation catalysts cannot tolerate sulfur well. *The Syntroleum Process*®, removes all traces of sulfur from the natural gas feed stock during the feed preparation process, so Syntroleum S-2 fuel contains nearly zero sulfur. In newer technology engines, the near zero sulfur content of GTL fuel may prove most beneficial by enabling sulfur sensitive emission control devices.

Syntroleum S-2 fuel has very low aromatic content with no detectable polynuclear aromatics and as a result has a very high cetane number. Aromatics increase the density and heating value of the fuel and improve cold flow properties [12]. However, aromatics decrease the cetane number and have been shown to increase NO_X and PM emissions in previous studies [13, 14, 15]. Higher aromatic content in diesel fuel increases combustion temperatures, contributing to higher NO_X emissions. Reducing aromatic content has also shown to lower PM emissions from older engines, although there seems to be little effect on PM emissions from newer engines [12].

The heating value of diesel fuel is directly proportional to the fuel density. The heating value can be raised by increasing the aromatic content or by changing the distillation profile to increase the initial and/or final boiling point [12]. The Syntroleum S-2 fuel has heating values that are just slightly higher than those of the petroleum-based diesel fuels used in this study.

The distillation profile is expressed as the temperature at which successive portions of the fuel evaporate. The back-end volatility of diesel fuel expressed as the 90-percent or 95 percent distillation recovery temperature (T90/T95) has been shown to have a small impact on emissions [10, 12, 15]. When volatility is reduced, a slight increase in HC and CO emissions and a small decrease in NO_X emissions were observed. However, diesel fuel volatility is a minor factor in emissions and any impact based on T90/T95 temperature is likely obscured by other fuel properties such as paraffin content and cetane number [10].

Highly paraffinic fuels, such as Syntroleum S-2, may have cold-flow properties that are unsuitable for operation in some climates. Low temperature performance of diesel fuel is characterized by the cloud point, pour point and cold filter plugging point (CFPP). With additives, winter diesel fuels are available with cold-resistance guarantees to at least -22 C. Studies have shown that diesels fuels containing a higher percentage of iso-paraffin compounds have much better low-temperature properties [12]. During the final manufacturing process, Syntroleum S-2 fuel undergoes a degree of isomerization and as a result contains a high percentage of iso-paraffins. Syntroleum S-2 can be manufactured to meet cloud point, pour point and CFPP specifications for ASTM D-975 grade diesel fuel without low-temperature additives [12].

Typically, GTL fuels and severely hydrotreated ultra-low sulfur petroleum-derived diesel fuels have poor lubricities due to a lack of polar molecules [17]. Lubricity additives, which contain a polar group, attracts to metal and forms a thin surface film on the engine areas subjected to wear. Like other ultra-low sulfur fuels, Syntroleum S-2 requires a lubricity agent as part of its additive package [12].

3.2 WMATA Ultra-Low Sulfur D1 Petroleum-Derived Diesel Fuel

WMATA has recently switched to ultra-low sulfur No. 1 (ULSD1) diesel fuel as a means to reduce emissions and to enable the use of exhaust aftertreatment catalyzed particulate filters, which can virtually eliminate particulate (PM) emissions. WMATA's ULSD1 had a cetane number of 45 and an aromatic content of 21.6 wt% which is typical of petroleum-derived diesel fuels. The sulfur content was 18 ppm wt. Fuel density and heating values were typical of available diesel fuels and were very similar to that of the Jet A fuel used by the Denali National Park fleet.

3.3 Denali National Park Low-Sulfur Jet A Fuel

A large volume of conventional petroleum-derived fuels is imported into Alaska to meet a much larger fraction of the state's overall energy needs than anywhere else in the U.S. Alaska's vast areas of rugged terrain and extreme temperatures make the distribution of diesel fuel expensive and difficult. Ultra-low sulfur diesel costs 5 cents/gallon more than conventional diesel fuel in the lower 48 US States. Special handling is required to transport the fuel to Alaska (25 cents/gallon estimated) and from Fairbanks to Denali by truck (50 cents/gallon estimated). Due to these additional costs, it is not economically feasible for Doyon/Aramark to use ultra-low sulfur diesel fuel in the Denali Park tour bus fleet. Presently, Denali Park utilizes low sulfur (~450 ppm S) Jet A fuel. Jet A fuel has properties that are very similar to type 1 diesel fuel. With the exception of the sulfur content the Denali Park Jet A fuel had similar properties to the ULSD1 fuel used at WMATA.

Table 1: Fuel Properties

Property	Syntroleum S-2	WMATA Ultra-Low Sulfur D1	Denali Park Low Sulfur Jet A	Units	Method
Cetane Number	73.6	45	44.6		ASTM D-613
API Gravity @ 60 deg F	52.4		43.1	deg.API	ASTM D-4052
Density @ 60 deg F	0.7687	0.8300	0.8095	gm/mL	ASTM D-4052
Kinematic Viscosity @ 40 deg F	1.705	1.773		cSt	ASTM D-445
Kinematic Viscosity @ 100 deg F	1.761			cSt	
Flash Point , PMCC	140	156	102	deg F	ASTM D-93(A)
Total Sulfur	5	17.9	447	ppm wt	ASTM D-5453
Hydrocarbon Type – FIA (Oxygenate Corrected)					
Aromatics	1.1	19.7	15.1	vol. %	ASTM D-1319
Olefins	0.3	1.1	1.0	vol. %	
Saturates	98.6	79.2	83.9	vol. %	
Aromatics by Supercritical Fluid Chromatography					
Monoaromatics	0.35	18.3	15.52	wt%	ASTM D-5186
Polynuclear Aromatic Hydrocarbons	< 0.1	3.4	2.94	wt%	
Total Aromatics	0.35	21.6	18.46	wt%	
Heat of Combustion					ASTM D-240
Gross	20460	19675	19865	BTU/lb	
Net	19084	18447	18633	BTU/lb	
Low Temperature Properties					
Cloud Point	-14	-46	< -40	deg F	ASTM D-2500
Pour Point	-30	-48	< -40	deg F	ASTM D-57
Carbon/Hydrogen/Nitrogen/Oxygen Content					
Carbon Content	84.75	86.19	86.13	wt%	ASTM D-5291M
Hydrogen Content	15.19	13.46	13.53	wt%	ASTM D-5291M
Nitrogen Content	< 0.05			wt%	ASTM D-5291M
Oxygen Content	< 0.10	< 0.10		wt%	ASTM D-5291M
Distillation					ASTM D-86
IBP	321.0	354.4	267.6	deg F	
5% Recovery	370.2	391.7	334.5	deg F	
10% Recovery	380.3	397.0	346.2	deg F	
20% Recovery	399.3	411.6	357.8	deg F	
30% Recovery	422.5	421.1	370.9	deg F	
40% Recovery	446.1	430.0	385.8	deg F	
50% Recovery	471.3	438.6	401.5	deg F	
60% Recovery	494.9	447.9	417.7	deg F	
70% Recovery	521.2	458.5	436.0	deg F	
80% Recovery	550.8	471.4	458.7	deg F	
90% Recovery	588.5	489.2	488.0	deg F	
95% Recovery	613.6	504.2	510.7	deg F	
FBP	619.8	527.0	533.2	deg F	
Recovery	97.1	99.1	97.8	%	
Residue	1.8	0.5	1.4	%	
Loss	1.1	0.5	0.8	%	

4.0 TEST METHODOLOGY

4.1 Chassis Dynamometer

Chassis dynamometer testing is the most accurate and repeatable method of characterizing emissions from in-use heavy-duty vehicles and provides the most useful data for prediction of atmospheric emissions inventories, evaluation of clean-vehicle programs at transit agencies and truck fleets, and accessing the success of retrofit programs. Chassis dynamometer systems have been developed and used for many years and it has been demonstrated that they are reliable tools for studying vehicle emissions. The West Virginia University Transportable Heavy-Duty Vehicle Emissions Testing Laboratories were constructed to gather emissions data from in-use heavy-duty vehicles. Detailed information pertaining to the design and operation of the laboratories can be found in technical papers [20, 21, 22]. The dynamometer unit consisted of power absorbers and a set of selectable flywheels, which allowed simulation of tire rolling losses, aerodynamic drag and inertial load equivalent to a gross vehicle weight of up to 60,000 pounds. The vehicle to be tested was driven onto the chassis dynamometer and positioned on two sets of rollers (Figure 3). The outer wheel of the dual wheel set on each side of the vehicle was removed and replaced with hub adapters that couple the drive axle directly to the dynamometer units on each side of the vehicle (Figure 4). Torque cells and speed transducers continuously measured drive axle torque and speed. Road load drag on the vehicle was mimicked partially by the irreversible (frictional) losses in the laboratory, and was adjusted to the correct value at each speed using eddy current power absorbers with closed-loop torque control. A human driver operated the vehicle according to a driving schedule.

Figure 3: The vehicle being tested is positioned on the dynamometer rollers.

Figure 4: Hub adapters connect the vehicle's drive axle to the power absorber units.

4.2 Dynamometer Driving Cycle

Emissions are known to be dependent on the duty cycle of the vehicle and thus the dynamometer test schedule used. The Ultra-Clean Transportation Project included emissions testing of urban transit buses in Washington DC and testing of national park tour buses in Denali Park, Alaska. In the interest of consistency and in order to allow comparison between the two bus fleets the Washington Metropolitan Transit Authority Cycle (WMATA) was selected as the dynamometer test schedule for the project. This cycle, though not necessarily representative of the actual Denali tour bus duty cycle, was chosen for the Denali Park buses in the interest of consistency. The WMATA Cycle was derived from vehicle speed data logged from transit buses during normal operation in Washington DC and surrounding areas. Vehicle activity data was logged from several WMATA transit buses during normal passenger service on multiple routes within the WMATA system. Vehicle speed data were recorded from a Global Positioning System. These data comprised a database of vehicle activity, which was analyzed to characterize the duty cycle of a typical WMATA transit bus. The WMATA Cycle is shown in Figure 5.

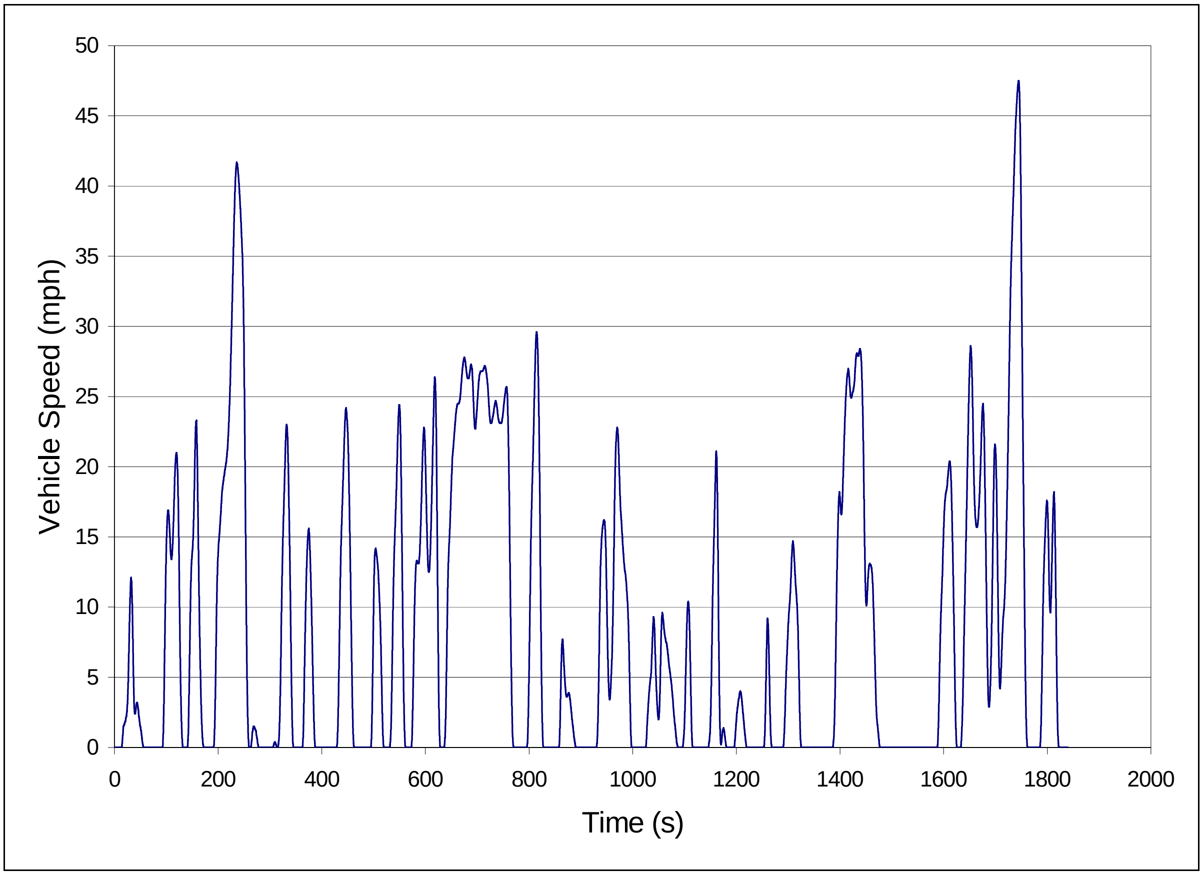

Figure 5: WMATA Cycle target speed versus time schedule.

4.3 Emissions Sampling Equipment

The emissions measurement system used a full-scale dilution tunnel measuring 18 inches (45 cm) in diameter and 20 feet (6.1 m) in length. The exhaust was mixed with HEPA filtered ambient air and the quantity of diluted exhaust was measured precisely by a critical flow venturi system (CVS). The diluted exhaust was analyzed using NDIR for carbon monoxide (CO) and carbon dioxide (CO_2), and using chemiluminescent detection for oxides of nitrogen (NO_X). NO_X emissions were corrected for standard humidity. Hydrocarbons (HC) were analyzed using flame ionization detection (FID). Simultaneous pre-tunnel bag samples were taken during each test to establish ambient background gas concentrations. The gaseous emissions measurements were performed in accordance with the CFR Title 40, Part 86 Subpart N (CFR40) [23] to the extent possible. A carbon balance using fuel properties and exhaust emissions data was used to determined fuel economy. Particulate matter (PM) was collected using 70-mm fluorocarbon coated glass fiber filter media and PM mass emissions were determined gravimetrically. Dilution tunnel background samples were collected for establishing particulate matter background levels. Even though the tunnel has HEPA filtered dilution air, PM backgrounds are essential because the dilution tunnel walls may shed particles that are re-entrained into the sample stream or outgas heavy hydrocarbons that condense onto the PM. Emissions were reported in distance-specific units (mass of pollutant emitted / unit distance traveled – g/mile).

5.0 RESULTS AND DISCUSSION

The project was divided into four phases. In phase 1, a single WMATA bus was tested with and without a catalyzed diesel particulate filter to evaluate compatibility of the Syntroleum S-2 fuel with diesel particulate filter technology. Six tour buses were tested in Denali National Park, Alaska during phase 2. In phase 3, Six WMATA buses were tested in Washington DC. In the final phase, three out of the six WMATA buses were re-tested to evaluate the performance and emissions after the vehicles had been operating on Syntroleum S-2 fuel for a period of at least six months. The results of each of the four emissions measurement campaigns are discussed in following sections.

5.1 Phase 1 – WMATA DPF Equipped Transit Bus

WMATA has recently switched to ultra-low sulfur No. 1 diesel fuel as a means to reduce emissions and to enable the use of exhaust aftertreatment catalyzed particulate filters, which can virtually eliminate particulate (PM) emissions. While the Syntroleum S-2 fuel is lower in sulfur and aromatic content than WMATA’s conventional diesel fuel, these are both low-emissions fuels compared to conventional No. 2 diesel fuel which typically has a sulfur level of ~400 ppm. Therefore, it was recognized at the outset of the program that it would be difficult to distinguish emissions differences between Syntroleum S-2 fuel and WMATA’s ultra-low sulfur petroleum derived fuel. This difficulty would be compounded if the buses tested were equipped with diesel particulate filters. Consequently, it was decided that the six WMATA test buses would be equipped with diesel oxidation catalysts rather than catalyzed particulate filters. However, there was still interest in potential benefits of the Syntroleum S-2 fuel when used in conjunction with catalyzed particulate filters. The nearly zero sulfur and aromatic content of the Syntroleum S-2 fuel suggest that it is well suited for use with catalyzed diesel particulate filters. In order to evaluate the compatibility of the Syntroleum S-2 fuel with catalyzed diesel particulate filters, WVU measured the emissions from a single WMATA transit bus operated on Syntroleum S-2 fuel with and without an Engelhard DPX^{TM} catalyzed diesel particulate filter in April 2004.

5.1.1 Test Vehicle Information

The test vehicle was a 2000 model year Orion 40-foot municipal transit bus equipped with a 1999 model year Detroit Diesel Corporation (DDC) Series 50 diesel engine. The transit bus (Number 2027) was owned by the Washington Metropolitan Area Transit Authority (WMATA) and was operated in municipal transit service in the Washington D.C., Northern Virginia and Southern Maryland area. The transit bus had a gross vehicle weight rating of 42,540 lbs and an unloaded curb weight of 27,800 lbs. It could accommodate 39 seated passengers and 20 standing passengers. The bus emissions were characterized at a simulated weight of 33,125 lbs representing approximately one-half of the maximum passenger capacity (150 lbs/person approximate weight) including the driver.

The DDC Series 50 engine was a 4-stroke cycle, turbocharged, in-line 4-cylinder, lean-burn, compression ignition engine with a displacement of 8.5 liters. The engine had a power rating of 275 hp at 2100 rpm. In its original equipment (OEM) configuration, the bus was equipped with a diesel oxidation catalyst (DOC) but had been retrofitted with an Engelhard DPX passive catalyzed particulate filter. The Engelhard DPX was a catalyzed ceramic wall-flow filter. It utilized a dual-function platinum precious-metal catalyst in combination with a base-metal-oxide catalyst. The catalyst coating was impregnated into the walls of the filter element. Particulate matter was trapped as exhaust gas flowed through the porous walls of the filter element. The catalyst coating promoted oxidation of the collected PM, HC and CO when exhaust temperatures were 375 F or above for at least 25% of the time. Nitrogen dioxide (NO_2) produced from nitric oxide (NO) in the exhaust stream by the catalyst enhanced low temperature oxidation of PM.

WMATA bus 2027 was tested first in the as received configuration with the Engelhard DPX particulate filter installed using in-tank ULSD1 fuel. The particulate filter was then removed and replaced with an OEM-style diesel oxidation catalyst (DOC) and the tests were repeated using the ULSD1 fuel. The fuel was then changed to the Syntroleum S-2 fuel supplied in 55-gallon drums and tests were performed with the DOC in place. Prior to beginning these tests the engine fuel filter was changed and the fuel system was flushed with the Syntroleum S-2 fuel. Finally the DOC was removed and the Engelhard DPX was re-installed and tested with the Syntroleum S-2 GTL fuel. Table 2 shows the bus specifications along with the test matrix and the corresponding WVU test sequence numbers.

Table 2: Phase 1 Test Vehicle Information

WMATA Transit Bus Number 2027 Specifications		
Chassis	MY 2000 Orion	
Engine Manufacturer/Model	MY 1999 Detroit Diesel Corporation Series 50	
Engine Ratings	275hp @ 2100rpm	
After-treatment System	Diesel Oxidation Catalyst	
Transmission Type	4-speed Automatic	
GVWR/Curb Weight	42,540 / 28,800 lb	
VIN	1VH6H2A23Y6600264	
Engine Serial Number	04R0031355	
Odometer Reading	218466	
WVU Test Sequence Number	**Fuel Type**	**Exhaust Aftertreatment**
4178	ULSD1	Engelhard DPX
4181	ULSD1	OEM DOC
4184	Syntroleum S-2	OEM DOC
4187	Syntroleum S-2	Engelhard DPX

5.1.2 Oxides of Nitrogen Emissions

Measured NO_X emissions are plotted in Figure 6. Each bar represents the average of at least three separate repeat test runs and the error bars indicate the spread of the data by showing the maximum and minimum individual test results. NO_X formation in the combustion chamber is a temperature and pressure driven process. Higher in-cylinder temperatures and pressures increase the formation of NO_X. Fischer-Tropsch fuels generally produce moderate reductions in NO_X emissions. The benefit arises from the lower aromatic content, higher cetane number and shorter ignition delay period associated with combustion of Fischer-Tropsch fuels compared to typical petroleum-derived diesel fuel [4]. An increase in the cetane number results in a reduction in the ignition delay period, causing a reduced volume of fuel to undergo premixed combustion and a larger portion undergo diffusion-controlled combustion. This results in lower in-cylinder temperatures and lower rates of NO_X formation. The lower aromatic content of the Fischer-Tropsch fuel also leads to lower in-cylinder combustion temperatures and lower NO_X emissions [4]. Measured NO_X emissions, shown in Figure 6, were reduced by 28 percent when changing from ULSD1 to Syntroleum S-2 fuel with a DOC and 23 percent with the DPX.

A slight decrease in NO_X emissions of approximately 6% was observed with the DPX. This is likely due to conversion of a small amount of NO_2 to N_2 over the DPX filter [24]. Figure 6 also shows the fraction of the NO_X emissions comprised of nitric oxide (NO). Oxides of nitrogen emission from diesel engines are primarily composed of NO. NO_X emissions from engines without aftertreatment devices may include 3% to 15% NO_2 depending on engine design and operating conditions and are typically 3% to 5% averaged over a transient test cycle. Emissions from vehicles equipped with catalyzed particulate filters may consist of 30% to 40% NO_2.

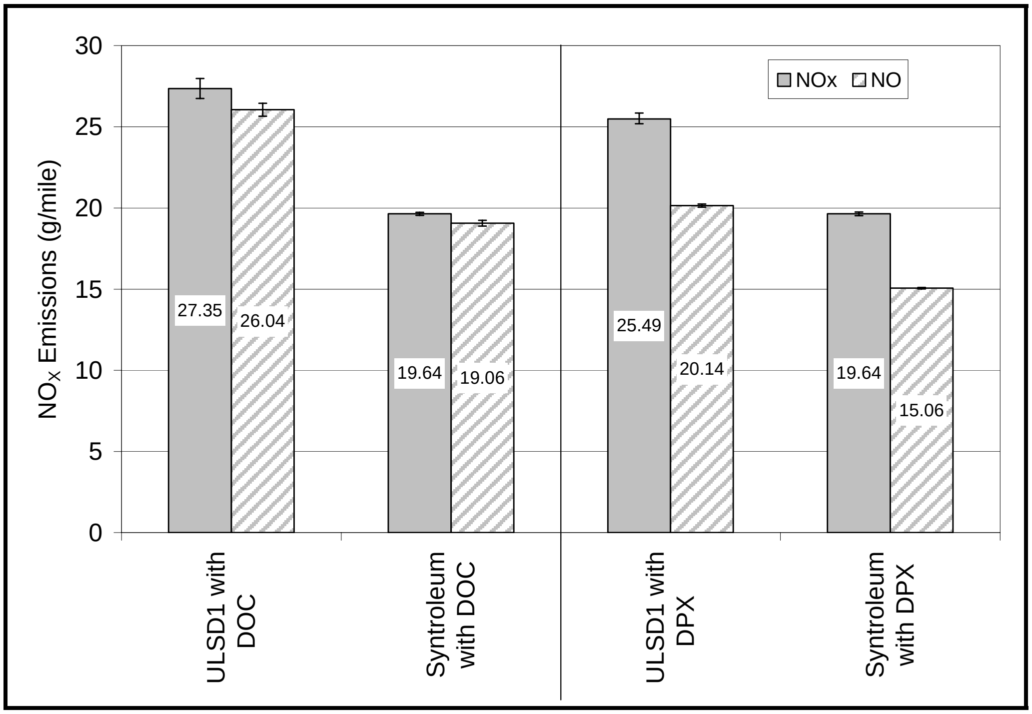

Figure 6: Phase 1 oxides of nitrogen (NO_X) emissions.

5.1.3 Particulate Matter Emissions

Particulate emissions are plotted in Figure 7. Use of the Syntroleum S-2 fuel resulted in significant reductions in PM emissions with both the DOC and DPX aftertreatment devices. With the OEM oxidation catalyst installed, PM was reduced by 35% compared to the ULSD1 fuel. Installation of the Engelhard DPX reduced PM emissions by 93% from 0.31 g/mile to 0.02 g/mile when operating with ULSD1 fuel. Use of the Syntroleum S-2 fuel in combination with the DPX further reduced the PM emissions from 0.02 g/mile average to 0.003 g/mile representing a reduction of over 99% compared to the OEM oxidation catalyst with ULSD1 fuel. The percent reduction in the case of the DPX is difficult to characterize because the very low levels of PM mass are close to the measurement limit of the laboratory. Differences in the performance of the DPX with Syntroleum fuel and ULSD1 fuel may not be significant given test-to-test variability.

Increased cetane number, lower aromatic content and near zero sulfur content of the Syntroleum S-2 fuel contributed to reductions in PM emissions. The effect of cetane number on particulate emissions is less clear with some studies indicating decreased PM, others the opposite trend and some others showing no effect [4]. A number of studies have found that the soluble organic fraction (SOF) of the PM was significantly reduced when the cetane number increased, but that the benefit was offset by an increase in the insoluble portion of the PM [4]. Reduced aromatic content particularly polycyclic aromatics (PAH) may also contribute to lower particulate emissions. Some studies have shown that at low engine speeds and loads, particulate emissions are largely composed of unburned fuel PAH. Studies have found that reducing fuel PAH resulted in reduction in HC, NO_X and PM emissions [4]. Fuel sulfur is converted to SO_2 and sulfates which, along with bound water manifest themselves as PM emissions. There is generally a linear relationship between fuel sulfur consumption and the sulfate portion of PM emissions with a conversion rate of between 1 to 2 percent for engines without aftertreatment. The contribution of sulphates to the total particulate mass is only a few percent so that the reduction of PM through reduction of fuel sulfur content is limited. However, the high precious metal and platinum loading in passive catalyzed particulate filters such as the Engelhard DPX substantially increase the formation of sulfates. The near zero sulfur content of Syntroleum S-2 fuel may offer a marginal advantage over ultra-low sulfur petroleum derived diesel for vehicles equipped with catalyzed particulate filters but the advantage is difficult to characterize quantitatively due to the very low PM emissions levels.

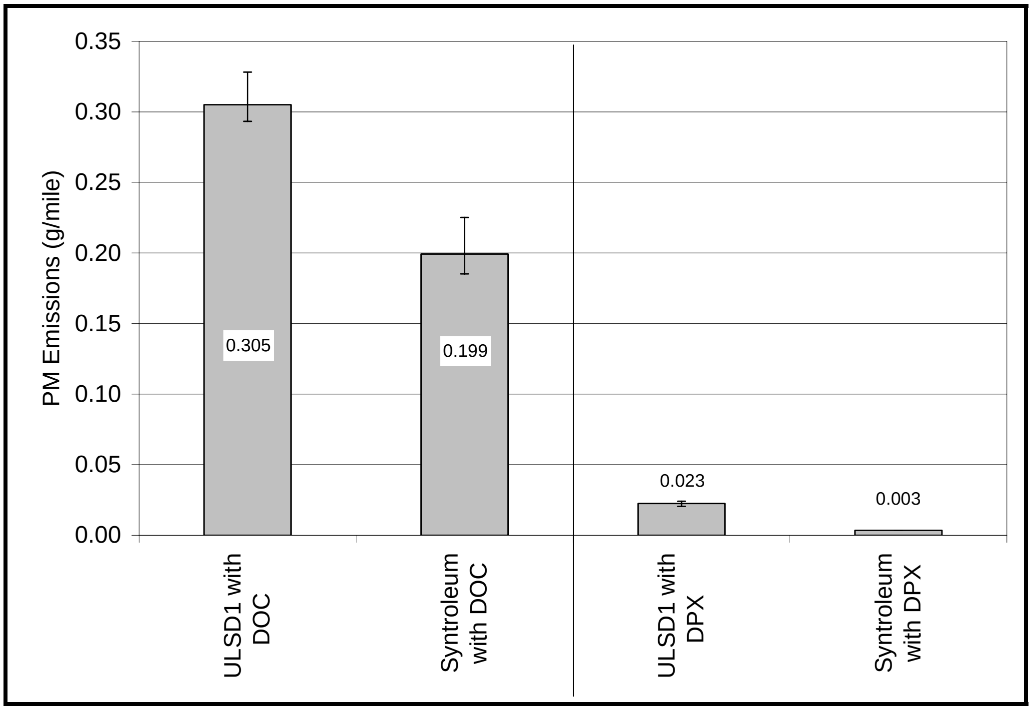

Figure 7: Phase 1 particulate matter (PM) emissions.

5.1.4 Hydrocarbon and Carbon Monoxide Emissions

Hydrocarbon results are plotted in Figure 8. In the OEM configuration with the DOC installed, hydrocarbon emissions increased by 14 percent when comparing Syntroleum S-2 to ULSD1. With the Engelhard DPX installed, hydrocarbon emissions from both fuels were reduced to levels that were at or below the detection limit of the laboratory methods and were essentially indistinguishable from ambient background hydrocarbon levels.

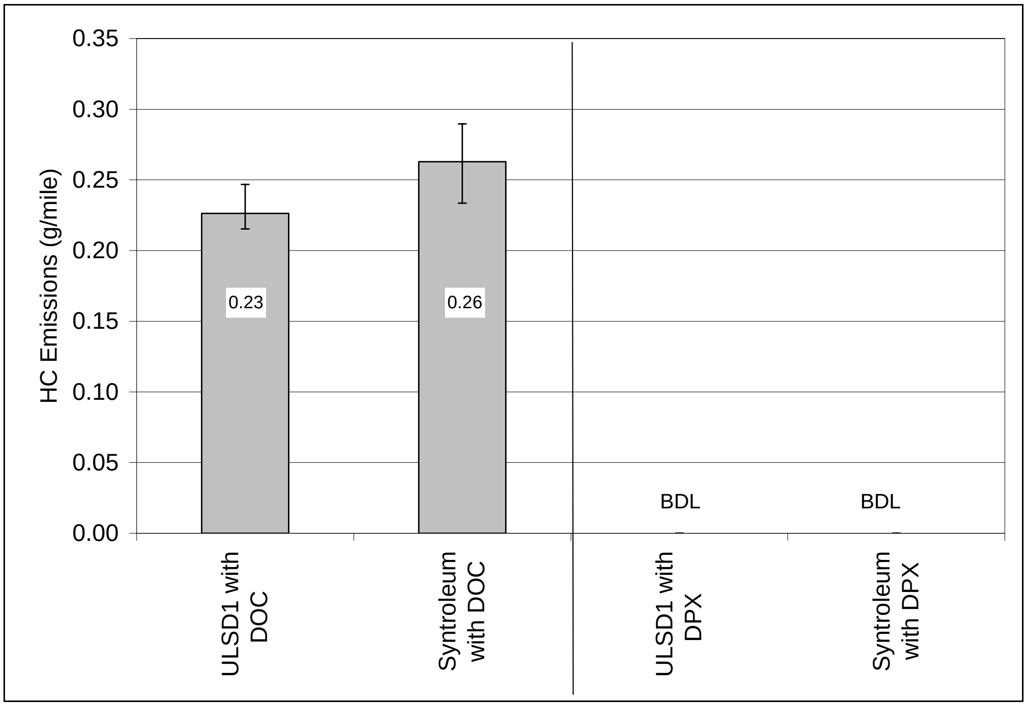

Figure 8: Phase1 hydrocarbon (HC) emissions.

In the OEM configuration with the DOC installed, use of the Syntroleum S-2 fuel produced a reduction in CO emissions of 7.1 percent compared to the USLD1 fuel. As expected, the Engelhard DPX produced substantial reductions in CO emissions with both fuels as shown in Figure 9. These results were in agreement with those of previous emissions studies conducted by WVU involving the Engelhard DPX catalyzed diesel particulate filters [9]. This type of exhaust aftertreatment system has proven very effective in reducing HC and CO emissions when used in conjunction with very low sulfur fuels.

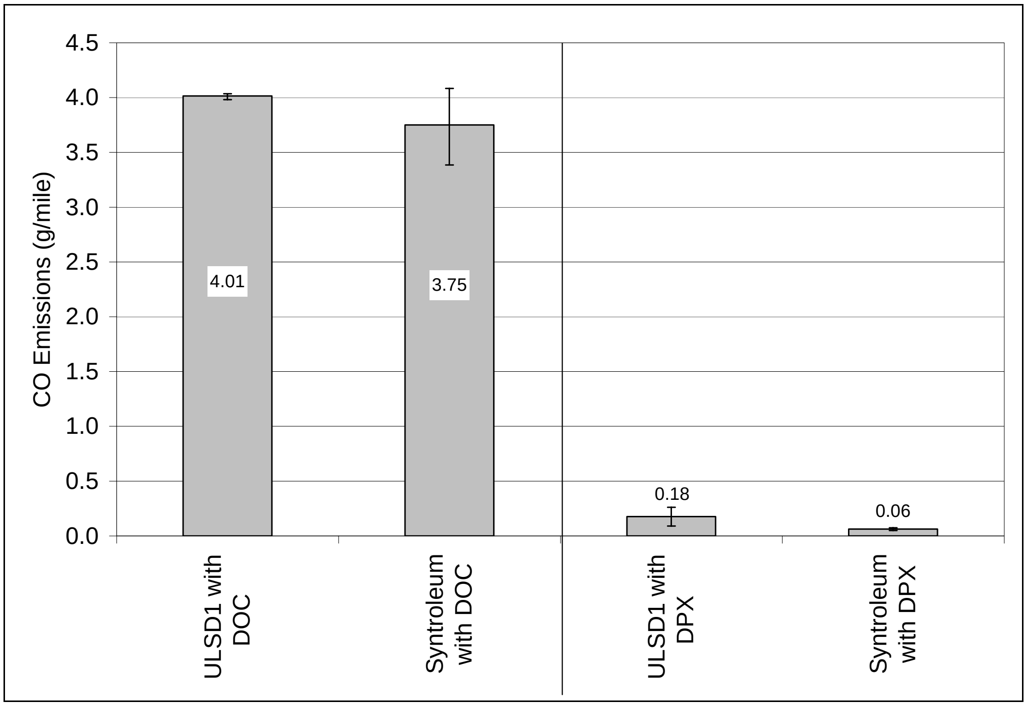

Figure 9: Phase 1 carbon monoxide (CO) emissions.

5.1.5 Fuel Economy Results

Fuel economy results, shown in Figure 10, indicate a slight improvement in fuel economy as a result of the Syntroleum S-2 fuel. The error bars shown on the plot are between duplicate runs. Fuel consumption is influenced by the energy content of the fuel (its lower heating value) and the thermal efficiency of the engine, which is influenced by the fuel through its effect on combustion efficiency. These may be affected by the cetane number, density and chemical composition of the fuel. It is also noted that CO_2 emissions could vary from test-to-test and the fuel economy differences shown may not be statistically significant.

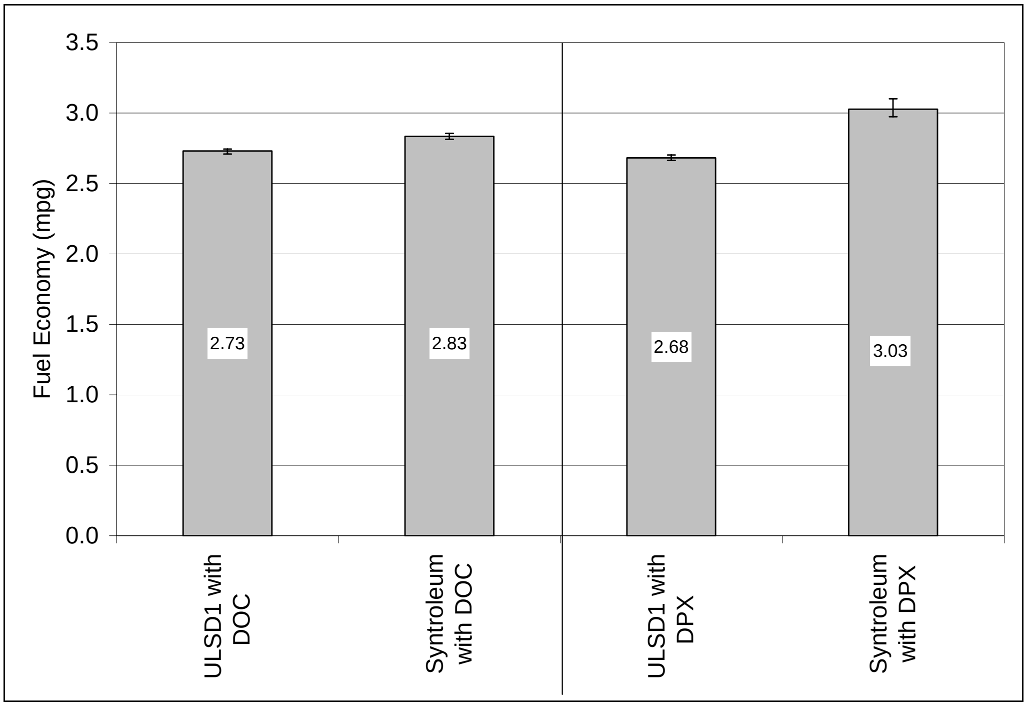

Figure 10: Phase 1 fuel economy.

5.1.6 Summary of Phase 1 Results

The exhaust emissions of a 40-foot transit bus equipped with a 1999 model year DDC Series 50 engine and fueled with a Syntroleum S-2 fuel were measured and compared to emissions from the same transit bus fueled with ultra-low sulfur petroleum-derived diesel fuel. Tests were conducted with two different types of exhaust aftertreatment systems; an OEM-style diesel oxidation catalyst and an Engelhard DPX catalyzed particulate filter.

- Results indicated that use of Syntroleum S-2 fuel produced reductions in NO_X emissions of 23-28% compared to the WMATA baseline ultra-low sulfur petroleum-derived diesel fuel.
- With the OEM diesel oxidation catalyst installed particulate matter emissions were reduced by approximately 35% when Syntroleum S-2 fuel was used.
- Results also indicated that with the Engelhard DPX installed, PM emissions were lower with the Syntroleum S-2 fuel compared to the ULSD1. However, it must be noted that the PM levels emitted from the Engelhard DPX are at or below the detectable limits of the current PM measurement methodology and practice and that the difference in DPF-out PM emissions between the two fuels may not be statistically significant.
- Results indicated that the Syntroleum S-2 fuel produced a slight increase in hydrocarbon emissions but this increase is not statistically significant considering the run-to-run variability.
- The Syntroleum S-2 fuel produced a slight decrease in carbon monoxide emissions compared to the USLD1 fuel in the DOC configuration.
- The Engelhard DPX reduced both HC and CO emissions to near ambient background levels regardless of fuel formulation.
- Results seem to indicate a slight improvement in fuel economy associated with the Syntroleum S-2 fuel.

5.2 Phase 2 – Denali National Park Tour Buses

Emissions measurements were conducted on six identical Thomas Transit Liner buses equipped with 2004 Caterpillar C7 ACERT engines at Denali National Park Alaska in July 2004. The buses were operated by Doyon/Aramark and provided park tours to Denali Park visitors.

5.2.1 Test Vehicle Information

The test buses had a gross vehicle weight rating of 36,200 lbs and an unloaded curb weight of 21,830 lbs. They could accommodate 49 seated passengers including the driver. All buses tested were equipped with Telma eddy current retarders, but they were disabled during testing to eliminate any additional and unquantified load placed on the engine by the retarder system. The buses were tested at simulated weights of 29,180 lbs representing the full capacity of the buses while touring Denali Park (150 lbs/person approximate weight).

The Caterpillar C7 ACERT engines were 4-stroke cycle, turbocharged/aftercooled, in-line 6-cylinder compression ignition engines with displacements of 7.2 liters. The engines had power ratings of 230 hp at 2400 rpm and 660 lb-ft of torque at 1440 rpm. Each test vehicle was equipped with an Allison MD3060 5-speed automatic transmission and a Dana Corporation rear axle. Exhaust from the Caterpillar C7 engine passed through a diesel oxidation catalyst (DOC) before exiting the four-inch exhaust system. The first three buses (531, 532, 536) were the baseline group and were tested with the JET A diesel fuel normally used at Denali National Park. The remaining buses (533, 534, 537A) were tested on the Syntroleum S-2 (SYNTRO) fuel. Test vehicle information is summarized in Table 3.

Table 3: Phase 2 Test Vehicle Information

Aramark Transit Bus Specifications				
Chassis	MY 2004 Thomas			
Engine Manufacturer/Model	MY 2004 Cat C7 ACERT			
Engine Ratings	230hp @ 2400rpm			
After-treatment System	Diesel Oxidation Catalyst			
Transmission Type	5-speed Automatic			
GVWR/Curb Weight	36200 / 21830 lb			
Bus Number	**VIN**	**Engine Serial Number**	**Odometer Reading**	**Fuel Type**
531	1T88U2C2751149858	KAL23694	8602	JETA
532	1T88U2C2951149859	KAL23696	7645	JETA
536	1T88U2C2X51149970	KAL24268	8144	JETA
533	1T88U2C2351149860	KAL24396	8086	SYNTRO
534	1T88U2C2551149861	KAL24760	6068	SYNTRO
537A	1T88U2C2151149971	KAL24425	6507	SYNTRO

5.2.2 Oxides of Nitrogen Emissions

Measured NO_X emissions are plotted in Figure 11. Each bar represents the average of at least three separate repeat test runs and the error bars indicate the spread of the data by showing the maximum and minimum individual test results. Fischer-Tropsch fuels are generally expected to produce moderate reductions in NO_X emissions. This is attributed to the low aromatics content, high cetane number and short ignition delay period [4]. Previous emissions measurements from Detroit Diesel Corporation (DDC) Series 50 powered transit buses at the Washington DC Metropolitan Transit Authority (WMATA) demonstrated a reduction in NO_X emissions of approximately 20% when operated on Syntroleum S-2 Fischer-Tropsch fuel compared to petroleum-derived ultra low sulfur diesel fuel.

The Denali Park buses, powered by Caterpillar C7 ACERT engines, exhibited the opposite trend from the WMATA buses. NO_X emissions from the three Syntroleum S-2 fueled buses were higher than the three sister buses fueled with Denali Park's standard JET A fuel. NO_X emissions from the three buses fueled with JET A fuel averaged 12.78 g/mile and were highly consistent from vehicle to vehicle. NO_X emissions from the buses fueled with Syntroleum S-2 fuel averaged 15.73 g/mile ranging from 14.55 g/mile to 16.83 g/mile. In order to verify that the higher NO_X results were not due to a malfunction or calibration problem with the measurement systems, WVU retested bus Number

532 fueled with JET A, at the end of the program. The results from the retest were consistent with the previous results for that same bus indicating that the higher NO_X emissions were indeed a fuel related or vehicle related phenomenon. They could not be attributed to any change or drift in laboratory function.

NO_X emissions from diesel, compression ignition engines are primarily composed of nitric oxide (NO) and nitrogen dioxide (NO_2). The Denali Park buses were not equipped with catalyzed diesel particulate filters and the NO fractions shown in Figure 11 are consistent with the levels that would be expected for buses not equipped with such filters. The NO results also follow the same trend with regards to fuel as the total NO_X results.

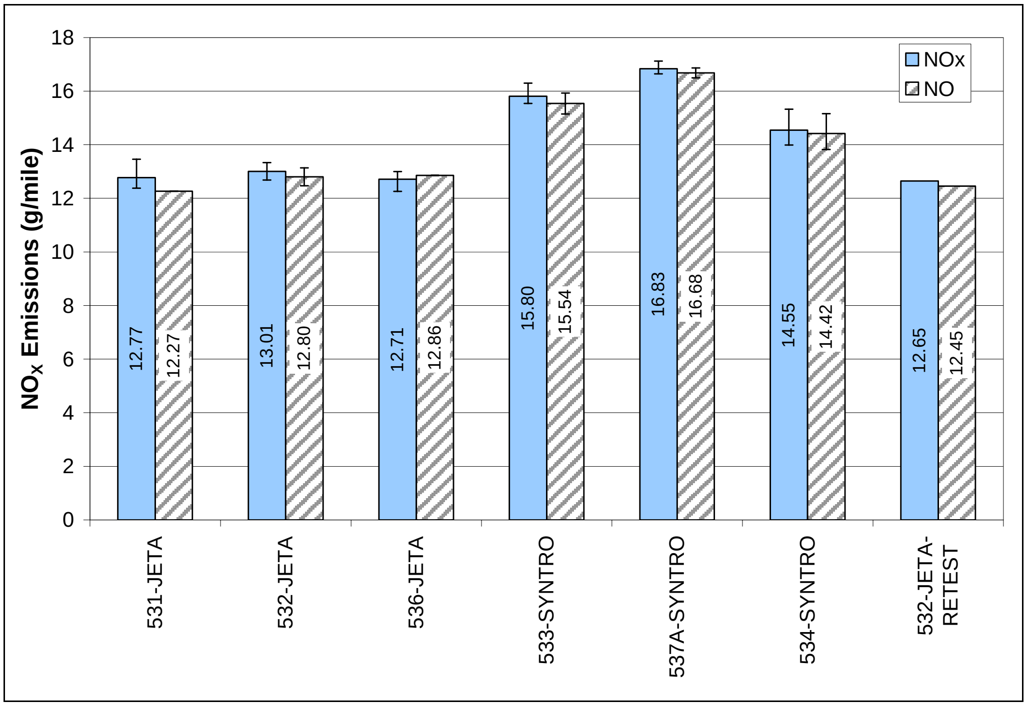

Figure 11: Phase 2 oxides of nitrogen emissions.

Unlike Detroit Diesel Corporation Series 50 engines, Caterpillar C7 ACERT engine does not employ exhaust gas recirculation to reduce NO_X emissions. The Caterpillar C7 ACERT engine employs multiple fuel injections to reduce the pre-mixed combustion and reduce NO_X emissions. This fuel injection strategy is believed to be highly sensitive to fuel properties especially cetane number. The Jet A fuel normally used in the Denali Park buses has a cetane number of 44.6 (Table 1) which is typical of most domestically available petroleum-derived diesel fuels. The Caterpillar ACERT engines were originally calibrated for a diesel fuel with a cetane number in the neighborhood of 40. The Syntroleum S-2 fuel had a cetane number of 73.6 which is substantially higher than typical diesel fuel for which the Caterpillar engines were calibrated. The most probable explanation for the higher NO_X emissions is that the Syntroleum S-2 fuel is igniting earlier in the combustion stroke effectively advancing the ignition timing, thereby increasing NO_X production. The critical time period for NO_X formation occurs when burned gas temperature in the cylinder is high. Fuel mixture burned early in the combustion process is especially important since it is compressed to a higher temperature, increasing the NO_X formation rate. It should be possible to mitigate the increased NO_X emissions by adjusting the calibration and injection strategy of the Caterpillar ACERT engines to account for the properties of the Syntroleum S-2 fuel.

The NOx emission results obtained with the buses at Denali National Park led to additional investigation and emission measurements conducted by ICRC and AVL Powertrain Engineering using both a Detroit Diesel Series 50 and a Caterpillar C-7 bus engine in dynamometer test cells at AVL's Ann Arbor laboratory. AVL measured emissions of NO_X, CO, THC and CO_2 from Caterpillar C-7 engine using the AVL 8-Mode test cycle which consists of eight steady-state modes designed to correlate with exhaust emissions results of the US FTP Heavy-Duty Transient Cycle. The composite emissions values are calculated by applying weighting factors to each mode. A more detailed discussion of the AVL 8-Mode test is covered in companion project report prepared by AVL and submitted to ICRC. Results reported by AVL for the Caterpillar C-7 engine showed a reduction in NO_X emissions on the order of 15% with the Syntroleum S-2 fuel compared to the Denali Park Jet-A fuel. The results obtained at AVL show the opposite trend from the results obtained from the Denali Park bus fleet which showed increased NO_X emissions with the Syntroleum S-2 fuel. No definite explanation for the contrasting results obtained from engine dynamometer tests conducted by AVL and the chassis dynamometer tests conducted by WVU on the Denali Park buses has emerged. However, there are two factors that may have contributed to these results.

First, the AVL 8-mode steady-state test may not have captured the effects of transient engine operation. For engines with advanced engine controls, NO_X emissions may be heavily influenced by the transient nature or the test cycle.

Second, the emissions tests conducted at AVL were performed with a fresh set of injectors where as emission testing of the Denali Park buses was conducted with in-use injectors. An inspection of Caterpillar C-7 ACERT fuel injectors performed at AVL following 1500 hours of durability testing on the Syntroleum S-2 fuel found evidence of deposit formation and partial blockage of the injector tip holes. It is possible that the fuel injectors in the Denali Park buses fueled with Syntroleum S-2 fuel may have suffered some level of injector nozzle blockage similar to that found in the AVL test engine. The Caterpillar ACERT technology relies on the fuel injection strategy (both injector hardware and injection rate shaping) to control NO_X emissions. Any condition such as deposit formation and blockage that affects fuel delivery to the combustion chamber or the fuel spay pattern could negatively impact NO_X emissions.

5.2.3 Particulate Matter Emissions

Particulate emissions are plotted in Figure 12. There was some vehicle-to-vehicle variability in the particulate emissions. PM emissions from the JET A fueled buses, averaged over the group was 0.188 g/mile. The Syntroleum S-2 fueled buses averaged 0.144 g/mile which constituted a reduction of approximately 25%.

As discussed earlier in Section 5.1.3 the higher cetane number and lower aromatic content of the Syntroleum S-2 fuel played a role in the reduction of PM emissions. Additionally, the very low sulfur content of the Syntroleum S-2 fuel may have partially contributed to this PM reduction, though it was limited.

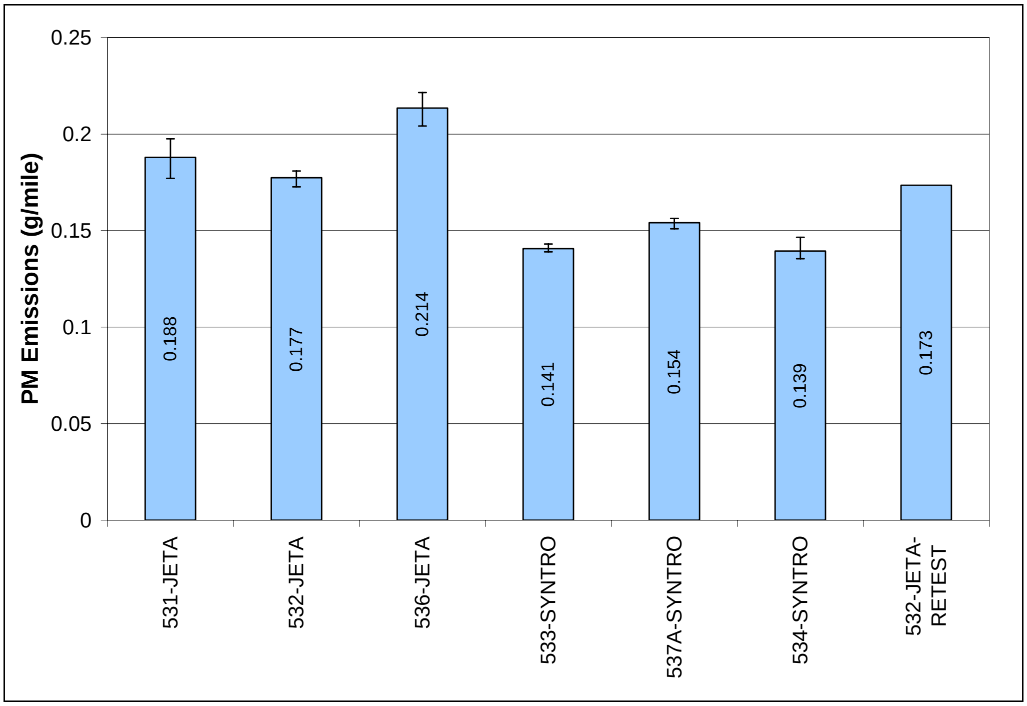

Figure 12: Phase 2 particulate matter emissions.

The Denali Park buses were equipped with diesel oxidation catalysts rather than catalyzed diesel particulate filters. It is important to note, however, that due to its near zero sulfur content, the Syntroleum S-2 fuel is highly compatible with catalyzed particulate filter technology. The high precious metal and platinum loading in passive catalyzed particulate filters such as the Engelhard DPX and Johnson-Matthey CRT substantially increase the formation of sulfates.

5.2.4 Hydrocarbon and Carbon Monoxide Emissions

Hydrocarbon results are plotted in Figure 13. HC emissions were very low for both fuels. The JET A fueled buses averaged 1.05 g/mile while the Syntroleum S-2 fueled buses averaged 0.197 g/mile an apparent reduction of 81%. It is noted however that the JET A results exhibited substantial bus-to-bus variability.

Carbon monoxide results are plotted in Figure 14. The buses fueled with JET A fuel averaged 11.20 g/mile ranging from 8.74 g/mile to 13.72 g/mile. The Syntroleum S-2 fueled buses averaged 3.55 g/mile, which is a reduction of 68% compared to the JET A fueled bus group.

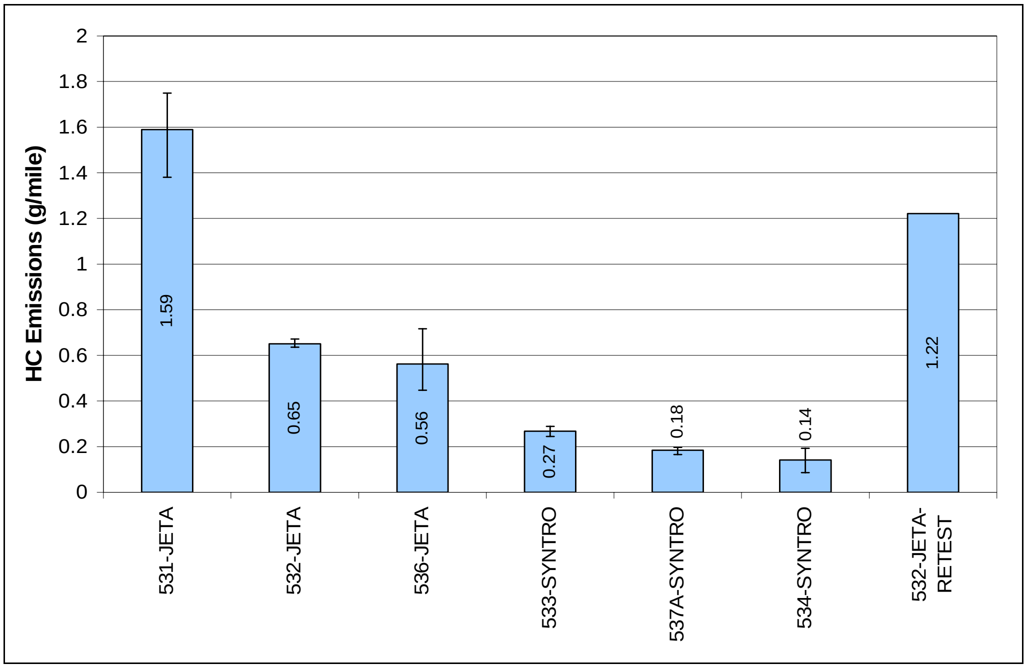

Figure 13: Phase 2 hydrocarbon emissions.

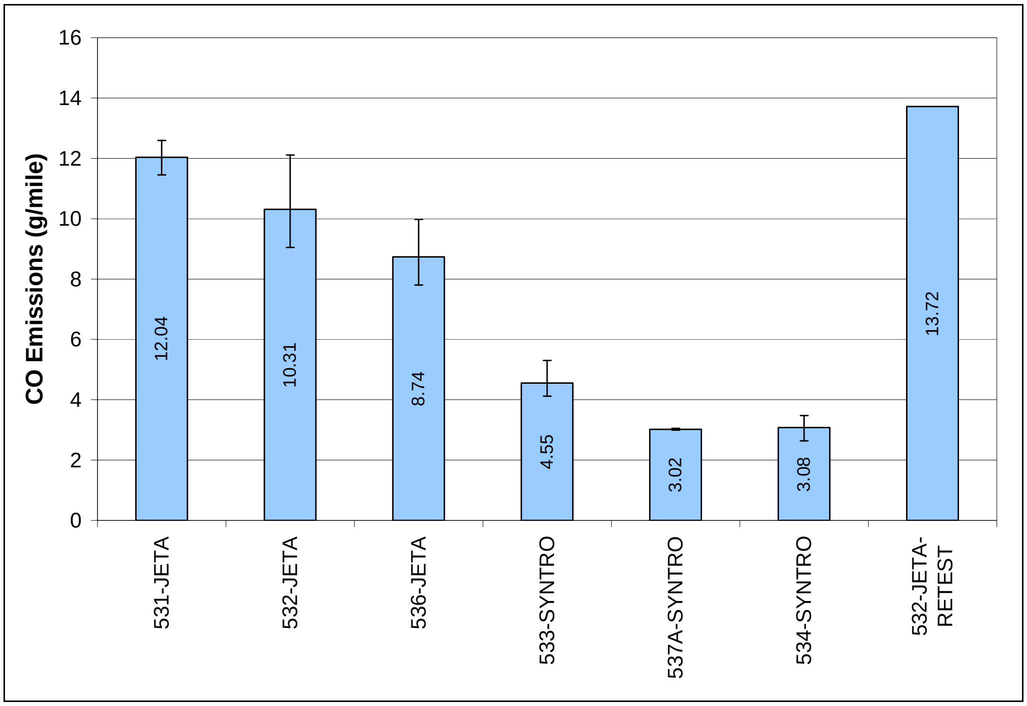

Figure 14: Phase 2 carbon monoxide emissions.

5.2.5 Fuel Economy Results

Fuel economy results are shown in Figure 15. Fuel consumption during the chassis dynamometer testing was very similar between the two fuels. The JET A bus group averaged 3.65 miles/gallon over the WMATA driving cycle while the Syntroleum S-2 buses averaged 3.61 miles/gallon. It is noted however that Doyon/Aramark report observing a slight increase in fuel economy from the Syntroleum S-2 fueled buses based on fleet fueling records.

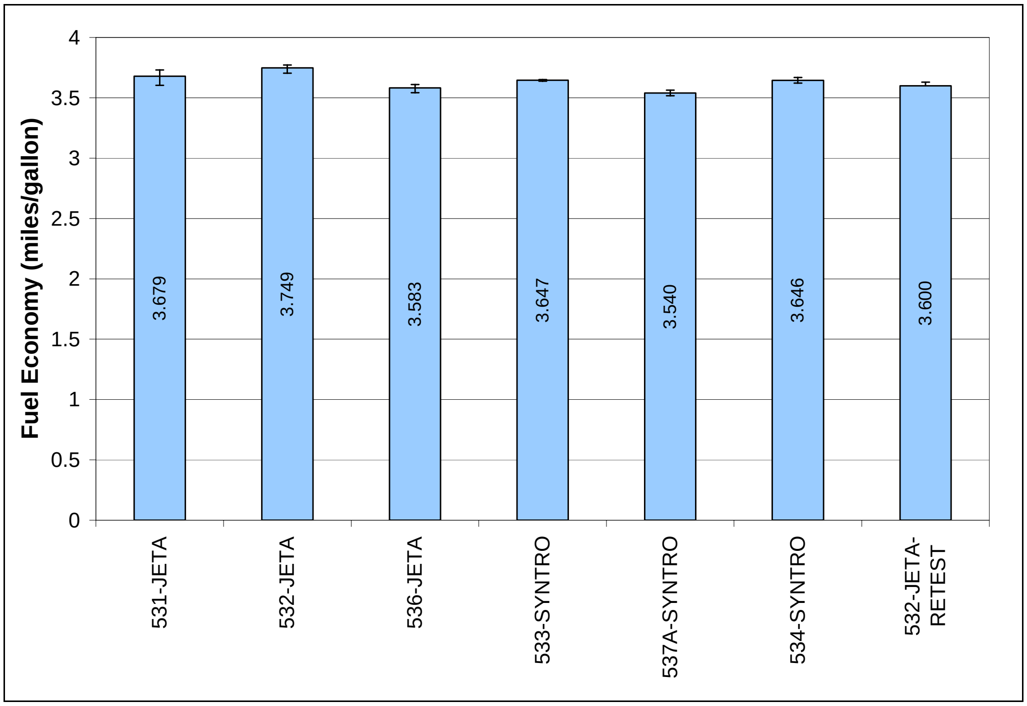

Figure 15: Phase 2 fuel economy.

5.2.6 Summary of Phase 2 Results

Emissions measurements were conducted on six identical Thomas Transit Liner buses equipped with 2004 Caterpillar C7 ACERT engines at Denali National Park Alaska. The exhaust emissions from buses fueled with Syntroleum S-2 fuel were compared to emissions from buses fueled with low sulfur petroleum-derived JET A fuel. All of the buses were equipped with diesel oxidation catalysts.

- Results indicated that use of Syntroleum S-2 reduced particulate emissions by approximately 25% compared to the low sulfur Jet A fuel.
- CO emissions were reduced by approximately 68% compared to the Jet A fuel.
- Averaged over the two groups, Syntroleum S-2 fuel also resulted in a reduction in HC emissions of 81% but it is noted that HC emissions were low from both fuels and that there was substantial variation within the JET A bus group.
- Use of the Syntroleum S-2 fuel with the Caterpillar C7 ACERT engines produced an increase in NO_X emissions of approximately 2.9 g/mile compared to the buses fueled with JET A fuel. This trend was contrary to the results observed from the Detroit Diesel powered buses at the Washington DC Metropolitan Transit Authority.
- The Caterpillar ACERT engines employ multiple injections to reduce NO_X emissions. The higher NO_X emissions observed with the Syntroleum S-2 fuel in the Caterpillar engines are probably due to earlier ignition resulting from the combination of the higher cetane number of the Syntroleum S-2 fuel and the “normal” engine calibration intended for conventional 40-45 cetane number fuel.
- There did not appear to be any significant difference in fuel economy between the two fuels.

5.3 Phase 3 – WMATA Municipal Transit Buses

In August 2004, the WVU Transportable Heavy-Duty Vehicle Emissions Laboratory returned to Washington DC to measure the emissions of six transit buses equipped with oxidation catalysts. Three buses fueled with Syntroleum S-2 fuel and three buses fueled with WMATA’s conventional ultra-low sulfur (30 ppm S max.) were tested.

5.3.1 Test Vehicle Information

The test vehicles were 2000 model year Orion 40-foot municipal transit buses each equipped with a 2000 model year Detroit Diesel Corporation (DDC) Series 50 diesel engine. The buses were owned by the WMATA and were operated in municipal transit service in the Washington D.C., Northern Virginia and Southern Maryland area. The transit buses had gross vehicle weight ratings of 42,540 lbs and an unloaded curb weight of 27,800 lbs. They could accommodate 39 seated passengers and 20 standing passengers. The bus emissions were characterized at a simulated weight of 33,300 lbs representing approximately one-half of the maximum passenger capacity. The buses were equipped with original equipment (OEM) diesel oxidation catalysts (DOC). Table 4 summarizes the test vehicle information.

Table 4: Phase 3 Test Vehicle Information

WMATA Transit Bus Specifications				
Chassis	MY 2000 Orion			
Engine Manufacturer/Model	MY 20009 Detroit Diesel Corporation Series 50			
Engine Ratings	275hp @ 2100rpm			
After-treatment System	Diesel Oxidation Catalyst			
Transmission Type	4-speed Automatic			
GVWR/Curb Weight	42,540 / 28,800 lb			
Bus Number	**VIN**	**Engine Serial Number**	**Odometer Reading**	**Fuel Type**
2093	1VH6H2A25Y6600332	04R0032003	181,688	ULSD1
2092	1VH6H2A23Y6600331	04R0032000	207,038	ULSD1
2094	1VH6H2A27Y6600333	04R0032183	194,125	ULSD1
2054	1VH6H2A28Y6600292	04R0031458	216,793	SYNTRO
2056	1VH6H2A21Y6600294	04R0031395	197,420	SYNTRO
2055	1VH6H2A2XY6600293	04R0031626	202,369	SYNTRO

5.3.2 Oxides of Nitrogen Emissions

Measured NO_X emissions are plotted in Figure 16. Each bar represents the average of at least three separate repeat test runs and the error bars indicate the spread of the data by showing the maximum and minimum individual test results. Measured NO_X emissions, from the buses fueled with Syntroleum S-2 fuel were reduced by 22 percent compared to the control vehicles fueled with petroleum-derived ULSD1. The ratio of NO to NO_X emissions was determined using a dual NO_X analyzer method. The method employs two unique analyzers, one operated in the NO_X mode, while the other analyzer operates in the NO mode. The technique and limitations have been previously described [9]. In Figure 16, the cross-hatched bar represents the NO fraction of the NO_X emission. Oxides of nitrogen emission from diesel engines diesel oxidation catalysts may include 3% to 15% NO_2 depending on engine design and operating conditions and are typically 3% to 5% averaged over a transient test cycle. The NO_X was generally comprised of 93%-97% NO and the NO/NO_X ratio was not generally affected by the fuel.

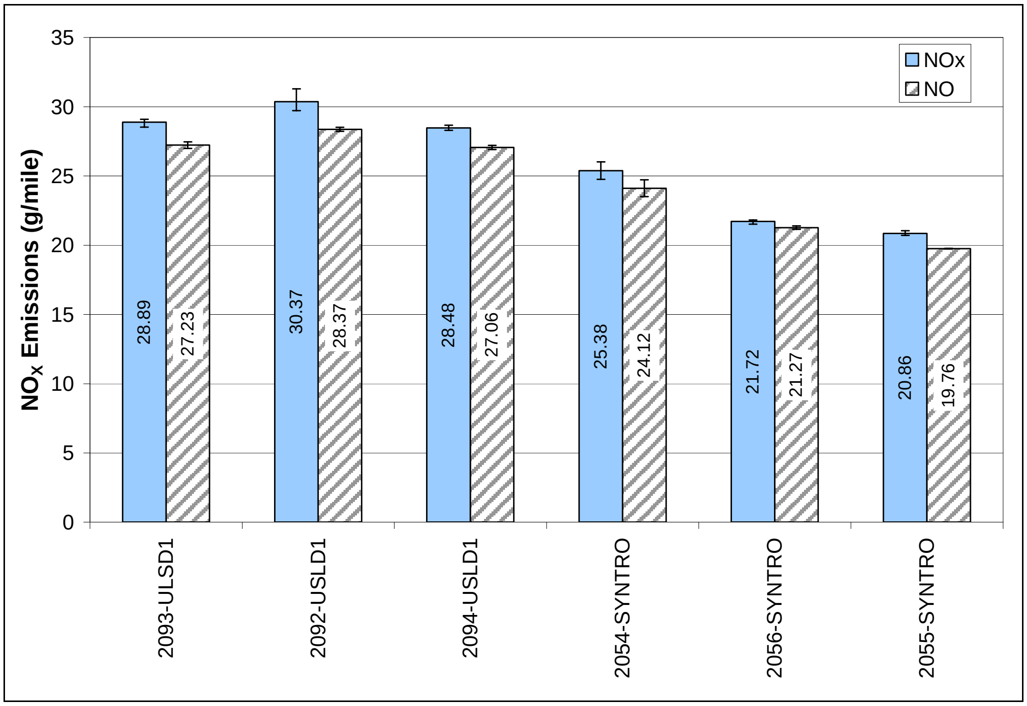

Figure 16: Phase 3 oxides of nitrogen emissions.

5.3.3 Particulate Matter Emissions

Particulate matter emissions are plotted in Figure 17. PM emissions exhibited considerable vehicle-to-vehicle variation. PM emissions from the ULSD1 group ranged from 0.178 to 0.399 g/mile with an average of 0.276 g/mile. The Syntroleum S-2 group ranged from 0.180 to 0.339 g/mile with a group average of 0.287 g/mile. There was no statistically significant difference between the two groups. While the Syntroleum S-2 is lower in sulfur and aromatic content than the ultra-low sulfur conventional diesel fuel, these are both low-emissions fuels compared to conventional No. 1 diesel fuel which typically has a sulfur level of ~400 ppm. It was recognized that it would be difficult to distinguish PM emissions differences between the two fuels considering vehicle-to-vehicle variations and the fact that the test vehicles were equipped with diesel oxidation catalysts.

It is also noted that the baseline fuel was a No. 1 diesel fuel which would be expected to have lower weight PM than a No.2 diesel fuel all else being equal. The Syntroleum S-2 fuel fell somewhere between No. 1 and No. 2 diesel fuel having a broader distillation range (321°F-619°F) and higher final boiling point (FBP) than the ultra-low sulfur No. 1 fuel (354°F-527°F). For comparison a conventional Federal No. 2 diesel fuel recently used by WVU in another program had a distillation range of 359°F-654°F. All else being equal the Syntroleum S-2 fuel with a higher T90 and FBP would be expected to have slightly higher weight PM than the baseline No. 1 diesel fuel.

Fuel sulfur is converted to SO_2 and sulfates which, along with bound water manifest themselves as PM emissions. There is generally a linear relationship between fuel sulfur consumption and the sulfate portion of PM emissions with a conversion rate of between 1 to 2 percent for engines without aftertreatment. The contribution of sulphates to the total particulate mass is only a few percent so that the reduction of PM through reduction of fuel sulfur content is limited. However, the high precious metal and platinum loading in passive catalyzed particulate filters such as the Engelhard DPX or Johnson-Matthey CRT substantially increase the formation of sulfates. It is important to note that the near zero sulfur content of Syntroleum S-2 GTL fuel may offer a marginal advantage over ultra-low sulfur petroleum-derived diesel for vehicles equipped with catalyzed particulate filters.

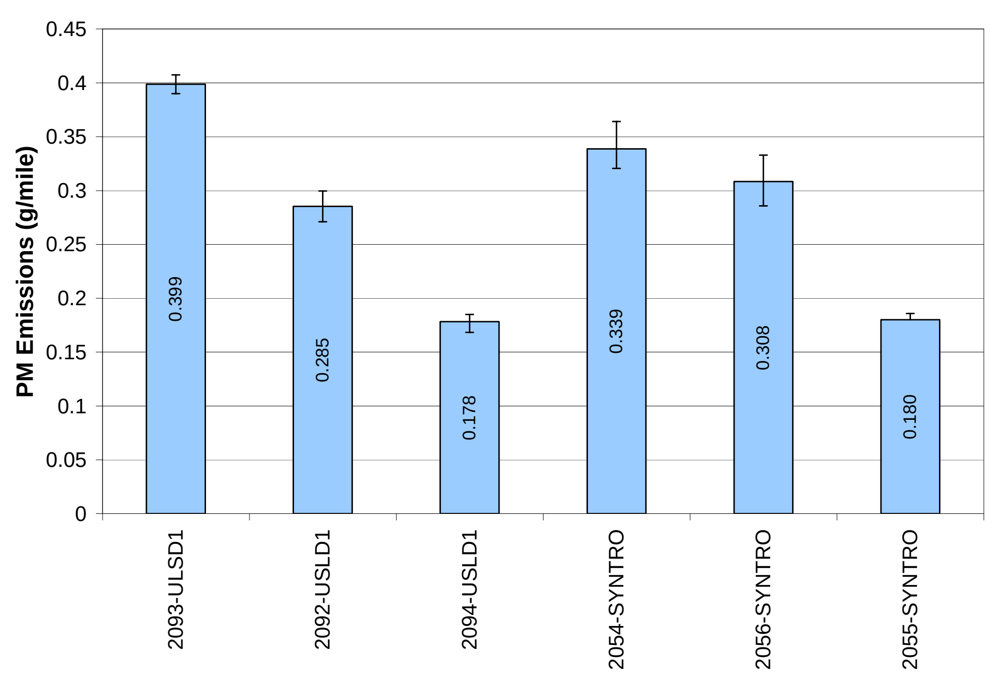

Figure 17: Phase 3 particulate matter emissions.

5.3.4 Hydrocarbon and Carbon Monoxide Emissions

Hydrocarbon results are plotted in Figure 18. Hydrocarbon levels from both groups of buses were very low as would generally be expected from vehicles equipped with oxidation catalysts. HC emissions from the ULSD1 fueled buses ranged from 0.02 – 0.23 g/mile with a group average of 0.11 g/mile. The Syntroleum S-2 fueled buses produced HC emissions ranging from 0.06-0.24 g/mile with a group average of 0.15 g/mile. Given the data scatter there appeared to be no significant difference between the two fuels in terms of HC emissions. HC measurement at these extremely low levels was difficult because ambient HC concentration, which was near the engine-out levels, could have confounded the measurement.

Carbon monoxide emissions are shown in Figure 19. The USLD1 fueled buses averaged 4.04 g/mile CO over the WMATA test cycle while the Syntroleum S-2 fueled buses averaged 3.95 g/mile. The results exhibited some vehicle-to-vehicle variability in both groups. However, there appeared to be little difference in CO emissions between the two fuels.

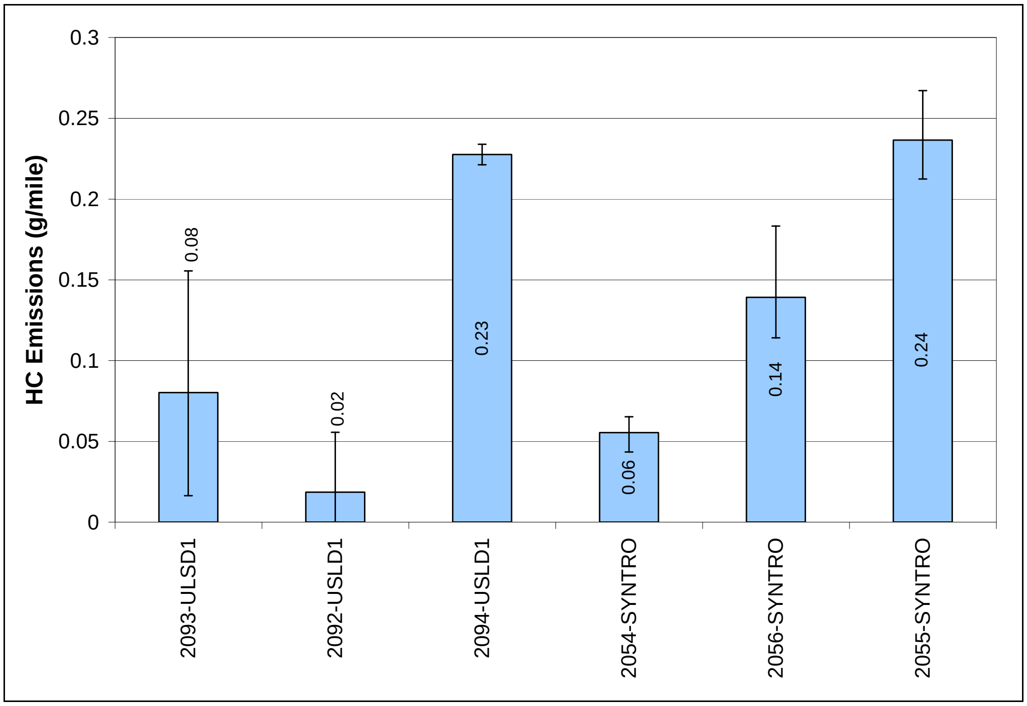

Figure 18: Phase 3 hydrocarbon emissions.

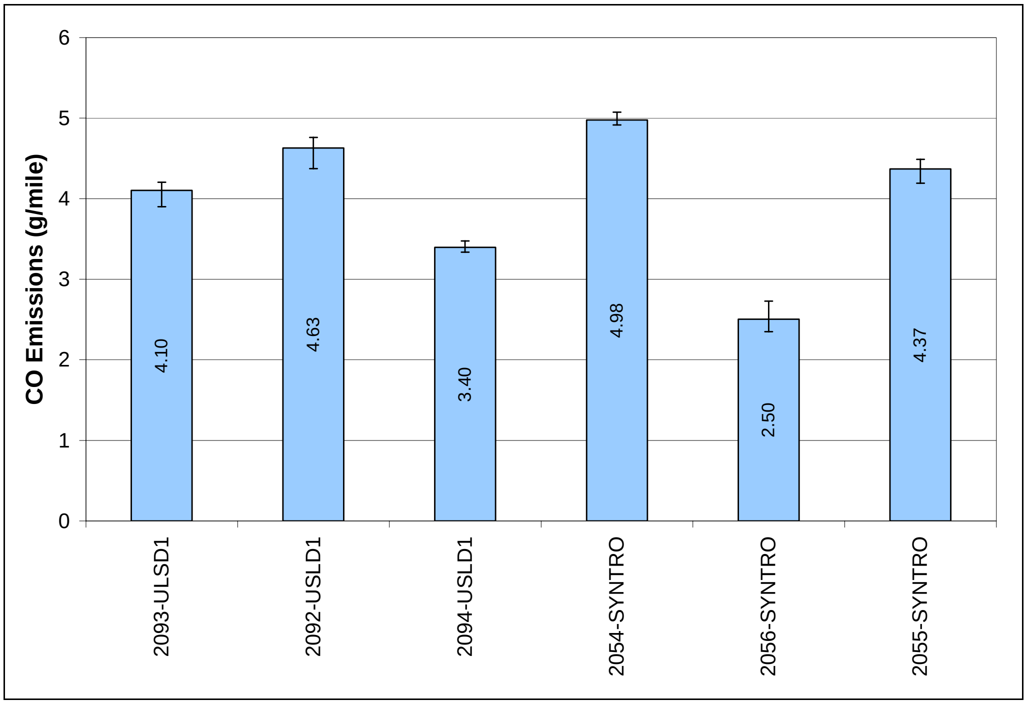

Figure 19: Phase 3 carbon monoxide (CO) emissions.

5.3.5 Carbon Dioxide and Fuel Economy Results

Carbon dioxide emissions are shown in Figure 20 and fuel economy results are shown in Figure 20. CO_2 emissions from the USLD1 group averaged 2809 g/mile ranging from 2612-2923. The Syntroleum S-2 fueled buses averaged 2736 g/mile of CO_2 ranging from 2612-2977 g/mile representing a difference of less than 3% between the two groups. Fuel economy was also similar between the two fuels with the USLD1 group averaging 3.44 miles/gallon and the Syntroleum S-2 group averaging 3.38 miles/gallon.

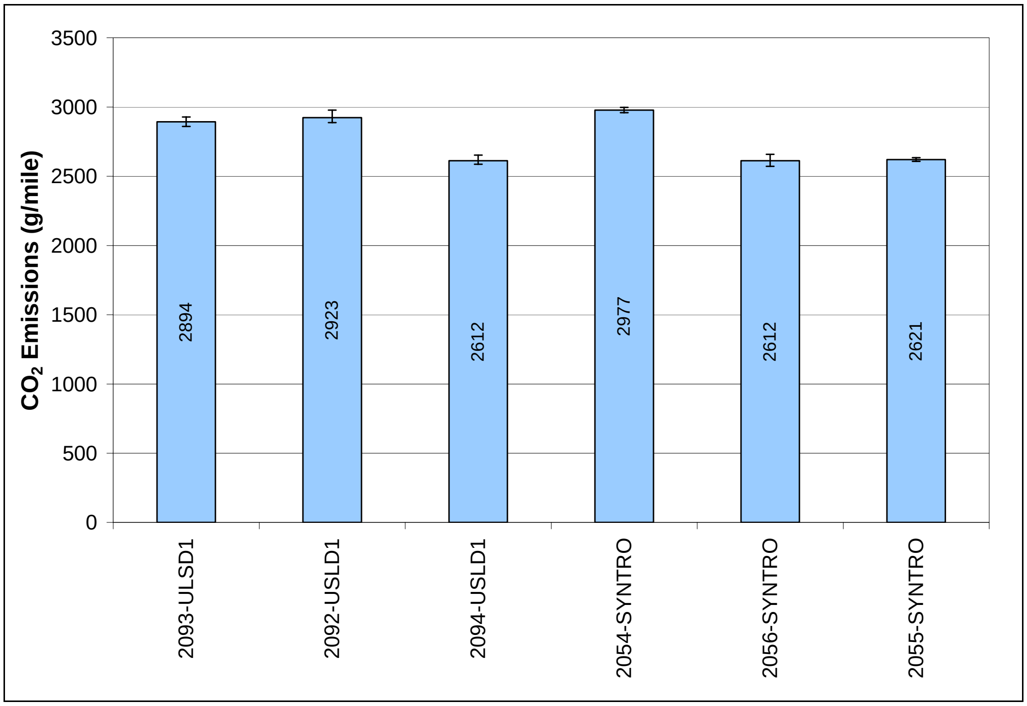

Figure 20: Carbon dioxide emissions.

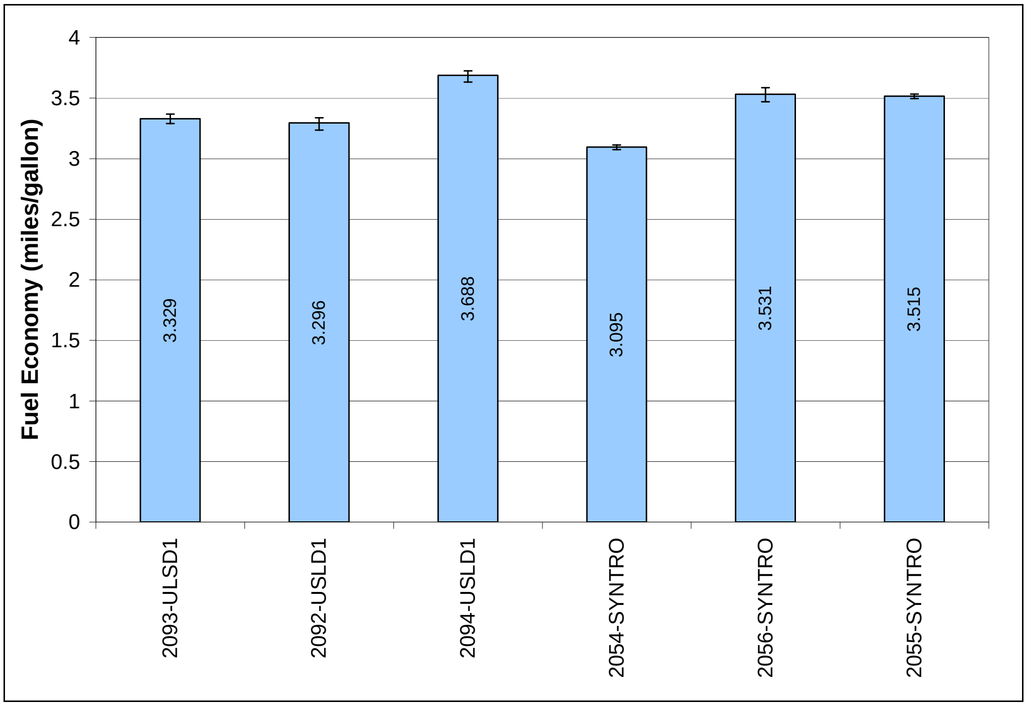

Figure 21: Fuel economy.

5.3.6 Summary of Phase 3 Results

Emissions tests were conducted on six 40-foot transit buses equipped with 2000 MY DDC Series 50 engines and diesel oxidation catalysts. Three buses were fueled with petroleum-derived ultra-low sulfur type 1 diesel fuel and three were fueled with Syntroleum S-2 fuel.

- Measured NO_X emissions, from the buses fueled with Syntroleum S-2 fuel were reduced by 22 percent compared to the control vehicles fueled with petroleum-derived ultra-low sulfur type 1 diesel fuel due to the low aromatic content and high cetane number.
- No significant differences were observed between the two fuels in terms of PM, HC and CO emissions. This similarity may be due in part to the fact that both groups of buses were equipped with diesel oxidation catalysts and that any differences in engine-out emissions may have been obscured by the catalytic action of the oxidation catalysts.
- Carbon dioxide and fuel economy results were also very similar between the two fuels.

5.4 Phase 4 – 6-Month Retest of WMATA Municipal Transit Buses

The final phase of emissions testing re-examined the Syntroleum-fueled WMATA buses after they had been operating in normal revenue service on the S-2 fuel for 6-months. WVU conducted the follow-up testing at WMATA in April 2005. The approach to the second round of testing at WMATA differed somewhat from the testing conducted in August 2004 as explained below.

Determination of whether or not Fischer-Tropsch (F-T) fuel would be acceptable for operating bus fleets was one of the questions that the Ultra-Clean Fuels Project was intended to answer. Therefore, the use of three “control” buses running on conventional fuel during the bus fleet demonstrations of F-T fuel in three other test buses in each fleet, provided a valuable reference in the event of any operating difficulties that could, potentially, have occurred with the then “new and unproven” F-T fuel. The approach to exhaust emission testing within the two bus-fleet demonstrations as spelled out in the original cooperative agreement between ICRC and NETL was to compare emissions from three F-T fueled buses to three similar “control” buses using their normal conventional fuel. This approach to emission measurements flowed rather naturally from the program’s overall approach. The approach worked fairly well within the Denali National Park bus fleet, because all six buses were brand new and thus they exhibited relatively little bus-to-bus variation in emissions (within the two fuel-groups), allowing a reasonable comparison of the effects of the two fuels on emissions despite the additional variable of buses or engines.

However, in the WMATA fleet, the buses had been in year-round, heavy-use urban transit service for four to five years. The first-round emission test results at WMATA showed significant bus-to-bus variability within both groups (of 3 buses on each fuel) that may have obscured the fuel effects that are of primary interest. Therefore, for the second round of emission measurements at WMATA, ICRC and WVU determined that the comparison should be back-to-back emission tests on both F-T and conventional fuels in the three buses that have been operating on F-T fuel for the past six months of the demonstration program, with no further emission testing of the 3 “control” buses.

5.4.1 Test Vehicle Information

The WMATA test buses have previously been described in Section 5.3.1. The intention was to re-test the three WMATA buses that been operated on the Syntroleum S-2 fuel (WMATA Bus Numbers 2054, 2055, 2056) on both the Syntroleum S-2 fuel and the ULSD1 fuel. However, Bus 2056 experienced a mechanical engine failure and could not be tested in Phase 4. (A companion ICRC project report to this report by WVU describes the findings from WMATA’s teardown and inspection of the engine in Bus 2056 with ICRC personnel present.) Following consultation with ICRC, WVU tested Bus 2093 as a replacement for Bus 2056. Bus 2093 was one of the ULSD1 control buses tested in Phase 3. Table 5 summarizes the transit buses specifications.

Table 5: Phase 4 Test Vehicle Information

WMATA Transit Bus Specifications			
Chassis	MY 2000 Orion		
Engine Manufacturer/Model	MY 20009 Detroit Diesel Corporation Series 50		
Engine Ratings	275hp @ 2100rpm		
After-treatment System	Diesel Oxidation Catalyst		
Transmission Type	4-speed Automatic		
GVWR/Curb Weight	42,540 / 28,800 lb		
Bus Number	**VIN**	**Engine Serial Number**	**Odometer Reading**
2054	1VH6H2A28Y6600292	04R0031458	252,652
2055	1VH6H2A2XY6600293	04R0031626	236,676
2093	1VH6H2A25Y6600332	04R0032003	216,937

5.4.2 Oxides of Nitrogen Emissions

NO_X emissions results are plotted in Figure 22. In Phase 4, measured NO_X emissions from Syntroleum S-2 fuel were reduced by 16 percent when compared to petroleum-derived ULSD1 fuel in the same buses. The cross-hatched bar in Figure 22 represents the NO fraction of the NO_X emissions. On average, the NO_X emissions were comprised of 97 percent NO. This agreed with typical NO fractions in NO_X emissions for diesel oxidation equipped diesel vehicles, which are usually 93-97 percent NO. The ratio of NO/NO_X was not affected by the fuel type.

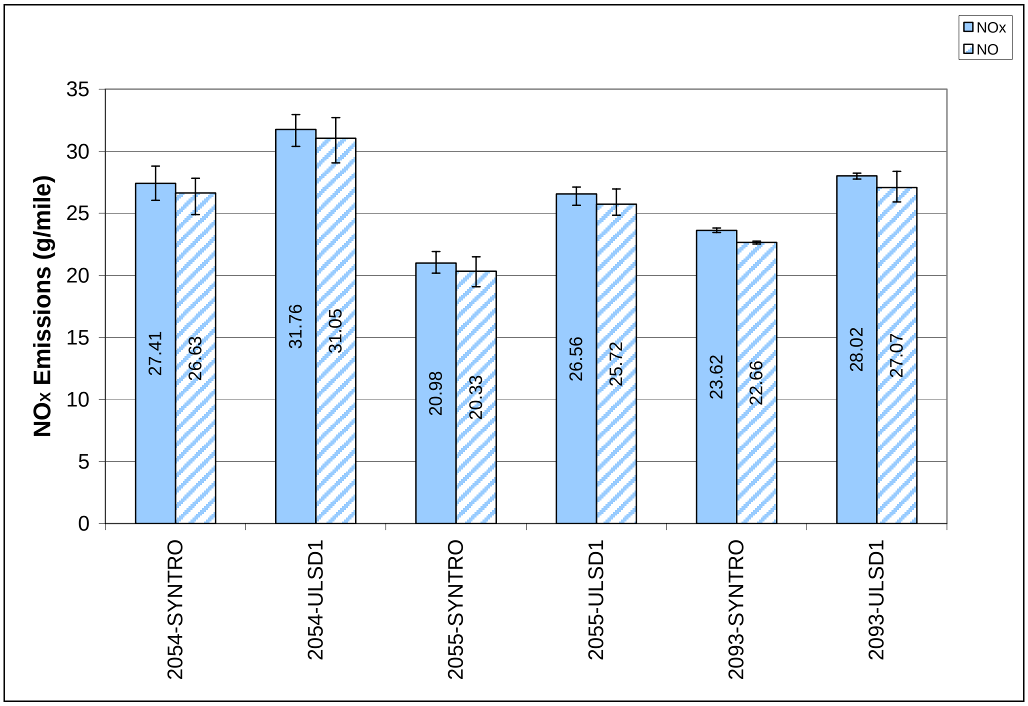

Figure 22: Phase 4 oxides of nitrogen emissions.

A comparison of measured NO_X emissions from Phase 3 and Phase 4 is shown in Figure 23. Bus number 2054 NO_X emissions from Syntroleum S-2 fuel were increased by 7 percent after the 6-month period. NO_X emissions from bus number 2055 fueled with Syntroleum S-2 fuel were increased as well, however NO_X emissions difference was less than 1 percent. In Phase 3 buses numbers 2054 and 2055 were originally tested using Syntroleum S-2 fuel. In Phase 4 these two buses were tested with both ULSD1 and Syntroleum S-2 fuels. Bus number 2093 was chosen to replace bus number 2056 and it was tested with both fuels as well. ULSD1 fuel emissions from bus number 2093 were reduced by 3 percent when compared to the original results obtained in Phase 3. In regard to the two fuels comparison, Syntroleum S-2 fuel NO_X emissions were reduced by about 17 percent in back-to-back tests in the same buses compared to ULSD1 over the baseline fuel. Overall, NOx emissions were remarkably consistent in tests at the beginning and at the end of the 6-month interval for those buses tested on a particular fuel in both Phases 3 and 4.

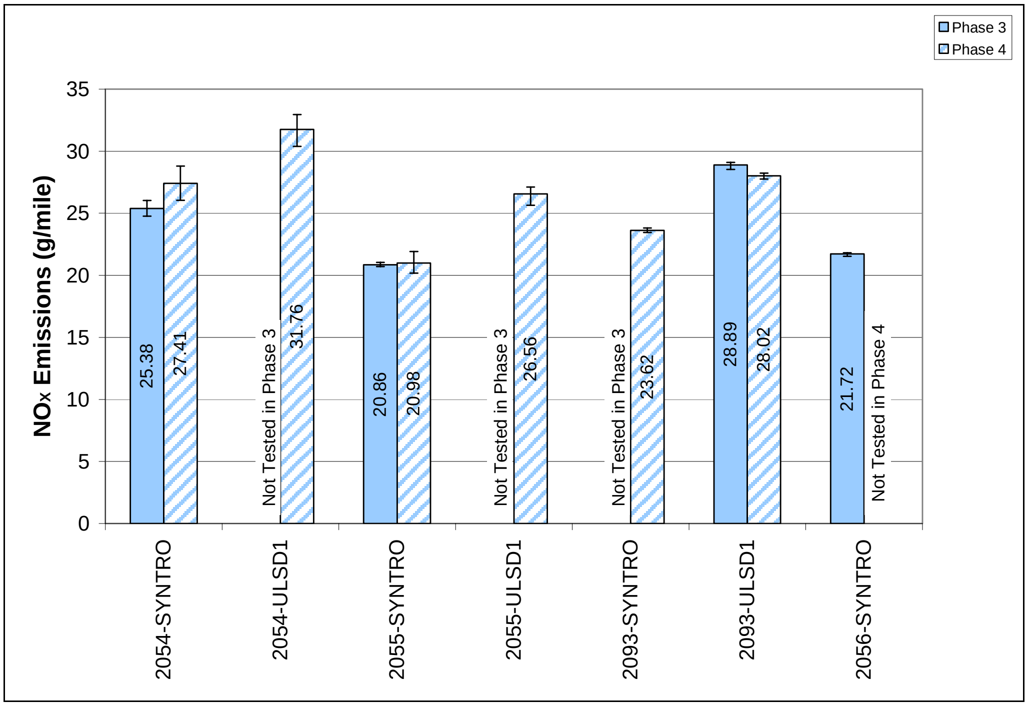

Figure 23: Phase 3 & 4 oxides of nitrogen emissions.

5.4.3 Particulate Matter Emissions

In contrast to the foregoing NOx emission results, particulate matter emissions for any particular bus/fuel combination decreased significantly from Phase 3 to Phase 4 for all three buses. In Phase 4 the PM emissions levels produced by Syntroleum S-2 fuel were lower, on average, by 35 percent compared to ULSD1 fuel PM emissions for the same buses. These results are represented by the cross-hatched bars in Figure 24. ULSD1 fuel PM emissions ranged from 0.188 to 0.334 g/mile with an average of 0.245 g/mile. The Syntroleum S-2 fuel PM emissions ranged from 0.120 to 0.203 g/mile with an average of 0.158 g/mile.

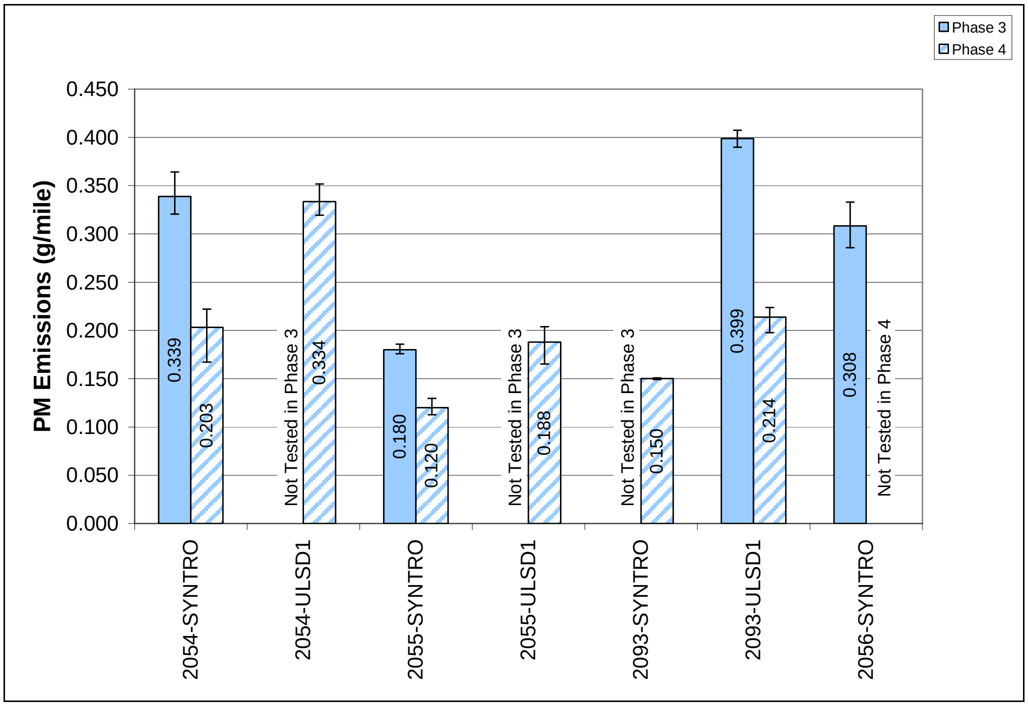

Figure 24: Phase 3 & 4 particulate matter emissions.

PM emissions over Phases 3 & 4 exhibited considerable phase-to-phase variability. In Phase 3 bus number 2054 produced 0.339 g/mile of PM emissions compared to 0.203 g/mile in Phase 4 when fueled with Syntroleum S-2 fuel. Bus 2093, fueled with ULSD1 also showed substantially lower PM emissions in Phase 4 than in Phase 3. Both Syntroleum S-2 fuel and ULSD1 fuel are both low-emission fuels compared to conventional No.1 and No.2 diesel fuels.

5.4.4 Hydrocarbon and Carbon Monoxide Emissions

In Phase 3, both HC and CO had shown significant bus-to-bus variability within each 3-bus fuel-group, such that the effect of fuel type was not discernable. In Phase 4, there was again large bus-to-bus variability in both HC and CO, with HC generally increasing and CO generally decreasing from Phase 3 to 4 for those bus/fuel combinations tested in both Phase 3 and Phase 4. Figure 25 shows the hydrocarbon emissions results. Phase 4 HC emissions from Syntroleum S-2 fuel were reduced by 30 percent when compared to ULSD1 fuel emissions. The Syntroleum S-2 fuel HC emissions ranged from 0.25 to 0.3 g/mile with an average of 0.28 g/mile. HC emissions produced from ULSD1 fuel ranged from 0.33 to 0.45 g/mile with an average of 0.4 g/mile. Since each bus was tested with both fuels in sub-sequent order it was evident that Syntroleum S-2 fuel possessed an appreciative advantage over ULSD1 fuel.

Carbon monoxide emissions are plotted in Figure 26. In Phase 4 the CO emission from the Syntroleum S-2 fueled buses were reduced by 24 percent compared to emissions produced by ULSD1 fuel. The CO emissions produced by Syntroleum S-2 fuel ranged from 2.46 to 3.85 g/mile with an average of 2.99 g/mile. ULSD1 fuel produced CO emissions in the range of 2.95 to 5.22 g/mile with an average of 3.94 g/mile. By combining the results of Phases 3 and 4 it was observed that the data exhibited vehicle-to-vehicle variation, however, there appeared to be no significant difference in CO emissions between the two fuels.

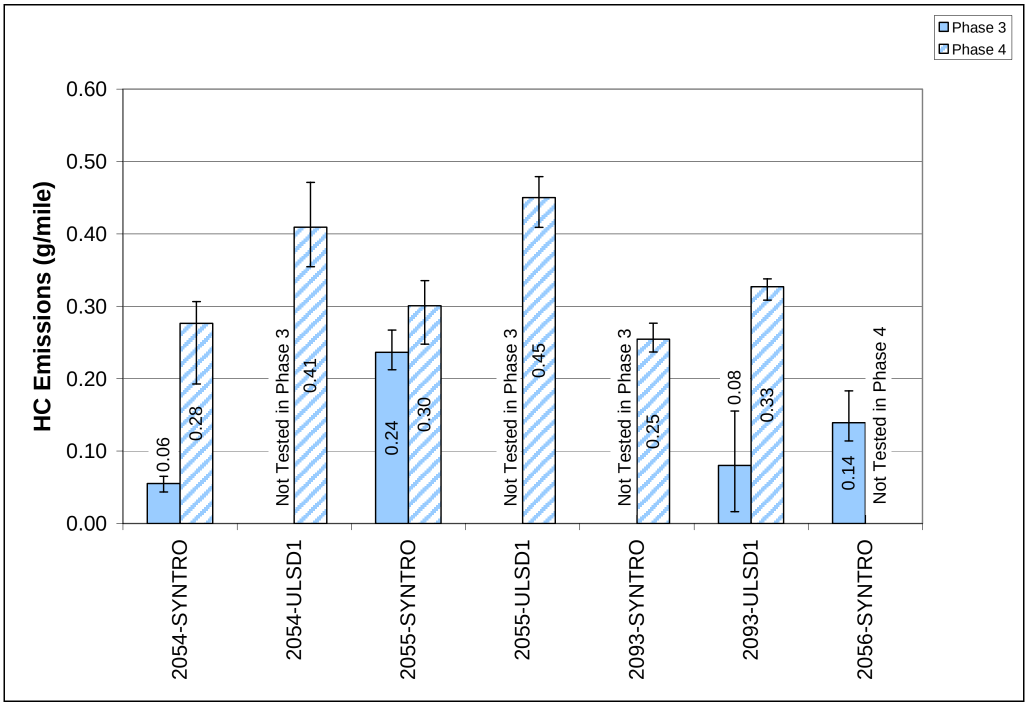

Figure 25: Phase 3 & 4 hydrocarbon emissions.

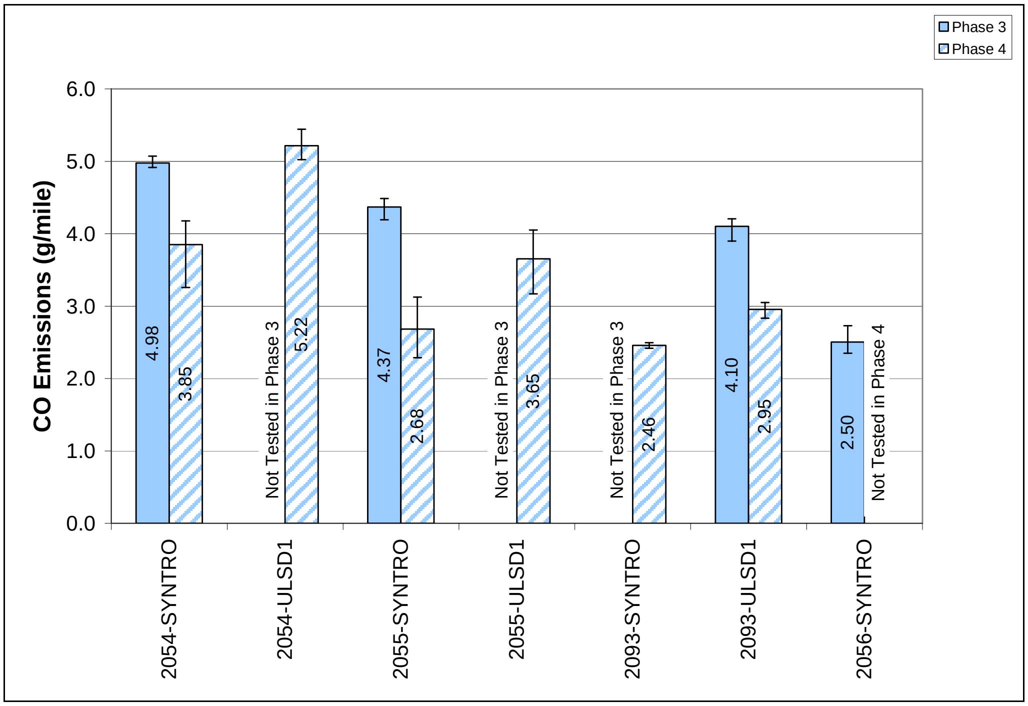

Figure 26: Phase 3 & 4 carbon monoxide emissions.

5.4.5 Carbon Dioxide and Fuel Economy Results

Carbon dioxide emissions are plotted in Figure 27 and fuel economy results are shown in Figure 28. CO_2 emissions from the Syntroleum S-2 fuel were reduced by about 4 percent compared to emissions produced by ULSD1 fuel. The range of CO_2 emissions produced by Syntroleum S-2 fuel was 2591 to 3361 g/mile with an average of 2887 g/mile. ULSD1 fuel CO_2 emissions ranged from 2795 to 3439 g/mile with an average of 3012 g/mile. The fuel economy was similar for both types of fuels with the Syntroleum S-2 fuel averaging 3.31 miles/gallon and the ULSD1 fuel averaging 3.27 miles/gallon representing a difference of about 1 percent.

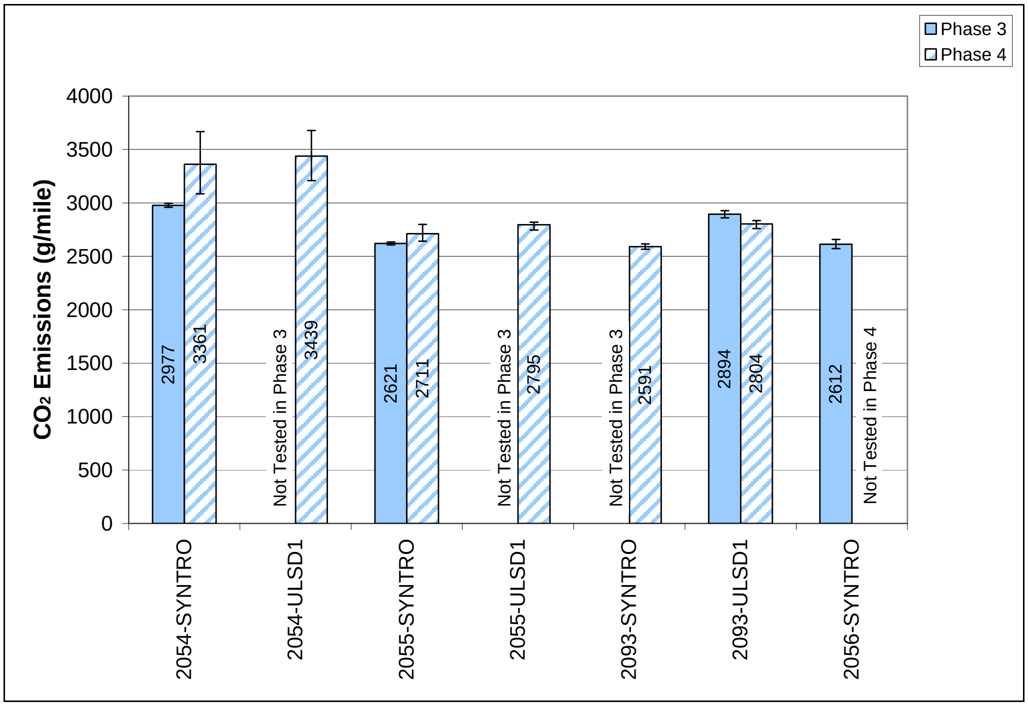

Figure 27: Phase 3 & 4 carbon dioxide emissions.

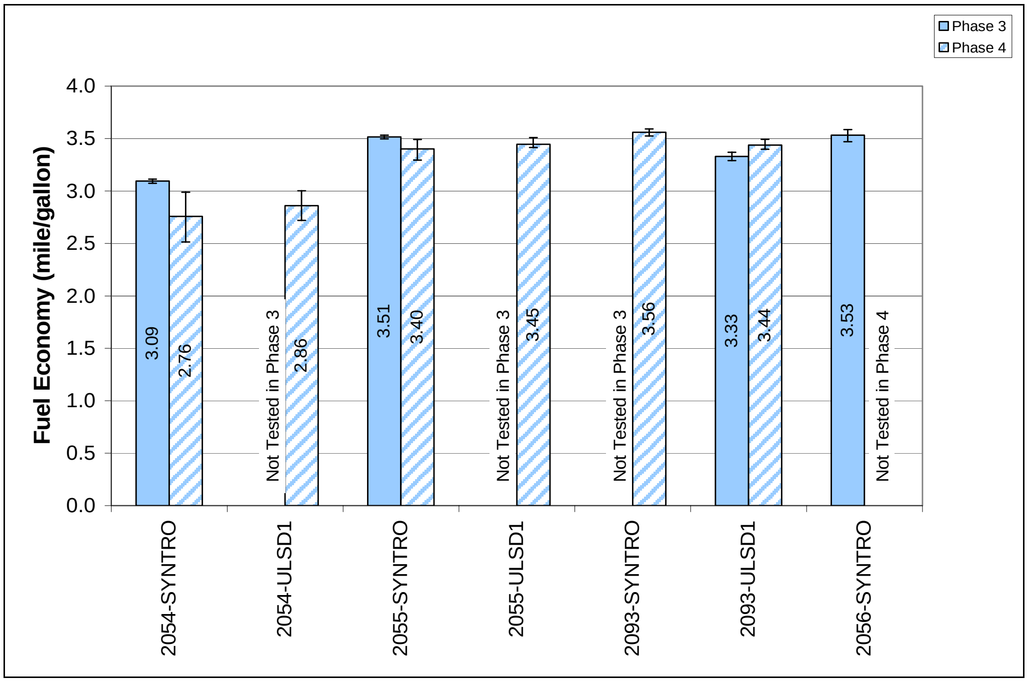

Figure 28: Phase 3 & 4 fuel economy results.

5.4.2 Summary of Phase 4 Results

Three WMATA transit buses which were tested previously during phase 3 were re-tested after they have been operating in normal revenue service on the Syntroleum S-2 fuel for a period of 6 months. Each of the three buses was tested with both Syntroleum S-2 and ULSD1 fuels.

- NO_X emissions produced by the Syntroleum S-2 fuel were reduced by 16 percent compared to ULSD1 fuel due to the low aromatic content and high cetane number.
- On average PM emissions when the buses were fueled with Syntroleum S-2 fuel were reduced by 35 percent compared to ULSD1 fuel.
- HC and CO emissions were similarly reduced when the buses were fueled with Syntroleum S-2 fuel. HC emissions were reduced by 30 percent and CO emissions were reduced by 24 percent compared to ULSD1 fuel.
- Carbon dioxide and fuel economy results were very similar for both types of fuels.

6.0 CONCULSIONS

The Ultra-Clean Fuels Production and Demonstration Program, sponsored by the U.S. Department of Energy's National Energy Technology Laboratory, was undertaken with the goal of pioneering a new generation of ultra-clean transportation fuels to significantly reduce tailpipe emissions from cars, trucks, and other heavy vehicles. Synthetic fuel was produced from natural gas at a small footprint plant by the Syntroleum Corporation and demonstrated in a select number of urban transit buses operated at Washington DC Metropolitan Transit Authority (WMATA) in Washington DC and in tour buses operated by Doyon/Aramark in Denali National Park, Alaska. Performance, exhaust emissions, and fuel economy of the buses operated on Syntroleum S-2 fuel were evaluated at each location and compared with identically equipped sister buses operated on petroleum-derived diesel fuels. The baseline diesel fuels were different at each demonstration fleet. The baseline fuel at WMATA was an ultra-low sulfur type one fuel while the baseline fuel and Denali Park was Jet-A fuel.

Results of two phases of emissions testing performed on the WMATA transit bus fleet showed reductions in NO_X emissions ranging from 16% to 22% for buses fueled with Syntroleum S-2 fuel compared to the ultra-low sulfur baseline fuel. These results are in agreement with published results from other studies of gas-to-liquid fuels. Results from the Denali Park bus fleet did not show a reduction in NO_X emissions compared to petroleum derived diesel fuel. The Denali Park buses were equipped with 2004 Caterpillar ACERT engines that utilize a sophisticated multiple-injection strategy that is sensitive to fuel properties. Calibration of the Caterpillar ACERT engine control system by the manufacturer to match fuel cetane level is apparently necessary to prevent an increase in NO_X (and could possibly even enable a NO_X reduction) when using Syntroleum S-2 fuel.

In Phase 1 and Phase 4 emissions testing at WMATA, PM reductions of approximately 35% were observed with the Syntroleum fuel compared to the ultra-low sulfur diesel fuel in the same buses. The reduction in PM is likely due to a reduction in the soot portion of the PM as noted in previous GTL studies [4, 10]. Results from the Denali Park fleet showed a PM reduction of 25% attributed to the Syntroleum S-2 fuel, though the comparison was made using different busses on each fuel. The buses tested in this program were all equipped with diesel oxidation catalysts. Although modest reductions in PM are possible through use of Syntroleum S-2 GTL fuel, the most beneficial attribute of Syntroleum fuel may arise by enabling the use of advanced sulfur sensitive aftertreatment systems, such as catalyzed diesel particulate filters, on newer technology engines. Results from Phase 1 testing of a WMATA transit bus equipped with a catalyzed diesel particulate filter demonstrated the compatibility of Syntroleum S-2 fuel with DPF technology.

Given vehicle-to-vehicle variability within the WMATA bus fleet, there appeared to be no substantial difference in HC and CO emissions between the Syntroleum S-2 and baseline ultra-low sulfur fuel. The Denali Park buses fueled with Syntroleum S-2 exhibited reductions of 81% and 68% in HC and CO respectively compared to the buses fueled on low sulfur Jet A fuel. In both fleets, there appeared to be no significant difference in the fuel economy of buses fueled with Syntroleum S-2 fuel and those fueled with petroleum derived diesel fuels.

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APPENDIX A: EMISSIONS DATA TABLES

Table A- 1: Phase 1 Emissions Data

Vehicle Configuration	Exhaust Aftertreatment	Fuel Type	Vehicle Number	Test ID	Run ID	CO	NOx	NO	HC	PM	CO_2	Miles	MPG	BTU/mile
						g/mile	g/mile	g/mile	g/mile	g/mile	g/mile			
2000 MY DDC Series 50	DPX	ULSD1	2027	4178	1	0.26	25.8	N/A	B.D.L	0.024	3624	8.37	2.66	48004
					2	0.09	25.2	20.2	B.D.L	0.021	3607	8.42	2.68	47776
					3	bdl	25.4	20	B.D.L	0.023	3575	8.39	2.7	47340
				Average		**0.18**	**25.5**	**20.1**	**N/A**	**0.023**	**3602**	**8.39**	**2.68**	**47707**
	OEM DOC			4181	1	3.98	28	N/A	0.22	0.33	3557	4.22	2.71	47203
					2	4.03	27.3	26.4	0.22	0.29	3517	4.21	2.74	46675
					3	4.04	26.7	25.6	0.25	0.29	3512	4.22	2.74	46619
				Average		**4.02**	**27.3**	**26.0**	**0.23**	**0.303**	**3529**	**4.22**	**2.73**	**46832**
		Syntroleum		4184	2	3.38	19.7	19.2	0.29	0.23	3376	4.17	2.73	45724
					3	3.78	19.5	18.9	0.27	0.19	3404	4.28	2.71	46106
					4	4.08	19.6	N/A	0.24	0.19	3425	4.24	2.69	46396
				Average		**3.75**	**19.6**	**19.05**	**0.27**	**0.203**	**3402**	**4.23**	**2.71**	**46075**
	DPX			4187	1	bdl	19.5	N/A	B.D.L	0.0034	3212	8.64	2.88	43405
					2	0.051	19.5	15	B.D.L	B.D.L	3246	8.36	2.85	43884
					3	0.075	19.8	15.1	B.D.L	B.D.L	3115	8.53	2.97	42101
				Average		**0.063**	**19.6**	**15.05**	**N/A**	**0.0034**	**3191**	**8.51**	**2.9**	**43130**

Table A- 2: Phase 2 Emissions Data

Vehicle Configuration	Exhaust Aftertreatment	Fuel Type	Vehicle Number	Test ID	Run ID	CO	NOx	NO	HC	PM	CO_2	Miles	MPG	BTU/mile
						g/mile	g/mile	g/mile	g/mile	g/mile	g/mile			
2004 MY CAT C7 ACERT	DOC	JET A	531	4235	1	12.6	12.4	N/A	1.75	0.18	2579	8.68	3.7	34033
					2	12.1	12.5	12.3	1.64	0.19	2560	8.63	3.73	33776
					3	11.5	13.5	N/A	1.38	0.2	2653	8.45	3.6	34961
				Average		**12.07**	**12.80**	**12.30**	**1.59**	**0.190**	**2597**	**8.59**	**3.68**	**34257**
			532	4239	1	12.1	12.7	12.5	0.64	0.17	2535	8.64	3.77	33408
					2	9	13	N/A	0.64	0.18	2540	8.65	3.77	33411
					3	9.8	13.3	13.1	0.67	0.18	2585	8.49	3.7	34013
				Average		**10.30**	**13**	**12.8**	**0.65**	**0.177**	**2553**	**8.59**	**3.75**	**33611**
			536	4243	1	8.43	12.3	N/A	0.52	0.2	2655	8.57	3.61	34899
					2	7.8	13	12.9	0.45	0.22	2667	8.53	3.6	35037
					4	9.98	12.9	N/A	0.72	0.21	2704	8.46	3.54	35570
				Average		**8.74**	**12.73**	**12.9**	**0.56**	**0.210**	**2675**	**8.52**	**3.58**	**35169**
		Syntroleum	533	4248	1	4.22	15.6	N/A	0.27	0.14	2524	8.61	3.65	34214
					2	5.3	15.5	15.1	0.29	0.14	2520	8.49	3.65	34186
					3	4.12	16.3	15.9	0.25	0.14	2532	8.45	3.64	34323
				Average		**4.55**	**15.80**	**15.5**	**0.27**	**0.14**	**2525**	**8.52**	**3.65**	**34241**
			537A	4252	1	2.99	16.6	N/A	0.2	0.16	2608	8.44	3.53	35332
					2	3.05	17.1	19.9	0.19	0.15	2621	8.37	3.52	35504
					3	3.02	16.7	16.5	0.16	0.15	2583	8.43	3.57	34983
				Average		**3.02**	**16.8**	**18.2**	**0.18**	**0.153**	**2604**	**8.41**	**3.54**	**35273**
			534	4257	1	3.12	14.3	N/A	0.15	0.14	2525	8.61	3.65	34198
					2	3.47	14	13.8	0.19	0.14	2516	8.57	3.66	34092
					3	2.64	15.3	15.2	0.09	0.15	2546	8.5	3.62	34474
				Average		**3.08**	**14.53**	**14.5**	**0.14**	**0.143**	**2529**	**8.56**	**3.64**	**34255**
		JET A	532 Retest	4254	3	13.7	12.6	N/A	1.22	0.17	2652	4.2	3.6	34996
				Average		**13.7**	**12.6**	**N/A**	**1.22**	**0.17**	**2652**	**4.2**	**3.6**	**34996**

Table A- 3: Phase 3 Emissions Data

Vehicle Configuration	Exhaust Aftertreatment	Fuel Type	Vehicle Number	Test ID	Run ID	CO	NOx	NO	HC	PM	CO_2	Miles	MPG	BTU/mile
						g/mile	g/mile	g/mile	g/mile	g/mile	g/mile			
2000 MY DDC Series 50	DOC	ULSD1	2093	4261	2	3.90	29.10	N/A	0.16	0.407	2928	4.27	3.29	38873
					3	4.20	29.04	27.47	0.02	0.390	2894	4.26	3.33	38421
					4	4.20	28.53	26.99	0.07	0.399	2860	4.26	3.37	37969
				Average		**4.10**	**28.89**	**27.23**	**0.08**	**0.399**	**2894**	**4.26**	**3.33**	**38421**
			2092	4263.00	2	4.37	31.29	N/A	0.056	0.271	2887	4.20	3.34	38331
					4	4.75	30.09	28.51	0	0.285	2977	4.21	3.24	39530
					5	4.76	29.73	28.23	0	0.300	2905	4.21	3.31	38581
				Average		**4.63**	**30.37**	**28.37**	**0.056**	**0.285**	**2923**	**4.21**	**3.30**	**38814**
			2094	4276	2	3.34	28.67	N/A	0.23	0.168	2652	4.23	3.63	35212
					3	3.38	28.46	27.21	0.23	0.182	2598	4.22	3.71	34486
					4	3.48	28.30	26.91	0.22	0.185	2587	4.23	3.72	34345
				Average		**3.40**	**28.48**	**27.06**	**0.23**	**0.178**	**2612**	**4.23**	**3.69**	**34681**
		Syntroleum	2054	4267	2	4.94	25.35	N/A	0.04	0.321	2960	4.19	3.11	40119
					3	5.07	26.03	24.72	0.06	0.332	2997	4.20	3.07	40617
					4	4.92	24.76	23.51	0.07	0.364	2975	4.18	3.10	40323
				Average		**4.98**	**25.38**	**24.12**	**0.06**	**0.339**	**2977**	**4.19**	**3.09**	**40353**
			2055	4273	2	4.19	21.04	N/A	0.21	0.179	2635	4.24	3.50	35714
					3	4.43	20.71	19.73	0.23	0.176	2608	4.29	3.53	35355
					4	4.49	20.81	19.79	0.27	0.186	2620	4.25	3.52	35517
				Average		**4.37**	**20.86**	**19.76**	**0.24**	**0.180**	**2621**	**4.26**	**3.51**	**35528**
			2056	4270	3	2.73	21.82	N/A	0.12	0.333	2606	4.26	3.54	35287
					4	2.35	21.81	21.39	0.18	0.306	2659	4.27	3.47	35994
					5	2.43	21.53	21.15	0.11	0.286	2572	4.26	3.59	34823
				Average		**2.50**	**21.72**	**21.27**	**0.14**	**0.308**	**2612**	**4.26**	**3.53**	**35368**

Table A- 4: Phase 4 Emissions Data

Vehicle Configuration	Exhaust Aftertreatment	Fuel Type	Vehicle Number	Test ID	Run ID	CO	NOx	NO	HC	PM	CO_2	Miles	MPG	BTU/mile
						g/mile	g/mile	g/mile	g/mile	g/mile	g/mile			
2000 MY DDC Series 50	DOC	Syntroleum	2054	4472	2	4.18	28.15	N/A	0.31	0.221	3668	4.20	2.51	49687
					3	4.04	28.80	27.82	0.31	0.222	3573	4.21	2.58	48400
					4	3.94	28.24	27.15	0.26	0.212	3558	4.22	2.59	48196
				Average		**4.05**	**28.40**	**27.48**	**0.29**	**0.219**	**3600**	**4.21**	**2.56**	**48761**
				4510	2	3.26	26.66	N/A	0.19	0.167	3132	4.45	2.94	42417
					3	3.69	26.56	25.58	0.29	0.187	3085	4.42	2.99	41794
					4	3.99	26.05	24.89	0.30	0.209	3151	4.41	2.92	42695
				Average		**3.65**	**26.42**	**25.23**	**0.26**	**0.188**	**3123**	**4.43**	**2.95**	**42302**
		ULSD1		4473	2	5.18	32.76	N/A	0.41	0.332	3678	4.23	2.72	48457
					3	5.30	32.41	31.01	0.47	0.319	3548	4.25	2.82	46755
					4	5.44	32.96	31.24	0.35	0.342	3626	4.29	2.76	47769
				Average		**5.31**	**32.71**	**31.12**	**0.41**	**0.331**	**3617**	**4.26**	**2.76**	**47660**
				4511	1	5.31	31.43	N/A	0.43	0.352	3287	4.34	2.93	43670
					2	5.04	30.63	N/A	0.41	0.329	3287	4.42	2.93	43665
					3	5.02	30.39	29.06	0.39	0.327	3209	4.43	3.00	42622
				Average		**5.12**	**30.81**	**29.06**	**0.41**	**0.336**	**3261**	**4.40**	**2.95**	**43319**
		Syntroleum	2055	4476	2	3.13	21.35	N/A	0.25	0.127	2799	4.21	3.29	37906
					3	2.76	20.43	19.38	0.30	0.122	2642	4.49	3.49	35778
					4	3.00	20.17	19.08	0.32	0.130	2659	4.46	3.47	36016
				Average		**2.96**	**20.65**	**19.23**	**0.29**	**0.126**	**2700**	**4.39**	**3.42**	**36567**
				4506	2	2.29	21.44	N/A	0.34	0.115	2744	4.40	3.36	37151
					3	2.40	21.92	21.05	0.31	0.113	2755	4.40	3.35	37311
					4	2.51	20.60	19.67	0.29	0.113	2670	4.51	3.45	36153
				Average		**2.40**	**21.32**	**20.36**	**0.31**	**0.114**	**2723**	**4.43**	**3.39**	**36872**
		ULSD1		4477	1	3.97	27.11	N/A	0.45	0.201	2802	4.39	3.44	37222
					2	3.90	26.90	25.45	0.41	0.201	2818	4.37	3.42	37421
					3	4.05	26.79	25.42	0.48	0.204	2816	4.35	3.42	37401

Table A- 4 Continued: Phase 4 Emissions Data

Vehicle Configuration	Exhaust Aftertreatment	Fuel Type	Vehicle Number	Test ID	Run ID	CO	NOx	NO	HC	PM	CO_2	Miles	MPG	BTU/mile
						g/mile	g/mile	g/mile	g/mile	g/mile	g/mile			
2000 MY DDC Series 50	DOC	ULSD1	2055	4477	1	3.97	27.11	N/A	0.45	0.201	2802	4.39	3.44	37222
					2	3.90	26.90	25.45	0.41	0.201	2818	4.37	3.42	37421
					3	4.05	26.79	25.42	0.48	0.204	2816	4.35	3.42	37401
				Average		**3.98**	**26.93**	**25.44**	**0.44**	**0.202**	**2812**	**4.37**	**3.42**	**37348**
				4507	2	3.53	26.63	N/A	0.45	0.165	2821	4.43	3.41	37455
					3	3.17	25.64	24.97	0.47	0.172	2746	4.42	3.51	36456
					4	3.30	26.32	24.85	0.45	0.185	2765	4.48	3.48	36718
				Average		**3.33**	**26.20**	**24.91**	**0.46**	**0.174**	**2777**	**4.44**	**3.47**	**36876**
		Syntroleum	2093	4503	2	2.42	23.81	22.76	0.25	0.149	2616	4.53	3.52	35426
					3	2.46	23.61	22.70	0.24	0.150	2589	4.51	3.56	35057
					4	2.49	23.45	22.52	0.28	0.151	2568	4.53	3.59	34775
				Average		**2.46**	**23.62**	**22.66**	**0.25**	**0.150**	**2591**	**4.53**	**3.56**	**35086**
		ULSD1		4502	4	2.98	28.24	N/A	0.34	0.220	2836	4.47	3.40	37636
					5	3.05	28.06	25.91	0.34	0.224	2816	4.47	3.42	37371
					6	2.83	27.76	26.90	0.31	0.198	2760	4.53	3.49	36626
				Average		**2.95**	**28.02**	**26.40**	**0.33**	**0.214**	**2804**	**4.49**	**3.44**	**37211**

ULTRA-CLEAN FUELS: FUEL, BLENDING, AND AFTERTREATMENT SYSTEM IMPACT ON GTL COMBUSTION AND EMISSIONS IN AN ADVANCED DI ENGINE

Final Report

Reporting Period: September 1, 2002 – December 31, 2005
(Cumulative Report)

Submitted by:

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DISCLAIMER

ABSTRACT

This project aims at developing the fundamental knowledge base of how Syntroleum gas-to-liquid (GTL) fuel, also referred to as Fischer-Tropsch (FT) fuel, affects the performance and emission characteristics of advanced engine systems. This project complements other production, testing, and assessment efforts in the overall Ultra-Clean Fuels Program. Specific tasks include performing engine experiments on a Cummins MY2002 ISB 5.9 liter 6 cylinder turbocharged after-cooled engine, employing cooled EGR and advanced electronic controls, to assess the manner in which the gas-to-liquid fuel impacts engine performance and emissions. In addition, this project also investigates the effects that FT fuel has on an exhaust aftertreatment system, specifically diesel particulate traps (DPT).

Compared to regular diesel fuel over the steady-state conditions tested, the FT fuel reduces particulate emissions substantially (25-75%), through sulfur and non-sulfur effects, but more significantly from a faster burn rate late in the combustion process. NOx emission reduction using the FT fuel ranges from 5-20%, as FT fuel removes the sensitive dependence of PM production on EGR, allowing significant NOx reductions through the use of higher EGR rates before PM levels become unacceptably high. Therefore, EGR and injection timings can be utilized more effectively with the FT fuel in controlling both particulates and NOx. A blend of 25% (by volume) FT fuel with 75% 400 PPM sulfur fuel demonstrated that the 25% FT fuel in the blend produced about 50% of the particulate reduction of using neat FT fuel, thus showing a more than proportional benefit of using blends. Chemical analysis of the PM confirmed these results and showed a more than proportional benefit of the blend in reducing both non-soluble soot and soluble organics. Furthermore, a detailed combustion analysis of the fuels over a wide range of engine operating conditions attempted to shed further insight into this phenomenon. Lastly, the effects of FT fuels on un-catalyzed cordierite diesel particulate traps were investigated. The use of FT fuel significantly extended the trapping period and reduced the regeneration frequency as compared to the baseline low sulfur diesel. Overall, FT fuel gives greater freedom to engine designers when trying to optimize the engine/emission-control/fuel system in modern engines, since it provides the fuel properties as another flexible set of variables that affect the combustion and emission processes. Furthermore, additional benefits can be realized through the use of more aggressive aftertreatment systems due to the zero sulfur nature of the FT fuel.

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FUEL, BLENDING, AND AFTERTREATMENT SYSTEM IMPACT ON GTL COMBUSTION AND EMISSIONS IN AN ADVANCED DI ENGINE

Final Technical Progress Report
Reporting Period: September 1, 2002 – December 31, 2005
(Cumulative Report)

by
Sloan Automotive Laboratory
Massachusetts Institute of Technology

EXECUTIVE SUMMARY

This subcontract at MIT complements other production, testing, and assessment efforts in the overall Ultra-Clean Fuels Program by exploring how advanced engine and emission control systems may benefit from the use of Syntroleum gas-to-liquid fuel.

Specific tasks in this subcontract project include:

(1) To assess how gas-to-liquid fuels impact engine performance and emissions, directly and in blends; to evaluate tradeoffs among fuel properties and blending ratios; to evaluate engine modifications in further improving engine emissions; and to determine combustion and emission characteristics.

(2) To explore opportunities of injection strategy control and exhaust-gas-recirculation (EGR) in pushing limits of NOx/particulates reduction using Syntroleum Fischer Tropsch (FT) fuels produced from a small footprint plant (SFP). The engine will be modified for various injection control and EGR systems. Since particulates are expected to be substantially lower with the GTL fuel, limits of NOx reduction via EGR and injection variables will be explored as well.

(3) To evaluate exhaust aftertreatment systems performance and design tradeoffs available using gas-to-liquid fuels. Optimize the fuel/engine/emission-control system.

Goals for this, the final, reporting period were to (i) investigate the impact of GTL fuels on the performance and loading characteristics of diesel particulate traps, (ii) develop a better understanding of the fundamental processes influencing particulate oxidation behavior inside the trap, and (iii) continue the detailed characterization of the gaseous and particulate exhaust constituents to explain the observed differences in trap performance. Tasks (1) and (2) have been covered in the past three years as previously reported. Work on Task (3) has been ongoing and was recently completed. Over the duration of this subcontract the differences in the measured combustion characteristics, PM chemical composition, and fuel properties were compared to the emissions variations between the fuels studied, and an explanation for the observed emissions behavior of the fuels was developed. Furthermore, the effects of various engine operating parameters, namely injection timing and EGR rates, on emissions with Fischer-Tropsch and conventional diesel fuels have been explored, and strategies proposed to take full advantage of the beneficial properties of Fischer-Tropsch fuels. Lastly, a detailed investigation into the effects of GTL fuels on the performance of diesel particulate traps was carried out as well. The goals this subcontract have thus been accomplished, however work on aftertreatment systems is still ongoing in other research programs at the subcontractor.

The experiments were performed on a Cummins model year 2002 ISB 300, 5.9 liter, 6-cylinder, turbocharged, heavy-duty direct injection diesel engine, rated at 224 kW (300 hp) at 2500 RPM. The engine has an active cooled EGR system with advanced electronic controls, heavily retarded injection timings, and employs a multiple fuel injection strategy. In-cylinder pressure measurements were used to calculate key thermal indicators representative of combustion variations. Results from the combustion analysis, obtained for a much expanded test matrix, confirm results presented in previous reporting periods and also provide further insight into key combustion differences between the fuels. Emissions characteristics also showed the same trends as those measured previously. Combustion rates and emission formation mechanisms were studied earlier using an analytical model based on heat release rates and published conceptual models of diesel combustion.

Specifically, compared to regular diesel, FT fuel reduces particulate emission substantially (25-75%). We concluded in the first year that most of this reduction came from sulfur in the 400 PPM sulfur diesel fuel, as the reduction was consistent with the expected sulfates contribution from the high sulfur fuel. However, the data from the second year using 15 PPM sulfur fuel also produced similar particulate reductions. In the third reporting period, Syntroluem carried out a detailed chemical analysis of the fuels, and a number of particulate samples were sent to the emissions-chemistry laboratory of a major engine manufacturer for analysis as well. The results of these tests provide increasing evidence for the contribution of a significant non-sulfur effect to the overall reduction in PM emissions.

The results of the combustion analysis provided further evidence for combustion derived PM reduction pathways. The reduced ignition delay due to the higher cetane number of the FT fuel, combined with the FT fuel's lower density reduces the amount of fuel consumed in the pre-mix burn phase and thus reduces the amount of PM generated as well. Furthermore, the faster burn rate of the FT fuel during the latter part of combustion also leads to increased particulate oxidation in the cylinder further reducing PM output. It was also shown in the previous reporting period that the faster burn rate of the FT fuel as compared to the conventional diesel at retarded injection timings did not produce the particulates increase that normally accompanied retarded injection timings for NOx control using the regular diesel fuel. Therefore, late injection timings can be utilized more effectively with the FT fuel in controlling both particulates and NOx.

Also, conventional diesel fuel normally produces more particulates as EGR increases. Results show that FT fuel removes the sensitive dependence of PM production on EGR rate, allowing significant NOx reductions through the use of higher EGR rates before PM levels become unacceptably high. Current results are consistent with earlier findings that NOx decreases by up to 20% with the FT fuel. It is possible that further optimization of the engine to take advantage of the large particulates reduction can reduce NOx even further.

The issue of fuel blending was investigated to verify whether the benefits of FT fuel are proportional to its content in the fuel blend, as previously reported. A blend of 25% (by volume) FT fuel with 75% 400 PPM sulfur fuel and a blend of 25% (by volume) FT fuel with 75% 15 PPM sulfur fuel were studied. The particulates data show that the 25% FT fuel in the blend produced about half of the particulate reduction of using neat FT fuel. This non-linear benefit is consistent with independent results reported elsewhere. In addition, the results of the detailed chemical analysis performed at the emissions-chemistry laboratory of a major engine manufacturer demonstrated more than proportional reductions, in the range of 40% to 60%, in non-soluble soot and soluble organics for the blend when compared to the reductions observed for the neat FT fuel alone. These results confirm the observed trends in the reduction in PM emissions for the blend.

Results of the work completed during the third reporting period related to the emissions and combustion characteristics of FT diesel and conventional diesel fuels were accepted for publication and presented at the ASME Internal Combustion Engine Division 2005 Fall Technical Conference in Ottawa, Canada.

The last phase of the project investigated the impact of using the FT fuel in conjunction with exhaust aftertreatment systems. Due to time and logistical constraints, combined with the fact that NOx aftertreatment technology has yet to reach the level of maturity and widespread acceptance of diesel particulate traps, no NOx aftertreatment systems were evaluated in this study. Therefore, Task (3) focused solely on exploring the potential benefits of using FT fuels in conjunction with diesel particulate traps.

Both a prototype diesel particulate trap system and a full-flow parallel trap unit were designed, fabricated, instrumented, and tested. The full-flow trap consists of two parallel cordierite substrates of 19.05 cm (7.5") in diameter and 30.5 cm (12.0") in length. In order to investigate the fundamental fuel effects on particulate trap loading characteristics, un-catalyzed Cordierite substrates were loaded with particulates generated from neat FT diesel and the low sulfur diesel (LSD). Trap temperature, pressure drop, particulate emissions, and gaseous exhaust composition were monitored before and after the trap. In order to determine more precisely the fuel effects on particulate composition and trap performance, a detailed analysis of the raw particulates was carried out as well.

The use of FT fuel significantly extended the trapping period and reduced the regeneration frequency as compared to the LSD. Furthermore, differences in the oxidation rates of the trapped particulates for the two fuels were observed as well, and help to explain the differences in the trap loading characteristics observed with the two fuels. The absence of sulfur in FT fuels permits the use of more aggressively catalyzed traps, as sulfur poisoning is not an issue. The reduced particulate emissions of FT fuels lead to increased time between trap regenerations, which in conjunction with advanced catalysts formulations reducing the temperatures required to initiate regeneration, may provide substantial improvements in trap durability and performance. Results of the work on the diesel particulate trap completed during the final reporting period were accepted for publication and will be presented at the ASME Internal Combustion Engine Division 2006 Spring Technical Conference in Aachen, Germany.

In summary, we observed modest NOx reductions but 25-75% particulates reductions from using FT fuel over both 400 PPM and 15 PPM sulfur diesels fuels. Benefits arise not just from the fuel composition, but also from combustion characteristics and interactions with the engine technology as well. It is not believed that the effect of fuel sulfur on the observed PM emissions is as pronounced as was previously reported. The blend of FT fuel studied produced a more than proportional reduction in PM emissions. Overall, FT fuel gives greater freedom to engine designers when trying to optimize the engine/emission-control/fuel system in modern engines, since it provides the fuel properties as another flexible set of variables that affect the combustion and emission processes. Furthermore, the zero sulfur nature and already low particulate emissions of the FT fuel allow for the use of additional and more aggressive exhaust aftertreatment devices, previously impossible due to the deleterious effects of fuel sulfur on the catalyst. Additional experiments related to investigate fundamental fuel and lubricant oil effects on diesel particulate traps are ongoing, and experiments utilizing NOx aftertreatment systems are planned in the future.

FUEL, BLENDING, AND AFTERTREATMENT SYSTEM IMPACT ON GTL COMBUSTION AND EMISSIONS IN AN ADVANCED DI ENGINE

Final Technical Progress Report
(September 1, 2002 – December 31, 2005)
ICRC: DOE Prime Contract No. DE-FC26-01NT41099
MIT: ICRC Subcontract No. 3044-SUB-02

1.0 SCOPE OF WORK FOR THIS REPORTING PERIOD

This subcontract at MIT complements other production, testing, and assessment efforts in the overall Ultra-Clean Fuels Program by exploring how advanced engine and emission control systems may benefit from the use of Syntroleum gas-to-liquid fuel.

Specific tasks in this subcontract project include:

(1) To assess how gas-to-liquid fuels impact engine performance and emissions, directly and in blends; to evaluate tradeoffs among fuel properties and blending ratios; to evaluate engine modifications in further improving engine emissions; and to determine combustion and emission characteristics.

(2) To explore opportunities of injection strategy control and exhaust-gas-recirculation (EGR) in pushing limits of NOx/particulates reduction using Syntroleum Fischer Tropsch (FT) fuels produced from a small footprint plant (SFP). The engine will be modified for various injection control and EGR systems. Since particulates are expected to be substantially lower with the GTL fuel, limits of NOx reduction via EGR and injection variables will be explored as well.

(3) To evaluate exhaust aftertreatment systems performance and design tradeoffs available using gas-to-liquid fuels. Optimize the fuel/engine/emission-control system.

Goals for this, the final, reporting period were to (i) investigate the impact of GTL fuels on the performance and loading characteristics of diesel particulate traps, (ii) develop a better understanding of the fundamental processes influencing particulate oxidation behavior inside the trap, and (iii) continue the detailed characterization of the gaseous and particulate exhaust constituents to explain the observed differences in trap performance. Tasks (1) and (2) have been covered in the past three years as previously reported. Work on Task (3) has been ongoing and was recently completed. Over the duration of this subcontract the differences in the measured combustion characteristics, PM chemical composition, and fuel properties were compared to the emissions variations between the fuels studied, and an explanation for the observed emissions behavior of the fuels was developed. Furthermore, the effects of various engine operating parameters, namely injection timing and EGR rates, on emissions with Fischer-Tropsch and conventional diesel fuels have been explored, and strategies proposed to take full advantage of the beneficial properties of Fischer-Tropsch fuels. Lastly, a detailed investigation into the effects of GTL fuels on the performance of diesel particulate traps was carried out as well. The goals this subcontract have thus been accomplished, however work on aftertreatment systems is still ongoing.

2.0 CUMULATIVE ACCOMPLISHMENTS

We have measured and correlated the NOx and particulate emissions trends with the combustion characteristics for a modern diesel engine (Cummins MY 2002 ISB 5.9 liters). Different injection timing strategies as well as EGR rates were explored. Initial results using limited quantities of the FT fuel and 400 PPM sulfur fuel showed NOx reductions of 6-13% and particulate reductions with the FT fuel up to 75% compared to the 400 PPM sulfur diesel fuel.

Subsequent tests expanded the test matrix. We explored substantial changes in fuel injection timings and EGR rates from the standard factory settings and included 15 PPM and 400 PPM sulfur diesel fuel, as well as FT/diesel blends (25% FT/75% 400 PPM and 15 PPM diesel by volume). While NOx reductions were still limited to 20% or less, the bulk of the data showed particulate reductions between 25-50%. Particulate reductions of up to 75% with FT fuel compared to the standard diesel were observed at extremely retarded timing and light load conditions, primarily due to the increase of particulate emissions of the regular diesel fuel at those extreme conditions.

Comparison with the ultra-low sulfur fuel indicates that the particulate reduction benefit of FT fuel originates beyond the zero sulfur content of the FT fuel. In fact, the analyses suggest that the FT fuel maintains its combustion rates, even as injection timings are severely retarded and EGR rates heavily increased to reducing NOx. This is in contrast to conventional diesel fuel, where these conditions result in an increase in particulates.

Detailed chemical analyses of the particulate composition confirmed the results obtained in previous tests. Furthermore, the analyses provided conclusive evidence for the contribution of significant non-sulfur effects to the observed emissions trends. In fact, fuel sulfur may actually have very little influence on the observed differences in PM emissions for the fuels studied. The combustion analysis, carried out over a much larger range of engine operating conditions than in previous reporting periods, provided additional insight into the combustion characteristics and differences in observed emissions trends.

Samples of each of the test fuels were also sent to Syntroleum for analysis, as not all of the relevant fuel property data was provided by the fuel manufacturers. The results of the Syntroleum study include detailed distillation maps and gas chromatogram (GC) profiles, and provided additional information to explain the combustion and emissions behavior of the fuels.

Results of the work completed during the third reporting period, related to the emissions and combustion characteristics of FT diesel and conventional diesel fuels were accepted for publication and presented at the ASME Internal Combustion Engine Division 2005 Fall Technical Conference in Ottawa, Canada.

Hence, we have shown that FT fuel offers additional flexibility to the engine designer in optimizing the combined fuel/engine/emission-control system.

Lastly, we investigated of the impact of using the FT fuel on emission control via exhaust aftertreatment. A prototype and full-flow diesel particulate trap was designed, fabricated, and tested using the FT and low sulfur diesel fuels. The FT fuel significantly extended the trapping period and reduced the regeneration frequency as compared to the LSD.

Furthermore, the absence of sulfur in FT fuels permits the use of more aggressively catalyzed traps, as sulfur poisoning is not an issue. Moreover, the reduced particulate emissions of FT fuels lead to increased time between trap regenerations, which in conjunction with advanced catalyst formulations reducing the temperatures required to initiate regeneration, may provide substantial improvements in trap durability and performance. Results of the work on the diesel particulate trap completed during the final reporting period were accepted for publication and will be presented at the ASME Internal Combustion Engine Division 2006 Spring Technical Conference in Aachen, Germany.

Therefore, all the goals of this subcontract have been accomplished. However, significant and increasing interest from industry has prompted additional experiments to study the fundamental fuel and lubricant oil effects on diesel aftertreatment systems. Experiments with diesel particulate traps, both catalyzed an un-catalyzed, are ongoing, and experiments utilizing NOx aftertreatment systems are currently planned for the future.

3.0 REPORT ORGANIZATION

Following the Literature Review and Background in Section 4, a summary of the Experimental Set-Up in Section 5, the Fuels Tested in Section 6, and the Test Matrices and Procedures in Section 7, the Results and a Discussion of the investigation into the effects on the combustion and emissions characteristics of FT fuel versus conventional diesels, as well as blends, will be presented in Section 8 (Task 1). Section 9 presents the Results and a Discussion of the effect of fuel properties and engine parameters on emissions (Task 2), Section 10 presents the Results and a Discussion of the investigation into the fuel effects on particulate trap loading and performance (Task 3), and Section 11 summarizes the major Conclusions of this subcontract.

4.0 LITERATURE SURVEY AND BACKGROUND

A number of studies in the open literature have demonstrated the emissions reduction potential of neat Fischer-Tropsch fuels and blends. In addition, the zero-sulfur content of FT fuel has also been shown to permit the use of advanced aftertreatment systems in order to realize an even greater reduction in PM and NOx emissions [1, 2]. While numerous studies have investigated the effect of FT fuels on engine-out emissions, little is understood about the underlying causes for the observed emissions behavior of the fuels, and much work in this area remains. Furthermore, most research with FT fuels has been conducted using older technology engines without many of the advanced subsystems used in toady's modern diesel engines.

The current work in this program distinguishes from previous studies in two respects. The current study is done on a modern advance engine that has incorporated much of the latest engine technology and control strategies (Model year 2002 heavy-duty engine). Secondly, the author is unaware of any studies to date in which the combustion and emissions characteristics of neat FT fuels and blends have been carried out on an engine employing a multiple injection strategy. Furthermore, very little data exists on the effects of FT fuels on the performance and operating characteristics of exhaust aftertreatment systems, namely diesel particulate traps.

Despite the numerous studies of FT fuels and their effects on engine out emissions, the underlying mechanisms responsible for the observed emissions behavior are still not well understood. It is widely accepted that a number of factors contribute to the emissions behavior of the fuel, the most important of which are: chemical and physical properties, combustion characteristics, and engine technology. Furthermore, much work remains in the area of aftertreatment systems to fully exploit the beneficial characteristics of FT fuels.

4.1 Emissions Benefits with Fischer-Tropsch Fuels

The emissions characteristics of FT fuels are well documented in the literature, and the results of a number of studies [3-14] on FT fuels have been presented in the first two reporting periods. This section presents a brief summary of the most significant effects of FT fuels on diesel engine emissions.

A comprehensive literature review covering a wide range of light- and heavy-duty vehicle and engine tests with Fischer-Tropsch fuels was presented by Alleman et al. in 2003. The review cited the FT fuel's near zero sulfur content, low aromatics content, and high cetane number as the major contributors to the reduction in PM and NOx emissions observed with Fischer-Tropsch fuels. In addition, the near zero sulfur content of the fuel enabled the use of state-of-the-art aftertreatment technologies. On the other hand, some of the studies mentioned in the review cited poor cold flow and lubricity properties for the FT fuel, and called for further investigation into the long-term durability implications [3].

One of the earliest significant studies into the effects of Fisher-Tropsch fuels on diesel exhaust emissions was carried out by Schaberg et al. in 1997. In this study, a 12.7-liter, 1991 emission level, DDC series 60 diesel engine was run using four neat test fuels and three fuel blends. Of the four neat fuels, two were Fischer-Tropsch fuels produced by the Sasol Slurry Phase

Distillate Process (SSPD), and the remaining two were conventional CARB and US 2-D petroleum-based fuels. In addition to the neat fuels, three blends of various amounts of SSPD in the US 2-D were tested as well. Results showed that the SSPD fuels reduced nearly all regulated emissions as compared to the US 2-D and CARB fuels, with the blends reducing emissions in proportion to the amount of SSPD fuel in the blend. Over all of the test conditions, the SSPD reduced HC, CO, NOx, and PM emissions by 49%, 33%, 27%, and 21% respectively, when compared with the 2-D fuel. In addition, the SSPD reduced the PM volatile organic fraction (VOF) by 34% relative to the 2-D fuel. When compared with the CARB diesel, the SSPD reduced HC, CO, NOx, and PM emissions by 15%, 23%, 15%, and 21% respectively, and yielded a reduction in PM VOF of 29%. Based on the results of the study, it was estimated that a blend of 40% SSPD with the US 2-D would result in equivalent emissions of the CARB fuel [4].

A more recent study carried out by Sirman et al. at Southwest Research Institute in 2000 investigated the fuel effects of six alternative diesel fuels in a modern 2.2L Daimler Benz OM611 engine. The fuels under investigation were a low-sulfur diesel, Fischer-Tropsch diesel, a California Reference fuel, and three blends. All six fuel formulations were compared against an ASTM D975 low sulfur No. 2 diesel (2DLS) control fuel. The neat FT fuel reduced particulate and NOx emissions by 37% and 6% respectively, and provided the greatest benefits in emissions reduction over all 13 test modes. Furthermore, a 20% blend of FT in ULSD was observed to produce the same NOx reduction as the neat FT fuel as well [15].

In another study, an unmodified 1999 Cummins 5.9 L, turbo-charged, direct injection B-Series engine was tested using a federal low sulfur diesel fuel, CARB diesel, Swedish City 1 diesel fuel, and Syntroleum's FT diesel. The results showed a reduction in emissions with the FT fuel of 41% for HC, 38% for CO, 20% for NOx, and 40% for PM compared to the federal low sulfur diesel [14].

4.2 Fuel Effects

The intercorrelations between fuel properties makes investigation into the effect of a specific property on emissions quite difficult. Relatively few studies have succeeded in adequately decoupling the change in a specific fuel property from changes in additional properties in the test fuel. Furthermore, it is nearly impossible to link changes in emissions to a particular fuel property when a number of properties are varied simultaneously [16]. The literature review compiled by Lee et al. focused solely on those studies where the intercorrelations between the fuel properties were decoupled, allowing for direct comparison between changes in a specific fuel property and engine-out emissions. In this review, the following fuel properties were identified as having a significant effect on diesel emissions: cetane number, fuel sulfur, density, and aromatics.

4.2.1 Cetane Number

Cetane number is the measure of a fuel's tendency to auto-ignite, with higher cetane number fuels exhibiting a shorter ignition delay. Recent studies have shown some benefit to reduced NOx emissions as cetane number was increased, however the impact of cetane number on particulates tends to be much less pronounced and engine specific. The reduced ignition delay with higher cetane number fuels leads to a reduction in pre-mixed combustion and a more gradual temperature rise in the cylinder, thus slowing the rate of NOx formation [17].

4.2.2 Sulfur

One of the most widely investigated diesel fuel parameters, the conversion of fuel sulfur to sulfate following the combustion process contributes to particulate exhaust emissions. Previous studies have shown that the amount of sulfur converted to PM is at least 1-2% of the fuel sulfur content irrespective of the total fuel sulfur level or engine type [18]. In addition to contributing to particulate emissions, fuel sulfur has also been linked to catalyst poisoning, limiting the use of exhaust aftertreatment systems with diesel engines. Furthermore, the production of sulfuric acid from fuel sulfur has detrimental effects on the durability of EGR systems as well [19]. Aside from influencing particulate emissions and its detrimental impact on specific engine subsystems, fuel sulfur is not known to have any effect on regulated gaseous engine-out emissions [16].

4.2.3 Density

A number of studies have linked fuel density to particulate emissions. It has been shown that reducing fuel density can lead to a significant reduction in particulate emissions in older technology engines; however the effect is substantially reduced in newer technology engines with advanced injection strategies and improved mixing. In addition to reducing particulates, less dense fuels tend to reduce NOx emissions as well. On the other hand, emissions of CO and HC's may increase as the fuel density is reduced. Aside from emissions, density also directly affects an engine's power output, with less dense fuels leading to reduced power output, all other factors remaining constant [3, 16].

4.2.4 Aromatics

Much of the data regarding the impact of aromatics on emissions in the past presented conflicting results and failed to decouple the effect of the aromatics from density, cetane number, and T90. Despite this fact, it is widely agreed that total aromatics do not contribute significantly to HC, CO, or PM emissions, and only slightly affect NOx emissions. On the other hand, poly-aromatics (PAH) can have a substantial impact on particulate emissions and a smaller effect on NOx and CO emissions. However, similar to density, the effect of poly-aromatics on emissions is seen to decrease with newer technology engines [16, 20].

4.2.5 Back-End Volatility

While the effect of back-end volatility, T90/T95, on emissions is generally considered minor and heavily dependent on the composition of the back end, this property can have a small effect on engine-out gaseous emissions. A number of studies have shown that reducing back-end volatility can lead to a slight increase in HC and CO emissions along with a decrease in NOx emissions. As mentioned above, T90/T95 has not been shown to have a noticeable effect on PM emissions [16, 21].

4.3 Combustion Characteristics

Although the effects of FT fuel on engine out emission have been well documented in the literature, there are very few published reports on the combustion characteristics of FT fuel. Furthermore, the author is not aware of any analysis of the combustion behavior of neat FT fuel or FT blends in a modern diesel engine employing a multiple fuel injection strategy and heavily retarded injection timing in addition to a number of other advanced engine subsystems.

Atkinson et al. presented perhaps the first detailed combustion analysis of FT fuel in a direct injection diesel engine. In this study, a Navistar T444E (7.3liter, V8) diesel engine was outfitted with two in-cylinder pressure transducers and subjected to twelve steady-state operating conditions. Over the entire test range, it was found that the higher cetane number of the FT fuel yielded a reduced ignition delay, and thus, reduced fuel evaporation before ignition. Furthermore, the FT fuel exhibited a slightly longer combustion duration and more uniform heat release rate than the baseline diesel. However, the total time from the start of injection to the end of combustion for each fuel was approximately equivalent. FT fuel was observed to reduce nearly all regulated emissions over the entire engine operating range, with the exception of hydrocarbons at some test conditions. It was also noted that FT fuel reduced the exhaust gas temperature, thus reducing NOx emissions. During the course of the Atkinson study the engine was operated completely stock, with no engine control parameters altered to compensate for the differences in the combustion characteristics of the two fuels [7].

Following the Atkinson study, McMillan and Gautam investigated the combustion and emission characteristics of FT and a federal low-sulfur diesel fuel in a Ricardo single-cylinder four-stroke DI research engine outfitted for in-cylinder pressure measurements. The engine was run at several steady-state operating conditions and timing was varied for each fuel at these conditions as well. McMillan and Gautam cited the higher cetane number and lower density of the FT fuel as primarily responsible for the observed differences in the combustion characteristics. They also observed similar overall burn durations and peak pressures for the two fuels; however the FT did exhibit a slightly shorter 50% to 90% mass fraction burn duration [22]. Consistent with the Atkinson study, nearly all regulated exhaust emissions were reduced with the FT fuel, and the higher cetane number of the FT contributed to its shorter ignition delay.

4.4 Engine Technology

While the fuel properties and combustion characteristics have a significant effect on exhaust emissions, the relative importance of each specific effect can change depending on the type of engine and its operating characteristics. Numerous studies have indicated that the relative impact of fuel properties on emissions decreases with modern technology engines. In addition, Mann et al. noted that fuel effects on engine calibration significantly influenced the observed emissions effects. In this study, seven diesel fuels were tested in a modern electronically controlled direct-injection diesel engine and significant changes in engine calibration settings (most notably EGR rate and injection timing) were observed [23]. More recently, the effects of multiple injections and injection pressure have also demonstrated a significant effect on engine-out emissions and heat release rate [24, 25].

4.5 Aftertreatment Systems

In order to comply with the increasingly more stringent emission standards in place by 2007 and 2010, heavy-duty diesel engines will need to employ some form of exhaust aftertreatment systems. Currently diesel particulate traps present the only technically feasible and economically viable means for reducing particulate emissions to the levels mandated by the new standards. On the other hand, the means for meeting the reduced NOx levels are not as apparent. Furthermore, a number of potential technologies and in-cylinder combustion strategies have been proposed to reduce NOx emissions, and much debate regarding the most effective means for meeting the mandated NOx levels remains. Currently there are a number of aftertreatment technologies in various stages of maturity with the potential to significantly reduce NOx emissions from diesel engines such as: NOx Adsorber Catalysts, Selective Catalytic Reduction (SCR) employing some form of Urea injection, Lean NOx Catalysts (LNT), and Plasma Assisted Catalysts. In addition, alternative NOx reduction strategies have been proposed to optimize the various engine subsystems (VGT, injection system, cooled EGR, and injection and combustion strategies) to minimize NOx emissions and then reduce the ensuing PM emissions via diesel particulate traps alone [26].

In order to narrow the scope of this study and carry out a detailed investigation of the FT fuel effects on diesel aftertreatment systems within this contract period, only one of the numerous aftertreatment systems mentioned above was selected. It was for the following main reasons that only the effect of FT fuels on diesel particulate traps, and not on any of the various NOx aftertreatment systems, was investigated:

1. Currently there exists no one singe NOx aftertreatment systems that appears most effective in meeting the mandated NOx levels from both a technical and economic perspective in the United States.

2. Diesel particulate traps and filters are currently seeing widespread implementation and use, and it is widely accepted that diesel particulate traps present the only means to reduce particulate emissions from diesel engines to the 2007 limits.

3. The PM emissions limits will take effect in 2007, whereas the NOx limits will slowly be phased in by 2010. Thus, additional time remains to further develop and refine NOx aftertreatment systems and in-cylinder NOx reduction strategies.

4. The increasingly widespread use of diesel particulate filters greatly simplified filter procurement, as a number of substrates and filters were directly available from several manufacturers. On the other hand, attempts to procure a NOx aftertreatment system for the Cummins ISB proved more difficult.

5. The large amount of time necessary to fabricate, instrument, install, and test the DPF, along with the lengthy trap loading times, did not allow time for the testing of additional aftertreatment systems within the duration of the current contract.

Particulate traps have been the subject of much investigation over the past twenty years; however many of the technical issues such as control and initiation of trap regeneration, sulfur poisoning in catalytic traps, ash accumulation, in addition to durability issues still remain. The absence of sulfur in FT fuels permits the use of more aggressively catalyzed traps, as sulfur poisoning is not an issue. Furthermore, the reduced particulate emissions of FT fuels leads to increased time between trap regenerations, which in conjunction with advanced catalysts formulations reducing the temperatures required to initiate regeneration, may provide substantial improvements in trap durability and performance. However, the deposition of particulates from FT fuels on the trap substrates and regeneration of the trap with FT particulates and FT fuel have not been adequately addressed. These issues remain the focus of the third phase of this program.

Advances in fuel technology offer potential to optimize the engine/fuel/emission-control system. One area is in catalysis or catalytic regeneration of particulate traps. It has been shown that the catalytic particulate regeneration process involves the oxidation of hydrocarbons, either in the ambient or in the adsorbed organic matter. Unfortunately, fuel sulfur conversion rates to sulfates, even at the low fuel sulfur levels, are concomitantly high. The presence of synthetic zero-sulfur fuel, namely the Fischer-Tropsch gas-to-liquid fuel, removes the sulfur and sulfate constraint. The synthetic fuel can be tailored to provide the optimum combination of HC, particulate composition, and catalysts for low-temperature particulate oxidation and trap regeneration, in the absence of fuel sulfur.

The following literature review presents information on the current knowledge base of Fischer-Tropsch fuels used in conjunction with advanced aftertreatment systems.

4.5.1 Diesel Particulate Traps

Few published reports exist in the open literature examining the effects of synthetic fuels, namely FT diesel, on particulate trap performance and regeneration. While the FT fuel alone demonstrates significant potential in reducing particulate emissions, the potential for further particulate reduction when the fuel is used in conjunction with advanced trap systems is even greater.

May et al. explored the emissions reduction potential of using FT fuels in a 2000 Power-Stroke 7.3L V8 engine calibrated to conform to US 1998 emissions limits and equipped with an exhaust aftertreatment system. The aftertreatment system consisted of a DeNOX catalyst, a secondary fuel system, auxiliary exhaust cooler, and diesel particulate trap. In this study the DPT was located directly behind the DeNOx catalyst. Two FT fuels and a baseline 15 PPM standard No. 2 diesel were evaluated, and the engine was run at select steady-state operating conditions from both the light- and heavy-duty FTP cycle. Initial results showed light-duty emissions within Tier 2 bin 8 standards and heavy-duty emissions approaching the 2007 limits for the FT fuel used in conjunction with the aftertreatment system. The fuel consumption penalty incurred ranged from an increase of 1.7% in the light-duty case to 5.6% in the heavy-duty case. Transient effects were not examined in this study, nor was the DPT regenerated on line. Furthermore, significant improvements are expected for more sophisticated engines employing a 4 valve/cylinder design with central injector, higher injection pressures, and a variable geometry turbo-charger as the engine under study was of a 2 valve/cylinder design and only equipped with a standard wastegated turbocharger [12].

More recently Frank et al. investigated the effects of fuel type and emission control systems on regulated gaseous emissions from heavy-duty diesel engines. A number of US and Canadian government agencies participated in this joint project along with numerous emission control and aftertreatment systems manufacturers. The study evaluated the gaseous emissions from a heavy-duty diesel engine using ten different test fuels, including FT diesel, as well as four aftertreatment configurations: engine out (no aftertreatment), diesel oxidation catalyst (DOC), continuously regenerating diesel particulate filter (CRDPF), and exhaust gas recirculation with CRDPF (EGR-DPF). The study found that the use of more aggressive aftertreatment devices had a much more pronounced effect on emissions than any of the non-standard fuels, including blends. Aside from the PuriNOx^{TM} fuel, the Fischer-Tropsch fuel tested consistently yielded the lowest NOx levels of any fuel regardless of the aftertreatment device. Furthermore, the FT fuel yielded the lowest PM emissions of all the fuels studied. However, interestingly, the authors noted that the removal of fuel sulfur did not appear to affect engine-out PM emissions, but did reduce PM emissions when lower sulfur fuels were used in conjunction with a DOC [2].

Additional contributions to the literature have also been made in the area of exhaust emissions characterization with engines using FT and other low-sulfur diesel fuels in conjunction with exhaust aftertreatment systems. Thompson et al. investigated the fuel effects on regulated emissions from advanced diesel engines and vehicles. In this study a number of conventional fuels were compared with Swedish Class 1 and FT diesel in two advanced light-duty diesel vehicles and three heavy-duty diesel engines, spanning the Euro-3 to Euro-5 certification range. Significant reductions in particulate emissions were realized with a combination of low-sulfur fuels and DPFs [1]. Lev-On et al. performed a detailed chemical speciation of the exhaust emissions from trucks and buses fueled with low-sulfur diesels and FT diesel. The study examined the chemical characterization of the exhaust emissions using test fuels with and without aftertreatment systems (DPF) for a number of truck and bus fleets. The detailed exhaust speciation included emissions profiles for TPM, PM_{10}, $PM_{2.5}$, inorganic ions, elements, VOC's, ethane, olefins, BTEX, and benzene, among others, and the reader is referred to the published report [27] for further details.

Despite the apparent progress made in this area, specifically in the characterization of the fuel effects on engine out emissions with and without exhaust aftertreatment systems, much work still remains. Current work in this project area has focused on FT fuel effects on fundamental particulate trap loading and regeneration characteristics, a topic not adequately addressed in the current literature.

5.0 EXPERIMENTAL SET-UP

While the engine and test bed were installed and setup prior to the initial reporting period (2002-2003), substantial changes to the test setup, data acquisition, and gaseous and particulate emissions sampling systems have been made throughout the duration of this project. This section describes the current experimental setup along with the major modifications to the various test systems. For a detailed description of the engine and test setup at each stage of the project, the reader is referred to the previous annual reports.

5.1 Engine

The engine used in this study was a pre-production development engine based on the Cummins 2002 ISB 300 platform. The Cummins ISB 300 is a turbocharged, 6-cylinder, 5.9-liter, four-stroke, direct injection diesel engine. The engine is rated at 224 kW (300 hp) at 2500 rpm and 890 N-m (660 lb-ft) at 1600 rpm. The ISB300 is certified to meet 2002 EPA emissions standards, and employs a number of advanced subsystems such as a Bosch common rail high-pressure fuel injection system, Holset variable geometry turbocharger, and cooled EGR. In addition to these subsystems, the engine also utilizes a multiple fuel injection strategy to further optimize the combustion process with three injection events (pre-, main-, and post-injection) per cycle. All of the advanced subsystems are electronically controlled by an electronic control module (ECM) (version CM 850) calibrated to meet 2002 emissions limits when operating with an EPA No. 2 diesel fuel. Table 5.1 lists the engine specifications.

Number Of Cylinders	6
Combustion System	Direct Injection
Aspiration	Turbocharged
Stroked (Displaced) Volume [liters]	5.9
Bore/ Stroke [mm]	102/120
Connecting Rod Length [mm]	192
Crank Radius [mm]	60
Compression Ratio	17.2
Valve Timing	IVO = 9.5° bTDC | IVC = 23.5° aBDC
	EVO = 142.0 °aTDC | EVC = 18.0° aTDC
Injection Nozzle	O.D. = 158 µm, L = 1.00 mm
	8 Sac-less (VCO) Nozzles Per Injector

Table 5.1. Pre-production Cummins ISB 300 engine details [28]

5.2 Engine Control Software

The ISB 300 engine provided by Cummins was fully electronically controlled and came equipped with an unlocked ECM. In addition, Cummins also provided their proprietary in-house software, Calibration Terminal (CalTerm) version 7.63, allowing for engine calibration changes and real-time monitoring and modification of engine parameters. Throughout the duration of this study, the engine was operated using the stock 300-horsepower calibration provided by Cummins. This calibration was based on a standard No. 2 diesel fuel and was used for the following two reasons: (1) to ensure the engine would run on the 2002 EPA-emission-certified performance maps, and (2) to evaluate the performance of the Fischer-Tropsch fuels and blends in a modern engine running on the stock control system.

CalTerm allows for the monitoring and modification of hundreds of engine parameters and calibration settings. In order to assess the impact of specific engine control parameters and the Fischer-Tropsch fuel on emissions, a number of engine control parameters were modified during the first two reporting periods. The most important parameters modified in the experiments include the start of main injection and EGR fraction. The response time after commanding an injection timing change is trivial, since the electronic control of fuel injection with the common-rail system provides a response time dependent only upon the speed of the signal from the ECM. For adjustments to the EGR fraction, changes take a few seconds to settle since the ECM tries to find the best path to move to a different state. The coupling of engine load, turbine inlet pressure, turbine exhaust backpressure, intake manifold boost pressure, and EGR valve position required the ECM to optimize changes to prevent the system from reaching an unstable state.

Following the first two reporting periods, no parameters were modified during the remainder of the investigation and all tests were conducted using the stock engine calibration provided by Cummins. Despite this fact, CalTerm was used to monitor and log a number of engine control parameters of interest such as charge flow, pilot injection quantity and timing, post injection quantity and timing, EGR fraction, boost pressure, and common-rail accumulator pressure, among others. Furthermore, CalTerm proved invaluable as a diagnostic tool aiding in the diagnosis of occasional engine problems by providing real-time logging and display of fault codes.

5.3 Dynamometer Setup and Dynamometer Controller

A Digalog AE 250 eddy current dynamometer, able to absorb up to 250 kW, was used to load the engine. A Maywood Instruments U4000, 500 kg load cell measures torque by resisting the rotation of the outer casing. A differential pressure switch on the cooling-water outlet protects the dynamometer from failing if the cooling water supply happens to shut off.

Connecting the engine to the dynamometer is a drive shaft assembly made with two Spicer 1710 Series flange yokes attached to a 10.16 cm (4”) O.D. tube. The flange yokes are rated to withstand up to 1220 N-m at steady state or spikes of up to 6500 N-m. The drive-shaft is installed at about an 8° to relieve stresses in the flange yokes as they rotate.

A Digalog Model 1022A-STD dynamometer controller was used to control engine speed while reading out the load from the Maywood Instruments load cell. The PID settings in the dynamometer controller were also adjusted to reduce load fluctuations when the commanded throttle setting changes. Before any tests were run, the controller and dynamometer were calibrated at two points, the 50% and 100% loads of the engine.

5.4 Data Acquisition System

A full complement of National Instruments data acquisition (DAQ) hardware and software was used to measure and record various temperatures, pressures, and flows. The heart of the system is the high-speed DAQ board, a National Instruments PCI-6024E. This board can read up to 200,000 samples per second. The high-speed DAQ board is limited to 16 single-ended channels (signals with a common ground) or 8 differential channels (signals with separate grounds). In order to get around this limitation, an SCXI-1000 multiplexing chassis was also used. The SCXI-1000 chassis can house up to 4 special modules containing various signal amplification, isolation, and noise suppression circuitry. The multiplexing chassis works by quickly scanning, one after another, all the channels of each module installed streaming the data into one differential channel of the DAQ board.

A special 32-channel module for thermocouples (SCXI-1102B) containing a fixed low-pass filter of 200 Hz was installed into the multiplexing chassis. The SCXI-1102B allows for gain and filter settings to be programmed on a per-channel basis. Most slow-speed signals were connected to this module. Attached to the SCXI-1102B is a TBX-1303 terminal block. The TBX-1303 provides a convenient location for the sensors to wire into while also containing a cold-junction-compensation sensor to provide a reference voltage to correctly scale any thermocouples plugged into the terminal block. A general 32-channel module (SCXI-1100) was used for mixed measurements. This module has user-selectable low-pass filter settings (4 Hz, 10 kHz, and no filter) that apply to all channels. Since high-speed cylinder measurements (see Section 5.4.2) were recorded through this module along with various slow-speed signals, the 10 kHz filter setting was used to provide some noise filtering while preventing the possibility of introducing phase errors into the high-speed signals due to poor low-pass filter response. Another TBX-1303 terminal block is attached to the SCXI-1100 module to facilitate sensor wiring.

Aside from the two modules mentioned above, an additional 32-channel SCXI-1102B module was also installed in the multiplexing chassis during the third reporting period in order to accommodate additional input signals from various emissions analyzers, exhaust thermocouples, and pressure transducers. This module also contained a fixed 200 Hz low-pass filter, and was connected to a TBX-1303 terminal block equipped with cold-junction-compensation sensors to correctly scale the thermocouple signals. The addition of the above-mentioned data acquisition hardware allowed for the acquisition and monitoring of over 96 input signals from various auxiliary sensors mounted on the engine and exhaust system.

5.4.1 Low Sampling Rate Measurements

The test engine and dynamometer are heavily instrumented with various thermocouples and transducers. Tale 5.2 lists the type of sensor, its location in the test setup, and which channel and module it is connected to. The following sections provide further details regarding specific sensors used during the experiments.

Measurement	Instrument Type	Device: 1102B (1)	Device: 1100	Device: 1102B (2)	Device: PCI-6024E
Cylinder 1 Exhaust TC	Type K TC	0	--	--	--
Cylinder 2 Exhaust TC	Type K TC	1	--	--	--
Cylinder 3 Exhaust TC	Type K TC	2	--	--	--
Cylinder 4 Exhaust TC	Type K TC	3	--	--	--
Cylinder 5 Exhaust TC	Type K TC	4	--	--	--
Cylinder 6 Exhaust TC	Type K TC	5	--	--	--
EGR TC: Before Cooler	Type K TC	6	--	--	--
EGR TC: After Cooler	Type K TC	7	--	--	--
Heat Exchanger: City Water Outlet	Type K TC	8	--	--	--
Heat Exchanger: City Water Inlet	Type K TC	9	--	--	--
Turbine Outlet TC	Type K TC	10	--	--	--
Intake Manifold TC	Type K TC	11	--	--	--
Exhaust Manifold TC	Type K TC	12	--	--	--
Coolant Reservoir TC	Type K TC	13	--	--	--
Heat Exchanger: Engine Coolant Outlet	Type K TC	14	--	--	--
Heat Exchanger: City Water Inlet	Type K TC	15	--	--	--
Engine Block Oil TC	Type K TC	16	--	--	--
Compressor Outlet TC	Type K TC	17	--	--	--
Fuel Supply TC	Type K TC	18	--	--	--
Dynamometer TC: Inner Loss Plate	Type K TC	19	--	--	--
Dynamometer TC: Outer Loss Plate	Type K TC	20	--	--	--
Dynamometer TC: Bearing no. 1	Type K TC	21	--	--	--
Dynamometer TC: Bearing no. 2	Type K TC	22	--	--	--
Dynamometer Water Pressure	Pressure Transducer	23	--	--	--
Thermo-Hygrometer	0-10 VDC	24	--	--	--
Exhaust Pressure	Pressure Transducer	25	--	--	--
Engine Block Oil Pressure	Pressure Transducer	26	--	--	--
Turbine Exhaust Pressure	Pressure Transducer	27	--	--	--
Intake Manifold Pressure	Pressure Transducer	28	--	--	--
Fuel Lift Pump Pressure	Pressure Transducer	29	--	--	--
Exhaust Manifold Pressure	Pressure Transducer	30	--	--	--
Coolant Reservoir Pressure	Pressure Transducer	31	--	--	--
Cylinder 6 Pressure Transducer	Pressure Transducer	--	0	--	--
Fluke Current Probe	Hall-Effect Sensor	--	1	--	--
Intake Air Flow Meter	Dual RTD	--	2	--	--
Dilution Tunnel: Pre-Dilution	Type K TC	--	3	--	--
Dilution Tunnel: Post-Dilution	Type K TC	--	4	--	--
Ambient Temperature	Type K TC	--	5	--	--
Post-Filter TC	Type K TC	--	6	--	--
Pre-Filter TC	Type K TC	--	7	--	--
Engine Torque	Digalog Controller	--	10	--	--
Engine RPM	Digalog Controller	--	11	--	--
Charge Air Cooler	Type K TC	--	13	--	--
PM Sample Flow 2	0-5 VDC	--	14	--	--
Exhaust Temperature	Type K TC	--	15	--	--
HFID Range 1-8	0-5 VDC	--	16-23	--	--
HFID Voltage	0-5 VDC	--	25	--	--
HFID Oven Temperature	0-5 VDC	--	26	--	--
PM Sample Flow 1	0-5 VDC	--	29	--	--
NOx Voltage	0-10 VDC	--	30	--	--
NO Voltage	0-10 VDC	--	31	--	--
Crankshaft Sensor	Hall-Effect Sensor	--	--	--	2
Exhaust TR TC	Pressure Transducer	--	--	0-9	--
Exhaust TL TC	Pressure Transducer	--	--	10-17	--
Exhaust TP	Pressure Transducer	--	--	19-21	--
CO2 Voltage	0-10 VDC	--	--	23	--
CO Voltage	0-10 VDC	--	--	24	--
O2 Voltage	0-10 VDC	--	--	25	--

Table 5.2. Measured parameters and corresponding instruments and DAQ channels

5.4.2 High-Speed In-Cylinder Pressure Measurements

High-speed measurements taken during the experiments consisted of in-cylinder pressure, intake manifold pressure, and engine-position-indexing signals. Since in-cylinder pressures in a diesel engine can rise very rapidly after the auto-ignition event, a high-resolution crank-angle encoder was installed onto the tone wheel to act as an external clock to the DAQ system. An 1800-pulse-per-revolution BEI encoder provides a 0.2° resolution for the high-speed data. The BEI encoder also has another channel that gives out one digital pulse per revolution. This once-per-revolution signal was used to trigger the high-speed DAQ measurements, ensuring the data recording started at the same point of an engine revolution, although not always on the same stroke. This removed the need to superimpose a reference signal to the cylinder pressure data.

The pre-production ISB 300 engine installed at MIT was actually used at Cummins to perform development work on the engine currently available on the market. When the engine was shipped to MIT, an AVL QC33C heavy-duty pressure transducer was already installed in cylinder number 6 (cylinder closest to flywheel). The QC33C is a quartz, piezo-electric pressure transducer that is actively liquid-cooled to reduce the effects of thermal shock. A Bernard Model 2500SS MIG welder cooler is plumbed into the pressure transducer and circulates and cools a 50:50 mixture of distilled water and ethylene glycol. The transducer's small current output is converted to a voltage using a Kistler Model 5010B charge amplifier. The charge amplifier's output is fed into the DAQ system.

Since piezo-electric pressure transducers only measure changes in pressure, a method of referencing the pressure is required. The intake manifold pressures recorded along with the in-cylinder pressure provide a value to peg the cylinder pressure. The in-cylinder pressure signal is usually averaged around BDC and then scaled to equal the intake manifold pressure.

In order to provide precise fueling, the engine's ECM not only must know where the pistons are in relation to TDC, it also needs to differentiate which aspect of the four-stroke cycle each piston is going through. To provide engine-position data, the engine has Hall-effect sensors on both the camshaft and tone wheel. The tone wheel is a 60 (-1) design, originally containing 60 equally spaced teeth with one removed to provide a point of reference. The signal from the tone-wheel sensor was also fed into the DAQ system to check the phasing of the in-cylinder pressure signal.

5.4.3 Pressure Transducer Calibration and Encoder Phasing

In order to obtain meaningful results from the high-speed in-cylinder pressure measurements, correct phasing of the pressure signal is of utmost importance. Two methods were used to correctly adjust the phasing of the start of the high-speed data recording with respect to TDC. The method used as a first approximation to set the proper phasing was to adjust the encoder so that the reference signal on the crankshaft tone wheel occurred 60.0° bTDC [28]. Once the encoder was set at this approximate position, the peak pressure was determined from a motoring pressure trace and 0.4° were added due to heat transfer and blow-by effects. This was the procedure recommended by Cummins and resulted in a more precise determination of TDC.

In order to obtain the motoring pressure trace for TDC determination, the engine was fired and only fueling to cylinder number 6 was cut. Fueling to this cylinder was cut by setting the engine parameter FSI_x_ExtCylMask_c to 001F (hexadecimal representation of cylinder 6) so that the motoring pressure traces could be recorded. The motoring traces were thus recorded and fine adjustments to the encoder made until proper phasing of the signal was achieved. As a final check for correct phasing, the log-pressure versus log-volume curves were plotted for the motoring pressure traces to verify that the compression and expansion lines did not cross [28].

5.5 Fueling System

In the first reporting period, work on this project used two Exact Flow Model EFM84 single-rotor turbine flow meters to measure volumetric fuel flow to and from the engine. This system was replaced due to a failure of one of the Exact Flow meters and a gravimetric system for fuel flow measurement was installed in its place.

The current system used to measure fuel flow rates consists of an Ohaus Scout II Pro balance and a four-liter beaker used to hold a given quantity of fuel. Fuel was supplied to the engine from the beaker via a three-way ball valve to allow for selection of either the beaker or fuel tank as the fuel source. Likewise, the fuel return to the beaker was controlled via a second three-way ball valve. The return line was also used to refill the beaker when the supply line was shut off. The balance was connected directly to the serial port of the data acquisition computer and fuel mass was monitored and recorded every second.

The duration of the fuel flow measurements was limited by the size of the beaker, approximately one gallon, necessitating that fuel flow data only be taken when gaseous emissions and slow-speed data were recorded to allow sufficient time for the beaker to be refilled. Additional corrective measures to compensate for temperature variations such as the counter-flow heat exchangers installed with the fuel flow meters were retained, although no longer necessary, as the mass flow of the fuel was measured directly by the balance.

All of the diesel fuel was contained in two separate 81.4-liter (22-gallon) ATL Inc. SP122B racing fuel cells. The first fuel cell was used to hold only the LSD, ULSD, and fuel blends while the second fuel cell was only used for the neat FT diesel. This was done to prevent any cross contamination between the neat FT fuel and baseline diesel fuels. A fuel control bulkhead consisting of a series of three-way valves allowed for switching between the individual fuel tanks. Additional valves in the bulkhead made it possible to bypass the entire return system in order to drain and purge the system when changing fuels. The fuel change procedure is described in detail in Section 7.4.1. All connections on the entire fuel system were made with stainless-steel braided Teflon lines to ensure trouble-free operation and comply with laboratory safety regulations

5.6 Intake Air Measurement and Preparation

An Eldridge Products, Inc. Series 8732 thermal mass flow meter measures airflow into the turbocharger's compressor inlet. The inline-style flow meter consists of a sensing element installed into a flow section. The flow section has a laminar flow element to ensure fully developed flow by the time the air reaches the sensing element. The sensing element uses two RTDs (resistance temperature detector) to measure airflow. One RTD measures the temperature of the incoming air stream. The second RTD is forced through self-heating to maintain a constant temperature above the incoming gas. The sensing element's signal processor uses both the required current to heat the second sensor and the initial temperature read by the first RTD to calculate the mass of air flowing through the flow section. A K&N paper filter fitted upstream of the thermal mass flow meter filters the ambient air in the test cell before it flows into the engine.

After being compressed by the turbocharger, the pressurized air leaving the turbocharger is extremely hot. To reduce peak pressures in the engine, the compressed air is cooled once it leaves the compressor. A Spearco Universal Air/Liquid Intercooler was used to cool the fresh charge leaving the turbocharger. The amount of charge-air cooling is controlled by a gate valve on the liquid side of the charge-air cooler that controls the flow of water through the core of the cooler. Connections between the engine and aftercooler are made with 7.54 cm (3") I.D. silicone rubber hose, capable of withstanding temperatures up to 450 K.

Despite these measures, the engine was never operated at rated speed and load due to problems experienced in previous tests with the durability of the intake air hoses and cooling capacity of the intercooler at these conditions. Intake air temperature and relative humidity were also continually monitored via a Omega Digital Thermo-Hygrometer that was wired into the data acquisition system.

5.7 Gaseous Emissions Analyzers

A gas analyzer system was designed and fabricated at the Sloan Automotive Laboratory. This system is capable of measuring exhaust gas concentrations in both the raw exhaust stream and dilution tunnel, as well as in the intake manifold to determine the EGR fraction. In this study, all gaseous emissions comparisons were based on measurements sampled from the raw exhaust using heated sample lines and filters to prevent any water from condensing out of the exhaust stream. Figure 5.1 shows a schematic of the emission sampling system and general experimental setup as it looked at the beginning of the third reporting period.

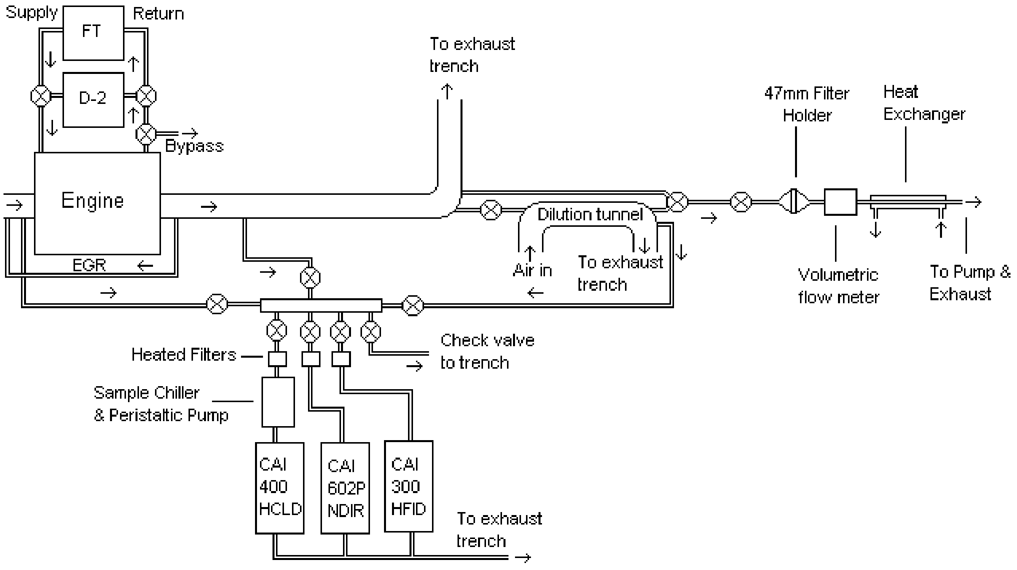


Figure 5.1. Emission sampling system schematic

A full suite of California Analytical Instruments (CAI) emissions analyzers comprised the heart of the gaseous emissions sampling system and enabled measurement of HC, NO/NOx, CO_2, CO, and O_2 exhaust concentrations. Following the second reporting period, the entire gaseous emissions and particulate sampling system was rebuilt, and new $CO/CO_2/O_2$ and SO_2 analyzers were installed.

Hydrocarbon emissions were measured using a CAI Model 300-HFID. The Model 300-HFID was calibrated with 300 PPM and 30 PPM propane (C_3H_8) span gasses and zeroed using highly purified compressed nitrogen gas. This calibration resulted in a total effective range of 0 – 900 PPM of C_1; however, during the experiments the HC analyzer was left on the 0 – 30 PPM range since HC emissions from the engine were extremely low. The operating principle of the 300 HFID is based on a flame ionization detector, whereby a flame ionizes the sample stream and electrodes in the instrument measure the particles. A mixture of 40% hydrogen, 60% helium, and hydrocarbon-free air was used to fuel the flame in the Model 300-HFID. The output of the HC analyzer was fed into the DAQ system, and the voltage signal was converted back to a PPM concentration and recorded.

A California Analytical Instruments Model 400 HCLD Heated Chemiluminescence NO_x analyzer was used to measure NO/NO_x concentrations in the raw exhaust. The analyzer works by using a photodiode detector and chemiluminescence to generate a low DC current proportional to the amount of NO in the sample gas. To calibrate the Model 400, a calibration gas of 296 PPM of NO and a zero gas of high-grade nitrogen was used. The output of the NOx analyzer was fed into the DAQ system, and the voltage signal was converted back to a PPM concentration and recorded.

A recently installed CAI 602P Non-Dispersive Infrared (NDIR) analyzer replaced the Horiba MEXA 554 JU for CO_2 measurements in previous studies. In addition to CO_2, the NDIR analyzer is also capable of measuring CO and O_2 concentration in the sample gas. The NDIR gas analyzer utilizes the basic principle that each gas component exhibits a unique absorption line spectrum in the infrared region to measure sample gas concentration. The analyzer was calibrated using the following span gas concentrations: 20.0% CO_2, 0.302% CO, and 20.0% O_2. Highly purified nitrogen gas was used to zero the analyzer as well. In addition, gas concentrations of 6.60% CO_2, 2.50% CO, and 4.115% O_2 were also used to verify correct analyzer operation. The output signals from each of the three channels ($CO/CO_2/O_2$) were wired into the DAQ system.

All of the above-mentioned gaseous emissions analyzers were mounted in a newly fabricated analyzer rack. The rack was designed to accommodate up to four different input sample lines to allow either simultaneous measurement of all gaseous emissions of interest or individual measurement of emissions from up to four different sample points. In addition to the analyzers, the rack houses a number of sample preparation and conditioning systems. The samples for all of the CAI instruments were carried from their respective sample points on the engine/exhaust system to the analyzer rack via heated sample lines. A detailed schematic of the gaseous emissions measurement system designed and fabricated for this project is shown in Figure 5.2.

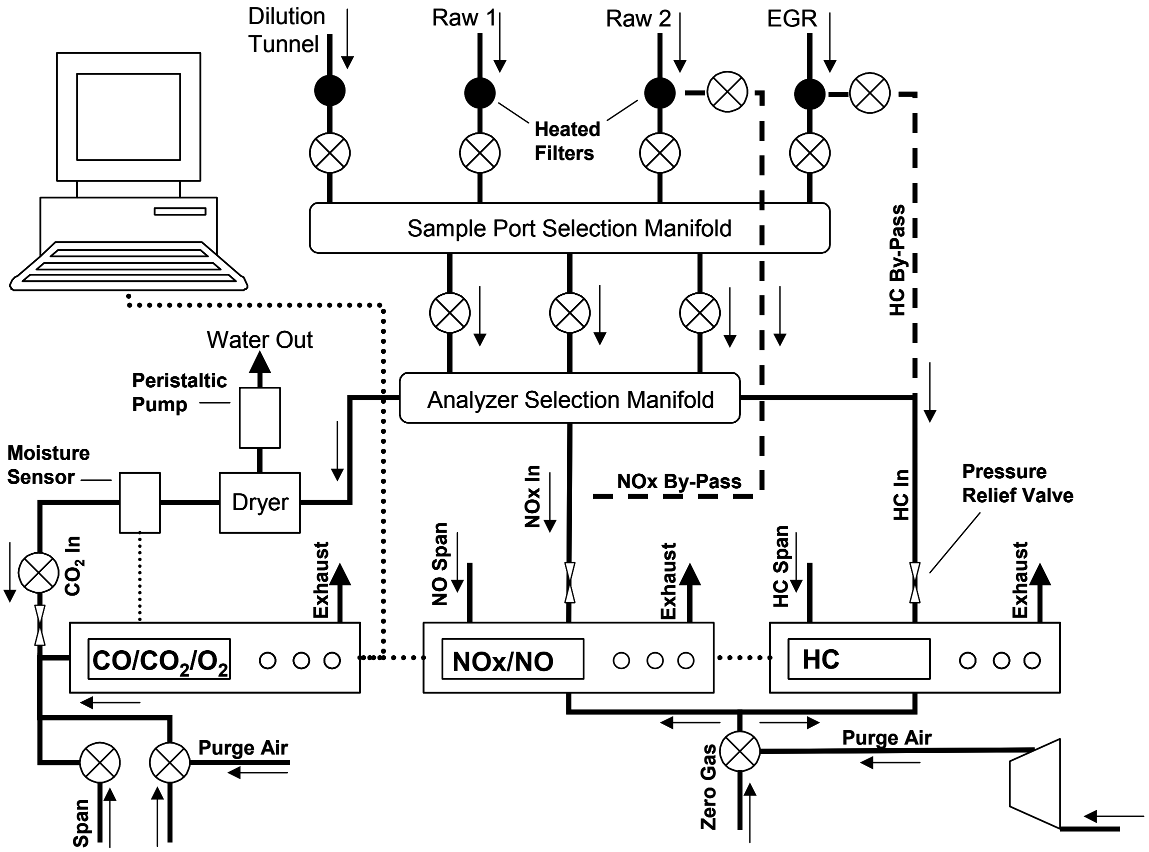


Figure 5.2. Gaseous emissions sampling system

The heated sample lines enter the rear of the analyzer rack and are connected directly to three individual Universal Analyzers Model 270S heated stack filters and one M&C Products Series FT heated filter. The Universal analyzers filters employ 2-micron ceramic filter elements to remove any large particulate matter that can clog sample and capillary tubes within the gas analyzers, and the M&C filter employs a slightly larger 3-micron filter element. A series of heated stainless steel lines connect the heated filters to one of two manifolds. The first manifold, and corresponding bulkhead mounted on the front panel of the analyzer rack, control sample port selection (Dilution tunnel, Raw1, Raw2, and EGR). The second manifold and corresponding bulkhead enable analyzer selection and control zero gas, span gas, and purge airflow.

Each CAI analyzer is also equipped with its own internal sample pump to facilitate sample gas transport from the engine through the heated lines to the analyzers. Early attempts to simultaneously run all of the analyzers on the same sample line resulted in extremely low sample flow rates and erroneous measurements due to interaction of the various sample pumps. In order to allow for simultaneous emissions sampling, two by-pass lines were added to the gas analyzer system as shown in Figure 5.2. The by-pass lines allow the sample gas to circumvent the common manifolds and flow directly into each of the three gas analyzers, thus eliminating the problem of negative pump interference.

In order to reduce the amount of zero gas consumed during analyzer warm-up and shut down, as well as to provide a convenient means for flushing the analyzer system before shut-down, a purge air system was also installed in the analyzer rack. The system consists of a Gast rotary vane vacuum pump used to pull ambient air into the system and additional bulkhead connections to direct the purge air to each of the analyzers and associated piping.

5.7.1 Sample Preparation

As the HC and NOx measurements were carried out wet, the sample gasses for these analyzers were routed directly from the bulkhead, via heated lines to the sample inlet port of the analyzers. Stainless steel tubing was used for all connections within the gas analyzer system, and all lines, manifolds, and valves were heated using Omegalux rope heaters controlled by two Powerstat variable autotransformers.

On the other hand, since the CO_2, CO, and O_2 emissions must be measured dry to avoid interference between any moisture in the exhaust stream and the optical measurement systems in the analyzer, the sample stream is first passed through a Universal Analyzers Model 520 single stage sample chiller to cool the sample to 3.5°C and remove any water vapor present in the sample stream. The water that accumulates in the sample chiller is then removed with a Universal Analyzers Model 7015-20 peristaltic pump. Furthermore, a secondary moisture sensor/filter assembly provides an additional check before the cool dry gas stream is routed into the NDIR analyzer.

5.7.2 Gaseous Emissions Sample Points

Gaseous emissions were sampled from three different locations on the engine/exhaust system in this study. All engine-out emissions were sampled from the raw exhaust stream at a sample point 10 pipe diameters away from the nearest elbow to ensure fully developed flow at the sample point. Additionally, emissions were also sampled from the intake manifold and mini-dilution tunnel. Intake manifold sampling consisted primarily of CO_2 concentration measurements in order to calculate the EGR fraction. The intake manifold emissions sample point was installed 304.8 mm (12”) from the EGR valve. For the gaseous emissions measurements taken from the mini-dilution tunnel, a sample point was installed 762.0 mm (30”) away from the tunnel inlet to ensure fully developed flow at the sampling point. CO_2 concentration measurements in the dilution tunnel were used to compute the dilution ratio by comparing the raw and dilute CO_2 measurements. Furthermore, the new sampling system enabled the verification of both the dilution ratio and EGR fraction, based on CO_2 measurements, with NOx measurements in these locations as well.

5.7.3 Sulfur Dioxide Measurements

An Antek Model 6000SE SO_2 analyzer was installed following the first round of testing. The Model 6000SE utilized two pyro furnaces each at 1000°C to convert any sulfur on the particulates and in the exhaust stream to SO_2 for measurement via UV fluorescence. As any NO present in the sample stream can adversely influence the SO_2 measurements, (100 PPM NO is detected as 1 PPM SO_2) the Antek is also equipped with an ozone generator to convert the NO to NO_2, which then no longer interferes with the analyzer. For a detailed description of the SO_2 analyzer and its principle of operation, the reader is referred to [29].

The Antek is capable of detecting SO_2 levels in the exhaust down to 250 PPB_v. Depending upon the fuel sulfur concentration, the Antek was calibrated using SO_2 span gas concentrations of 1.96 PPM, 5.23 PPM, and 32.29 PPM. Furthermore, breathing quality compressed air was used as the zero gas for the Antek. SO_2 emissions were sampled from the same locations as the other analyzers as described in Section 5.7.2, using heated sample lines to maintain as closely as possible the raw exhaust gas composition. An additional sample point for raw exhaust emissions was added downstream of the original raw exhaust sample point to accommodate the Antek's longer heated sample line. Although SO_2 emissions were primarily sampled from this second raw exhaust sample point, other sample points were occasionally used to verify correct analyzer operation and to double-check readings. A detailed schematic of the test bed with the SO_2 analyzer and second raw exhaust sample point is depicted in Figure 5.3.

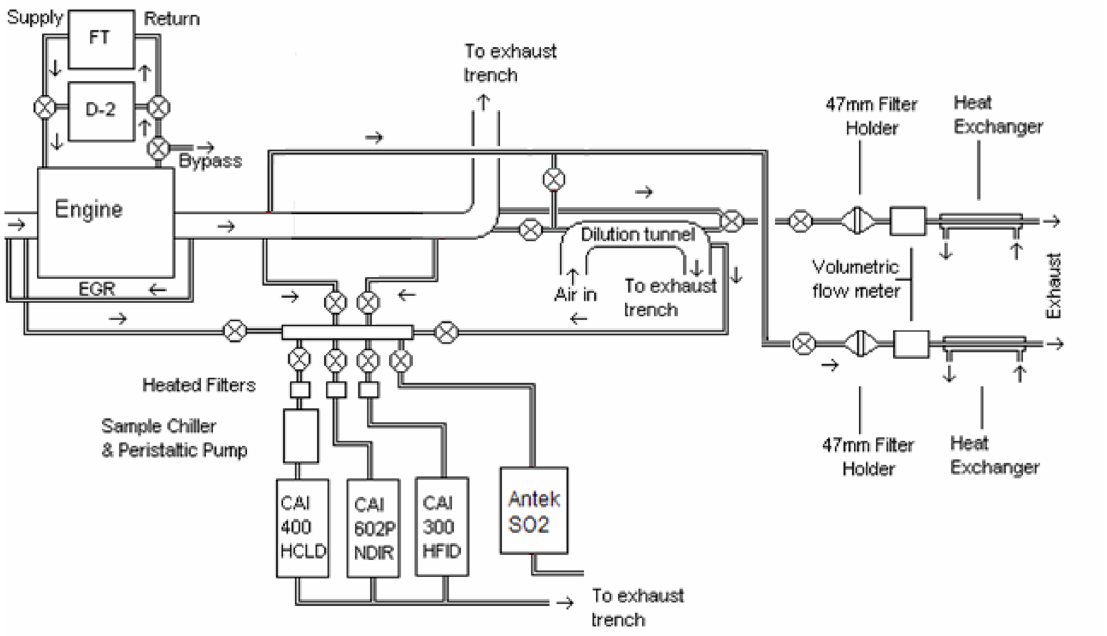


Figure 5.3. Modified test bed showing addition of SO_2 analyzer, second raw exhaust emissions sampling point, and modified PM sampling system

The modifications to the particulate sampling system shown in Figure 5.3 are presented in detail in Section 5.11.

5.8 Mini-Dilution Tunnel

Particulate Matter is defined by the EPA as all solid matter and condensable species that can be collected on a paper filter from a diluted exhaust sample held at no higher than 52°C [30]. In order to conform with the EPA mandated particulate sampling procedure and cool the exhaust to 52°C, some form of a dilution tunnel must be employed. Dilution tunnels introduce a given portion of ambient air into some or all of the exhaust stream. The mixing of ambient air with the hot diesel exhaust serves two purposes. First, it helps to cool the gasses to below 52°C, and, second, it simulates particle transformations (i.e. agglomeration, adsorption, and nucleation) that occur naturally on the road after the PM leaves the tailpipe.

The size of the dilution tunnel used in this study was limited by the available space in the test cell, and as a result, a mini-dilution tunnel was used that only dilutes a fraction of the exhaust stream. The tunnel is composed of 7.54 cm (3") O.D. stainless steel tubing, and is connected to the engine's exhaust system via a 1.88 cm (¾") O.D. stainless steel tube. A high-temperature ball valve and a Spencer Model 1001-½SS blower control exhaust flow to the tunnel. The blower maintains the pressure inside the tunnel below atmospheric, and ambient air is drawn into the tunnel through a HEPA filter element mounted near the raw exhaust inlet on the dilution tunnel system. The tunnel is 0.762 m (30") long from the raw exhaust inlet to the tunnel outlet to ensure fully developed flow and complete mixing of the raw exhaust and ambient air.

As mentioned in Section 5.7.2, the dilution ratio was measured by comparing the CO_2 readings in the tunnel to the CO_2 readings in the raw exhaust. Additional checks of the dilution ratio were also made by monitoring both raw and dilute NO/NOx readings.

5.9 Gravimetric Particulate Matter Sampling System

The gravimetric particulate matter sampling system was set up to accommodate both raw and dilute particulate samples. Dilute samples were drawn directly from the dilution tunnel, whereas raw samples were routed from a location on the exhaust system before the dilution tunnel via heated stainless steel sample lines to the particulate sampling system. Heated sample lines were used when sampling raw exhaust to prevent water from condensing out of the exhaust stream and onto the filter and tube walls.

Pall Corporation stainless steel 47mm filter holders were used to hold Pallflex® Fiberfilm Model T60A20 glass fiber filters, on which the particulate samples were collected. The Pallflex® Model T60A20 filters are recommended by the EPA for use in gravimetric filter measurements [31]. Additionally, the Model T60A20 filters can also withstand the elevated temperatures encountered during raw exhaust sampling, as they are rated for temperatures up to 315.5°C.

Exhaust gas was drawn through the particulate sampling system by a Gast Model 0823 rotary vane vacuum pump, and the sample flow through the paper filter was measured via an Omega FVL-1611 volumetric flow meter installed downstream of the filter holder assembly. The Omega FVL-1611 is capable of measuring flow rates up to 250 SLPM. The output from the flow meter was fed directly into the data acquisition system, and the flow rates were monitored and recorded continuously for the entire duration of the particulate collection.

In order to verify compliance with EPA dilute particulate sampling procedures, thermocouples were installed at locations slightly in front of the 47mm filter holders. The temperature readings were also fed into the National Instruments data acquisition system.

Shortly after the initial round of testing, the Gast rotary vane vacuum pump failed due to excessive water accumulation within the pump and the elevated temperatures to which the pump had been subjected during raw particulate sampling. Following the failure of the pump, the entire particulate sampling system was rebuilt. In addition to installing a larger and more robust rotary vane vacuum pump, Gast Model 1423, a number of protective measures were taken to prevent future pump failure as well.

The installation of the larger Model 1423 vacuum pump enabled a maximum flow rate of 13.2 CFM at 25 in Hg vacuum. The significantly higher flow rate of the pump allowed for the installation of a second particulate collection system in parallel with the original system, which reduced overall PM collection times by 50%. Secondary 10-micron Gast canister filters were also installed directly after the filter holder assemblies as an additional protective measure to ensure that no particulates would enter the new vacuum pump. Custom counter-flow heat exchangers were also designed and fabricated at the Sloan Automotive Laboratory and installed immediately after the canister filers. The heat exchangers were capable of cooling the sample gasses to between 20°C to 30°C, well below the pump's maximum allowable inlet temperature specified by the manufacturer. Following the heat exchangers and immediately before the pump, two SMC Model AMJ4000-N04B water separators were installed as well. The water separators are designed to remove any remaining moisture in the gas stream that did not condense in the heat exchangers. A schematic of the rebuilt particulate sampling system is shown in Figure 5.4.

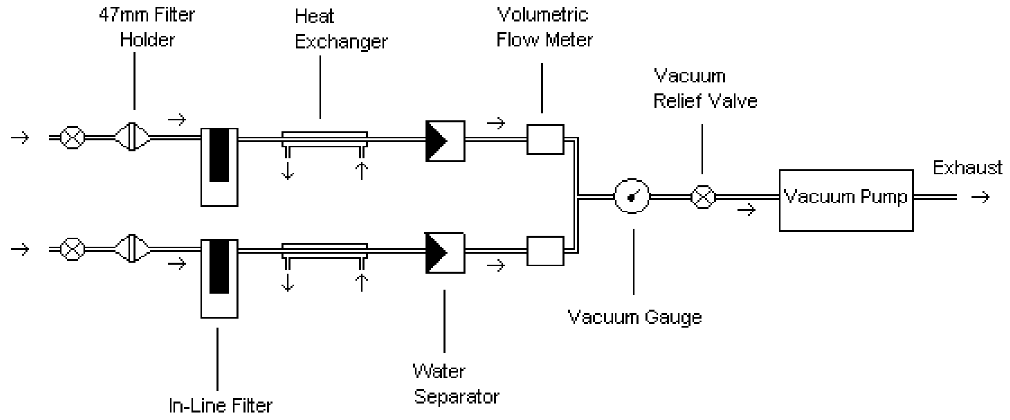


Figure 5.4. Dual branch particulate sampling system with sample conditioning systems in place.

5.10 SMPS System

For a detailed description of the Scanning Mobility Particle Sizer (SMPS) system, see Hallgren [32]. A background scan with and without the HEPA filter installed upstream of the dilution tunnel is found in Figure 5.5 showing the effectiveness of the HEPA filter. Other than the HEPA filter, no other dilution-air preparation was done.

Due to the short supply of FT fuel available during the first reporting period (one 203.5 liter (55-gallon) drum), no runs with the SMPS system were recorded when the data presented in Figure 5.5 was recorded. However, since the test engine has an EGR system, some characterizations of the effects of EGR on PM size distribution were done with the low sulfur diesel while the test setup was being shaken down. Please see Section 9.1.4 for a discussion of these scans.

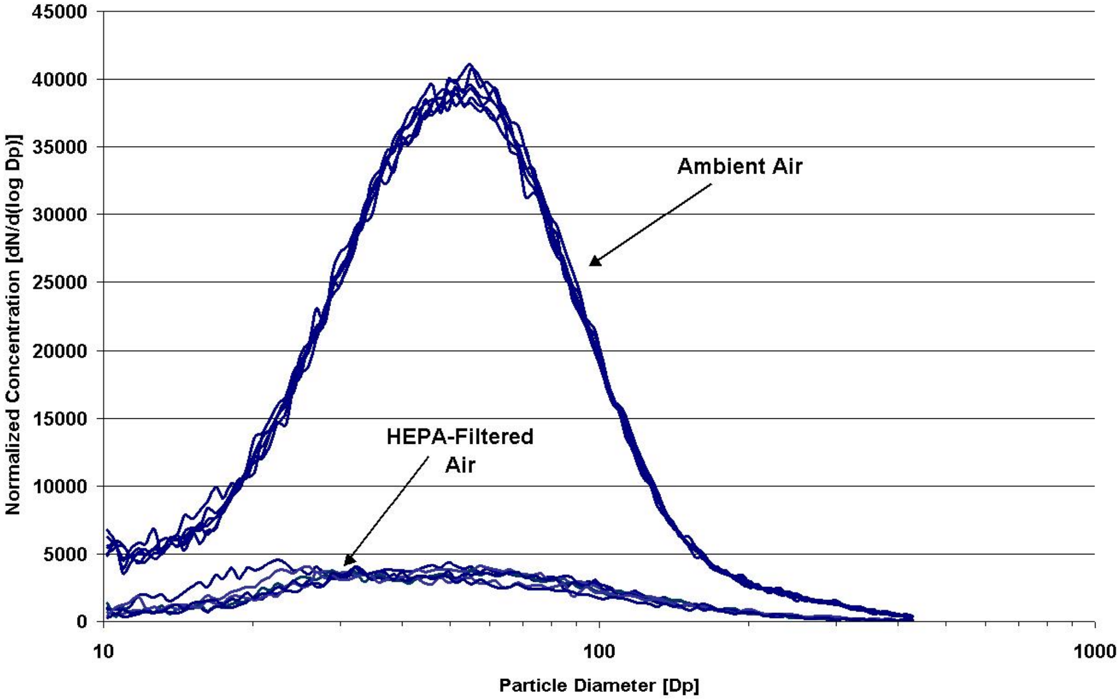


Figure 5.5. SMPS background scans with and without the HEPA filter installed

5.11 Exhaust Aftertreatment Systems

Initial trap design, sizing calculations, and fabrication and testing of a small prototype trap were completed at the beginning of the third reporting period. The prototype trap utilized a Corning Cordierite substrate, 14.37 cm (5.66") in diameter and 15.24 cm (6.00") in length, with a cell density of 100 cells per square inch. The substrate was un-catalyzed and canned in a stainless steel housing using an Interam 1100 HT mat mount supplied by 3M. While a trap of this size is much too small for the ISB operating at full-flow conditions, the prototype trap was only tested at low speed and load conditions for a short period of time before allowable backpressure limits were exceeded and testing was terminated. Pressure drop across the trap, as well as exhaust backpressure and trap temperature were monitored. The data collected from the prototype trap was used along with data provided by Cummins and Corning to carry out the sizing calculations for the full-flow unit. The prototype trap mounted on the test bed is depicted in Figure 5.6. The mini-dilution tunnel is visible in the far left of the photograph.

Figure 5.6. Prototype trap installed in the ISB exhaust system

Based on the partial flow data collected from the prototype trap tests, revisions were made to the original full-flow pistol cartridge design presented in the second annual report. The revisions were made partly based upon the data collected and experience gained testing the prototype unit, and partly to minimize the overall system complexity.

5.11.1 Particulate Trap Design

A parallel trap configuration was selected as the final design for the following reasons: first to retain some of the flexibility of the pistol cartridge design while minimizing complexity, and second to accommodate larger substrates more representative of the type used on an engine of this size. The primary design criteria are listed below:

- Maximum allowable backpressure for 1998 EPA certification: 3 in-hg
- According to Cummins 6 to 10 in-hg allowable without significant adverse effects
- 2 in-hg target clean trap pressure drop
- Minimize interference/interactions with stock engine calibration and ECM.

The original sizing calculations were verified by Corning and Corning's Cordierite substrate, 19.05 cm (7.5") in diameter and 30.48 cm (12.00") in length, with a cell density 200 cells per square inch was selected for the full flow design. Although Corning originally recommended their 8.0" diameter by 12.0" substrates for this application (D11.25"x14.00" for single flow), the slightly smaller 7.5" diameter substrate was selected due to its lower loading time and more widespread availability.

Once again, 3M supplied the custom Interam 1100 HT mat mounts to accommodate the larger substrate sizes. To avoid the difficulties encountered canning the prototype unit, a clamshell design was selected for the full-flow parallel trap. The clamshells allow for easy installation of the substrate and mounting system, as well as simplified removal of the substrate for additional laboratory/bench testing or replacement. The final trap design is shown in Figure 5.7.

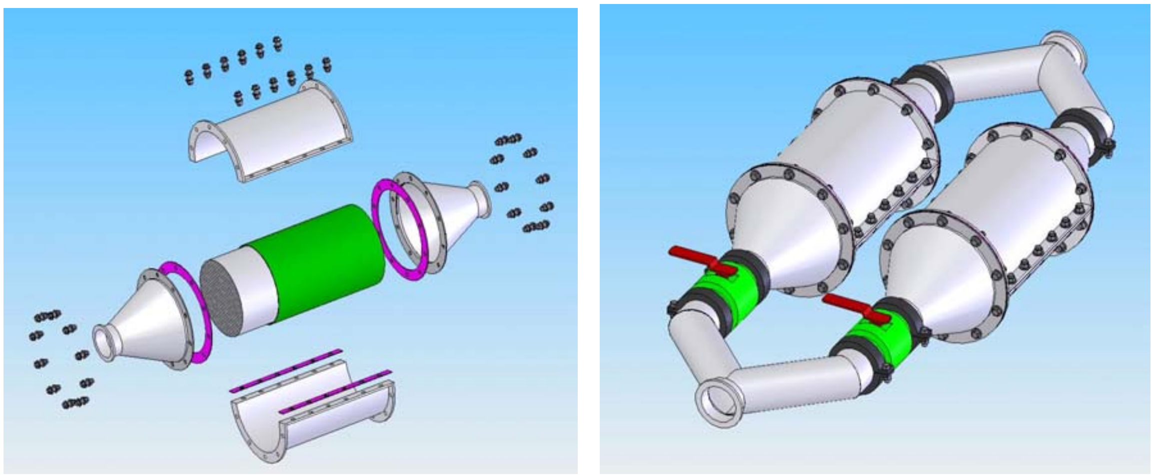


Figure 5.7. Schematic of full flow parallel particulate trap system

The graphic on the left depicts the substrate wrapped in the mat mount (green liner) as well as the associated hardware. Two circular gaskets between the can and end cones as well as gaskets between the two clamshells form a positive seal preventing any exhaust leakage. The parallel unit is also equipped with valves at the trap inlet to allow for greater flexibility in exhaust flow control as depicted in the schematic of the complete system on the right. Furthermore, individual trap units can also be easily removed for offline regeneration or bench testing by replacing the unit with either another trap or a blank (straight pipe).

5.11.2 Trap Instrumentation

Both substrates were heavily instrumented with thermocouples and pressure transducers to record the temperature and pressure profiles during trap loading and regeneration. Omega type K, model KMQXL thermocouples capable of withstanding temperatures as high as 1335°C (2440°F) were selected to monitor the temperatures within the substrate. Thermocouple diameters range from 0.020” to 0.040” to minimize any disruptions to the exhaust flow within the substrate. The smaller diameter thermocouples were installed in the inlet channels of the trap, whereas the larger diameter thermocouples were placed in the outlet channels. Details of the thermocouple locations and orientations within the substrate are provided in Figure 5.8. The thermocouples were arranged to provide temperature data in both the axial and radial directions within the substrate.

In addition to the thermocouples, Omega PX 212 pressure transducers were mounted at the inlets and exits of both traps to monitor the pressure drop across the trap as well as exhaust backpressure. Additional emissions taps were supplied at the trap inlets and exits as well, and the current gaseous emissions analyzer setup modified to allow for simultaneous sampling of HC, NO/NOx, CO, CO_2, O_2, and SO_2 both before and after the trap. All measurements were monitored and recorded using the NI LabView data acquisition systems as described in Section 5.4 and the location of the pressure transducers and emissions taps are shown in Figure 5.9.

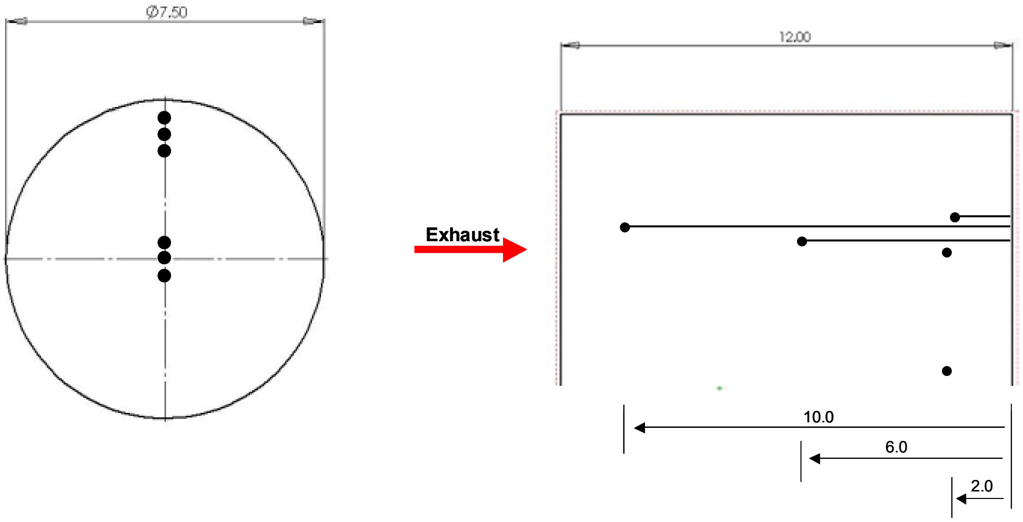


Figure 5.8. Thermocouple locations and orientation within trap substrate. The front view is shown at left, and the side view is shown on the right.

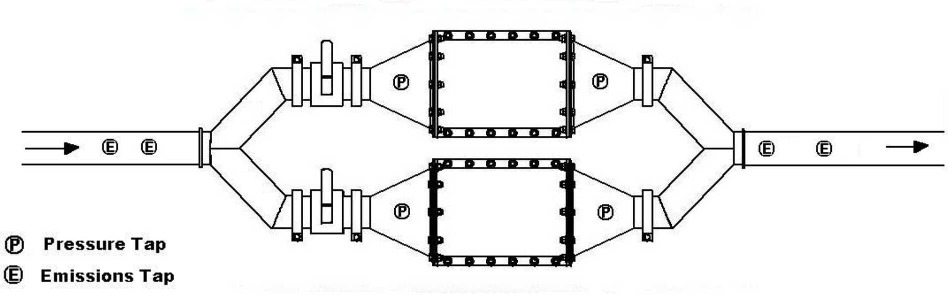


Figure 5.9 Pressure and emissions tap locations

Additional provisions were also made to enable simultaneous particulate sampling from both the pre- and post-trap exhaust stream to determine actual trapping efficiencies. In order to accomplish this, an additional tap and sample line were installed upstream of the trap and routed to the PM emissions sampling cart. A larger model Gast 1423 rotary vane vacuum pump capable of moving 13.2 CFM replaced the smaller model 823 pump to further reduce PM collection times and provide sufficient flow for the additional sample point.

In order to prevent the frequent pump failures experience in the past due to the high temperature and water content of the exhaust sample stream, a number of auxiliary devices were used to condition the sample stream after the sample filter holders and before the pump. The auxiliary equipment was installed in pairs, one for each sample stream, and consisted of a secondary 10 micron inline filter, larger capacity counter flow heat exchanger to cool the exhaust below 30 °C, and an SMC water separator to thoroughly dry the exhaust prior to the pump inlet. In addition a vacuum relief valve and associated gauges were also installed to monitor and control vacuum pressure.

Additional thermocouples and an Omega FVL-1611 volumetric flow meter were installed to monitor the flow and temperature through the second particulate sample filter as well. A detailed schematic of the emissions sampling system and layout of the test bed and particulate trap is presented in Figure 5.10. The lines in red depict the secondary PM sample system installed to facilitate the determination of the trap collection efficiency.

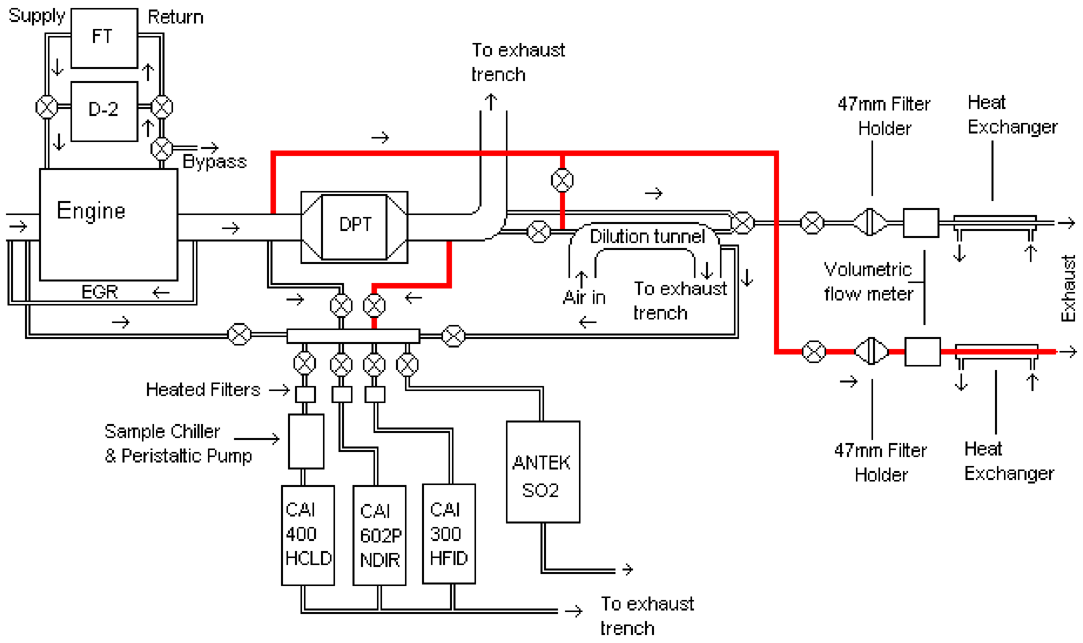


Figure 5.10 Schematic of test bed and exhaust sampling systems with DPF installed

The schematic shown above also depicts the updated gaseous emissions sampling system with four sample points for the measurement of pre-trap, post-trap, dilute, and EGR exhaust constituents. Furthermore, the new system is capable of sampling all emissions of interest from a single sample point simultaneously. Photographs of the full-flow trap installed on the test-bed are shown in Figure 5.11 below.

Figure 5.11. Schematic of full-flow trap on test bed. The pressure transducers, flow control valves, and thermocouples are shown in the photographs as well.

6.0 EXPERIMENTAL FUELS

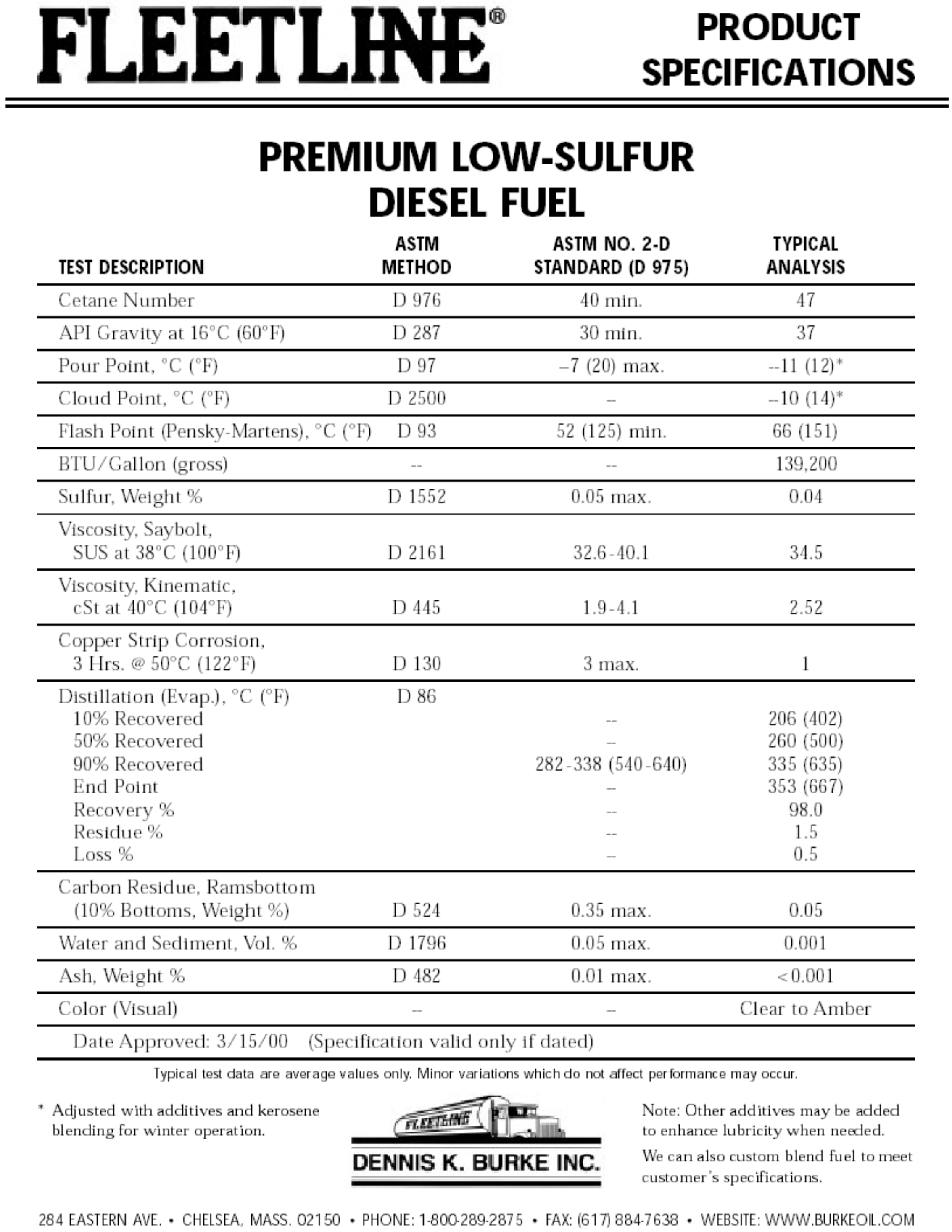
The three neat fuels under investigation in this study were a low sulfur diesel containing 400 PPM sulfur, an ultra-low sulfur diesel containing 15 PPM sulfur, and a Fischer-Tropsch synthetic diesel, produced from natural gas, containing zero sulfur. A blend of 25% FT and 75% low sulfur diesel by volume and a blend of 25% FT and 75% ultra-low sulfur diesel were used as well.

6.1 Number 2 Diesel Fuel

Two standard No. 2 diesel fuels were used to develop a performance and emissions baseline against which the Fisher-Tropsch fuel was compared. The baseline fuels were supplied by Fleetline, and differed primarily in sulfur content with the LSD containing 400 PPM sulfur by volume and the ULSD containing 15 PPM sulfur by volume. According to the information provided in the product literature, these fuels are formulated with "anti-oxidants to reduce volatility and prevent fuel degradation, inhibitors to fight gum and deposit formations in the fuel system, viscosity improvers for fuel injector lubrication and correct spray pattern, and additives for low-temperature operation" [28].

6.1.1 Low Sulfur Diesel Fuel

Fleetline's low sulfur diesel fuel was selected as one of the baseline fuels, as it is representative of typical worst-case fuels currently used in on-road heavy-duty diesel engines. The fuel, thus, provided a reference by which to compare potential improvements in performance and emissions observed with the FT fuel. The 400 PPM fuel sulfur content of the Fleetline low sulfur diesel used in this study still meets the current EPA Low-Sulfur Fuel requirement of no more than 500 PPM sulfur. In addition, according to the ASTM D 975 specifications for No. 2 diesel fuels, it should have a minimum cetane number of 40 and contain no more than 35% aromatics. A detailed listing of the fuel properties and specifications provided by the manufacturer is listed in Table 6.1.



FLEETLINE® **PRODUCT SPECIFICATIONS**

PREMIUM LOW-SULFUR DIESEL FUEL

TEST DESCRIPTION	ASTM METHOD	ASTM NO. 2-D STANDARD (D 975)	TYPICAL ANALYSIS
Cetane Number	D 976	40 min.	47
API Gravity at 16°C (60°F)	D 287	30 min.	37
Pour Point, °C (°F)	D 97	–7 (20) max.	--11 (12)*
Cloud Point, °C (°F)	D 2500	–	–10 (14)*
Flash Point (Pensky-Martens), °C (°F)	D 93	52 (125) min.	66 (151)
BTU/Gallon (gross)	--	--	139,200
Sulfur, Weight %	D 1552	0.05 max.	0.04
Viscosity, Saybolt, SUS at 38°C (100°F)	D 2161	32.6-40.1	34.5
Viscosity, Kinematic, cSt at 40°C (104°F)	D 445	1.9-4.1	2.52
Copper Strip Corrosion, 3 Hrs. @ 50°C (122°F)	D 130	3 max.	1
Distillation (Evap.), °C (°F)	D 86		
10% Recovered		--	206 (402)
50% Recovered		–	260 (500)
90% Recovered		282-338 (540-640)	335 (635)
End Point		–	353 (667)
Recovery %		--	98.0
Residue %		--	1.5
Loss %		–	0.5
Carbon Residue, Ramsbottom (10% Bottoms, Weight %)	D 524	0.35 max.	0.05
Water and Sediment, Vol. %	D 1796	0.05 max.	0.001
Ash, Weight %	D 482	0.01 max.	<0.001
Color (Visual)	–	–	Clear to Amber
Date Approved: 3/15/00 (Specification valid only if dated)			

Typical test data are average values only. Minor variations which do not affect performance may occur.

* Adjusted with additives and kerosene blending for winter operation.

DENNIS K. BURKE INC.

Note: Other additives may be added to enhance lubricity when needed.

We can also custom blend fuel to meet customer's specifications.

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Table 6.1. Manufacturer's specifications for the low sulfur diesel used as one of the baseline fuels

The lower heating value of the low sulfur diesel fuel was not listed in the product literature provided by Fleetline, and repeated attempts to contact the manufacturer were unsuccessful in obtaining the actual heating value. Therefore, the lower heating value for a standard No. 2 diesel fuel given in Syntroleum's S-2 product literature was used to allow for comparison of the lower heating values of the three different fuels used in the experiments. The value given in the Syntroleum brochure is: $Q_{LHV,No.2}$ = 129,400 Btu/gal [33]. In order to convert the heating value from a volumetric to mass basis, the density of the fuel is required. The API (American Petroleum Institute) gravity obtained using the ASTM D 287 method for the low sulfur diesel fuel is given in the manufacturer's specifications in Table 6.1 as 37. The ASTM D 287 method defines API gravity at 16°C as:

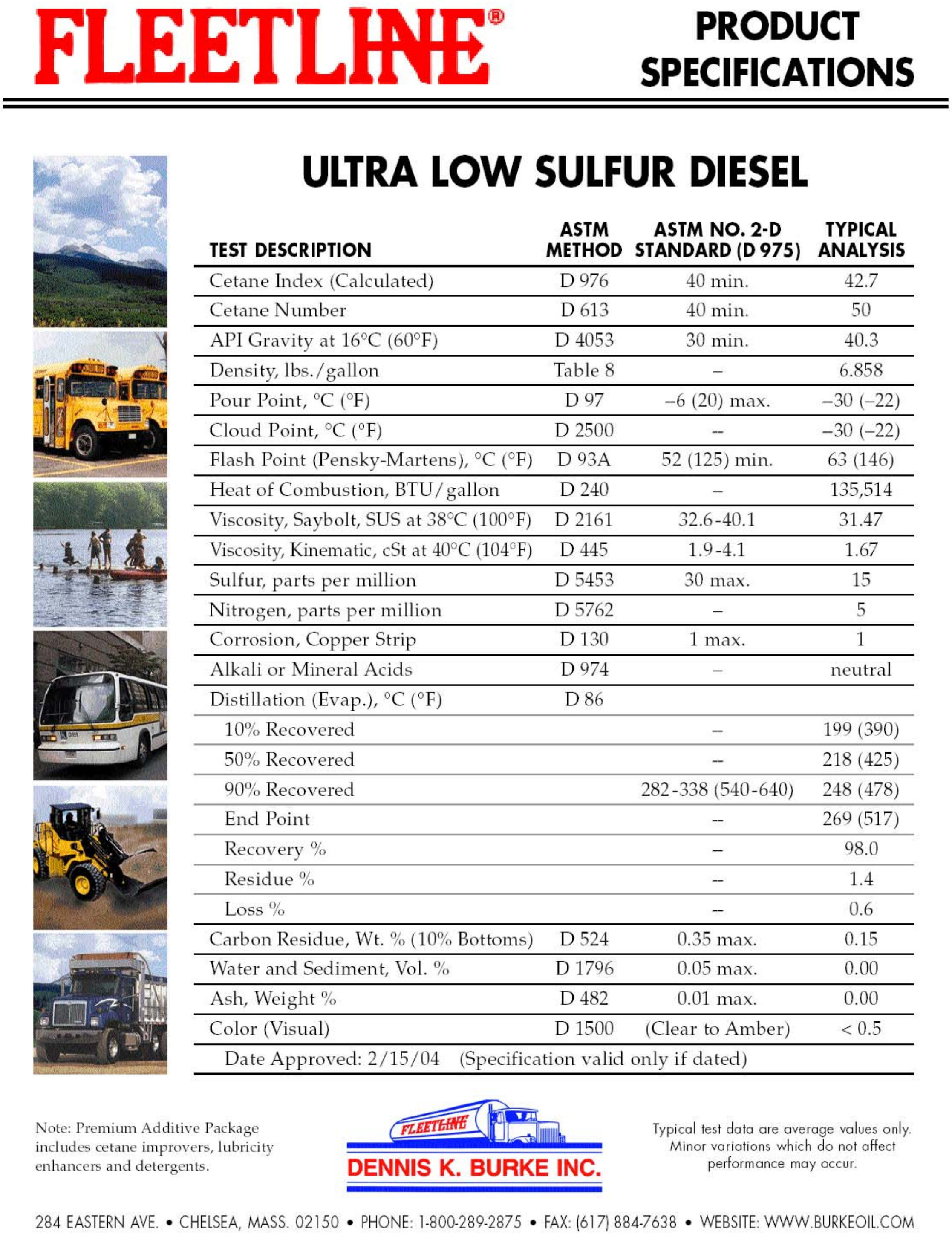
Equation 6.1

$$API\,@16^{\circ}C = \frac{141.5}{s.g.@16^{\circ}C} - 131.5$$

The fuel density was calculated using the given API gravity and Equation (6.1) as $\rho_{No.2}$ = 840 kg/m^3. Using the calculated density gives a lower heating value of $Q_{LHV,No.2}$ = 42.9 MJ/kg. This compares well with heating value data of typical light diesel fuels listed as $Q_{LHV,No.2}$ = 43.2 MJ/kg in [34].

6.1.2 Ultra-Low Sulfur Diesel Fuel

To provide a more realistic baseline for comparison with the FT fuel, tests were also carried out with Fleetline's ultra-low sulfur diesel fuel. This fuel meets the 2006 standard of 15 PPM sulfur by volume, and is representative of the types of diesel fuels that will be in use once the 2006 standards take effect. The fuel properties provided by Fleetline for the ultra-low sulfur diesel are listed in Table 6.2. Aside from a significant difference in sulfur content, the ULSD has a slightly higher cetane number and API gravity than the low sulfur diesel.



FLEETLINE®

PRODUCT SPECIFICATIONS

ULTRA LOW SULFUR DIESEL

TEST DESCRIPTION	ASTM METHOD	ASTM NO. 2-D STANDARD (D 975)	TYPICAL ANALYSIS
Cetane Index (Calculated)	D 976	40 min.	42.7
Cetane Number	D 613	40 min.	50
API Gravity at 16°C (60°F)	D 4053	30 min.	40.3
Density, lbs./gallon	Table 8	–	6.858
Pour Point, °C (°F)	D 97	–6 (20) max.	–30 (–22)
Cloud Point, °C (°F)	D 2500	–	–30 (–22)
Flash Point (Pensky-Martens), °C (°F)	D 93A	52 (125) min.	63 (146)
Heat of Combustion, BTU/gallon	D 240	–	135,514
Viscosity, Saybolt, SUS at 38°C (100°F)	D 2161	32.6-40.1	31.47
Viscosity, Kinematic, cSt at 40°C (104°F)	D 445	1.9-4.1	1.67
Sulfur, parts per million	D 5453	30 max.	15
Nitrogen, parts per million	D 5762	–	5
Corrosion, Copper Strip	D 130	1 max.	1
Alkali or Mineral Acids	D 974	–	neutral
Distillation (Evap.), °C (°F)	D 86		
10% Recovered		–	199 (390)
50% Recovered		–	218 (425)
90% Recovered		282-338 (540-640)	248 (478)
End Point		–	269 (517)
Recovery %		–	98.0
Residue %		–	1.4
Loss %		–	0.6
Carbon Residue, Wt. % (10% Bottoms)	D 524	0.35 max.	0.15
Water and Sediment, Vol. %	D 1796	0.05 max.	0.00
Ash, Weight %	D 482	0.01 max.	0.00
Color (Visual)	D 1500	(Clear to Amber)	< 0.5

Date Approved: 2/15/04 (Specification valid only if dated)

Note: Premium Additive Package includes cetane improvers, lubricity enhancers and detergents.

DENNIS K. BURKE INC.

Typical test data are average values only. Minor variations which do not affect performance may occur.

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Table 6.2. Manufacturer's specifications for the ultra-low sulfur diesel used as one of the baseline fuels

The purpose of using the ULSD fuel is twofold: first, to allow for evaluation of the fuel sulfur effect on emissions and, second, to compare FT fuel to a fuel that will be widely available in the future.

Once again, the lower heating value of the ultra-low sulfur diesel fuel was not listed in the table provided by Fleetline. In order to compare the lower heating value of the ULSD to the other fuels used in this study, the lower heating value for a standard No. 2 diesel fuel, $Q_{LHV,No.2}$ = 129,400 Btu/gal, given in Syntroleum's S-2 product literature was used once more [33]. The conversion of the heating value from a volumetric basis to SI units on a mass basis follows the same procedure outlined in Section 6.1.1. Accounting for the measured fuel density of 845 kg/m^3, yields a lower heating value for the ULSD of $Q_{LHV,No.2}$ = 42.7 MJ/kg [35]. This value also compares well with heating value data for typical light diesel fuels listed as $Q_{LHV,No.2}$ = 43.2 MJ/kg in [34].

6.1.3 No. 2 Diesel Combustion Equation

In order to compare differences in the combustion characteristics between the No. 2 diesel fuels and the Syntroleum S-2 FT diesel, a simplified chemical composition of $CH_{1.8}$ and a molecular weight of 170 g/mol [34] was used in order to write the ideal combustion equation (using the simplified chemical composition) for both the LSD and ULSD baseline No. 2 diesel fuels as follows:

Equation 6.2
$$12.3CH_{1.8} + \frac{17.835}{\phi}(O_2 + 3.773N_2) \rightarrow 12.3CO_2 + 11.07H_2 0 + 17.835\left(\frac{1}{\phi} - 1\right)O_2 + \frac{67.29}{\phi}N_2$$

Based on Equation 6.2, the air/fuel ratio for stoichiometric combustion for both of the baseline No. 2 diesel fuels is 14.50:1. This matches the accepted stoichiometric air/fuel ratio for light diesel fuels given in [34].

6.2 Fischer-Tropsch Diesel

The trend toward cleaner fuels for reduced emissions and improved compatibility with aftertreatment devices has led to renewed interest in Fischer-Tropsch fuels in recent years. Developed in the 1920's by Franz Fischer and Hans Tropsch, the FT process can be used to produce hydrocarbon fuels from a wide range of carbonaceous materials. This process consists of four major steps and is shown in Figure 6.1 below.

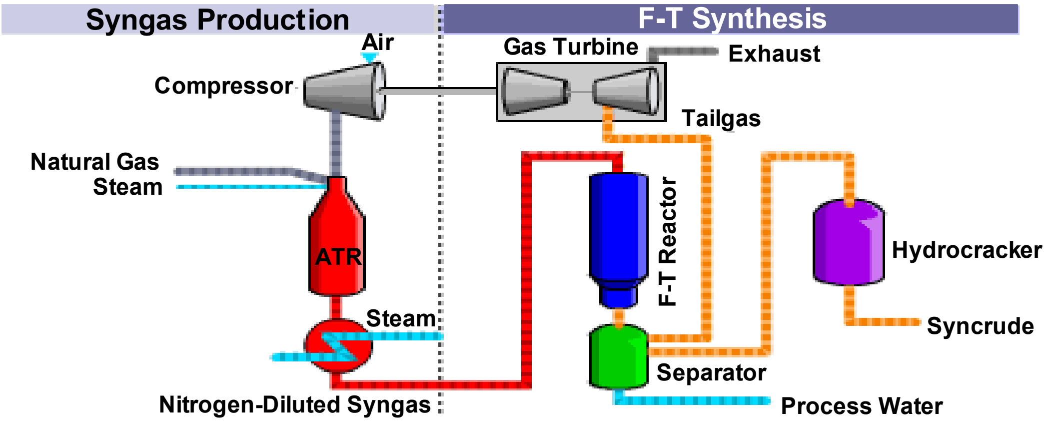


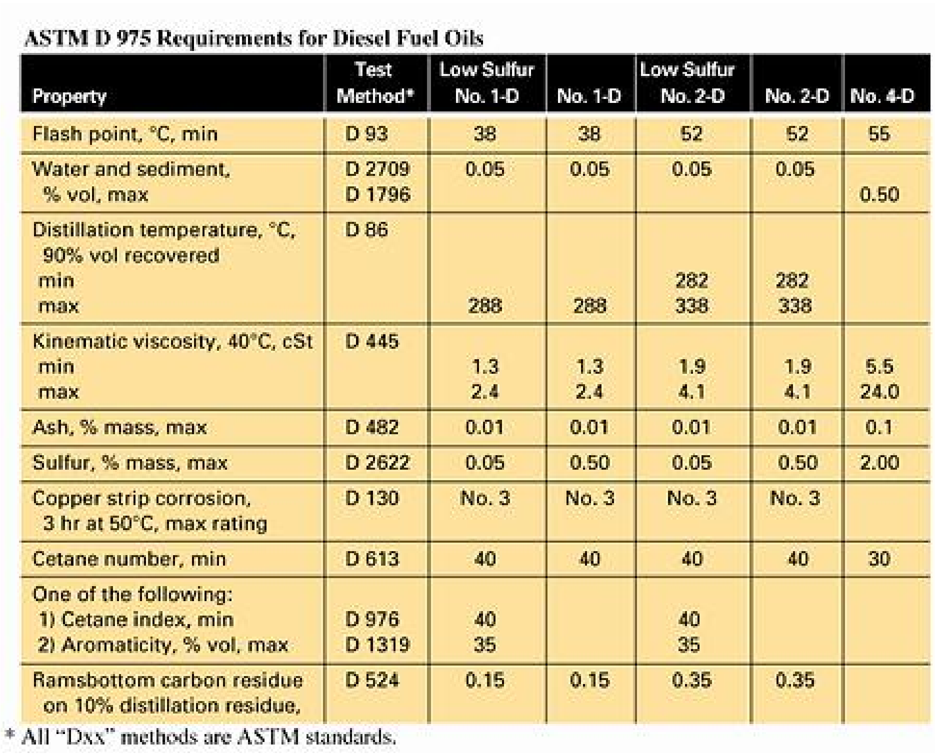
Figure 6.1. Production of Fischer-Tropsch fuels via the Syntroleum Process^{TM} [33]

The first step is the production of synthesis gas (CO and H_2) from the feedstock, typically natural gas, coal, or biomass. This step is followed by the purification of the synthesis gas, since the FT process relies heavily on the use of catalysts, and any sulfur in the synthesis gas can poison the catalysts, thus reducing fuel production. The third step is the FT catalysis process in which the synthesis gas is converted to heavy, straight-chain liquid hydrocarbons and waxes. The final step in the process consists of refining the heavy hydrocarbons by means of hydrocracking, isomerization, fractionation, and distillation to produce the desired fuel [3]. For a detailed description of the specific steps and reactions involved in the Fischer-Tropsch synthesis process, the reader is referred to [28].

6.2.1 Syntroleum FT Diesel Fuel Properties

The Fischer-Tropsch fuel (S-2) used in this study was provided by the Syntroleum Corporation. Syntroleum S-2 is produced using the Syntroleum Process™ described in the previous section. Utilizing a unique auto-thermal-reformer (ATR) to produce the synthesis gas from natural gas and untreated air reduces the overall production costs and makes Syntroleum S-2 fuel economically marketable [28].

The S-2 diesel used in this study meets or exceeds the ASTM requirements for typical diesel fuel oils, which are given in Table 6.3 .



ASTM D 975 Requirements for Diesel Fuel Oils

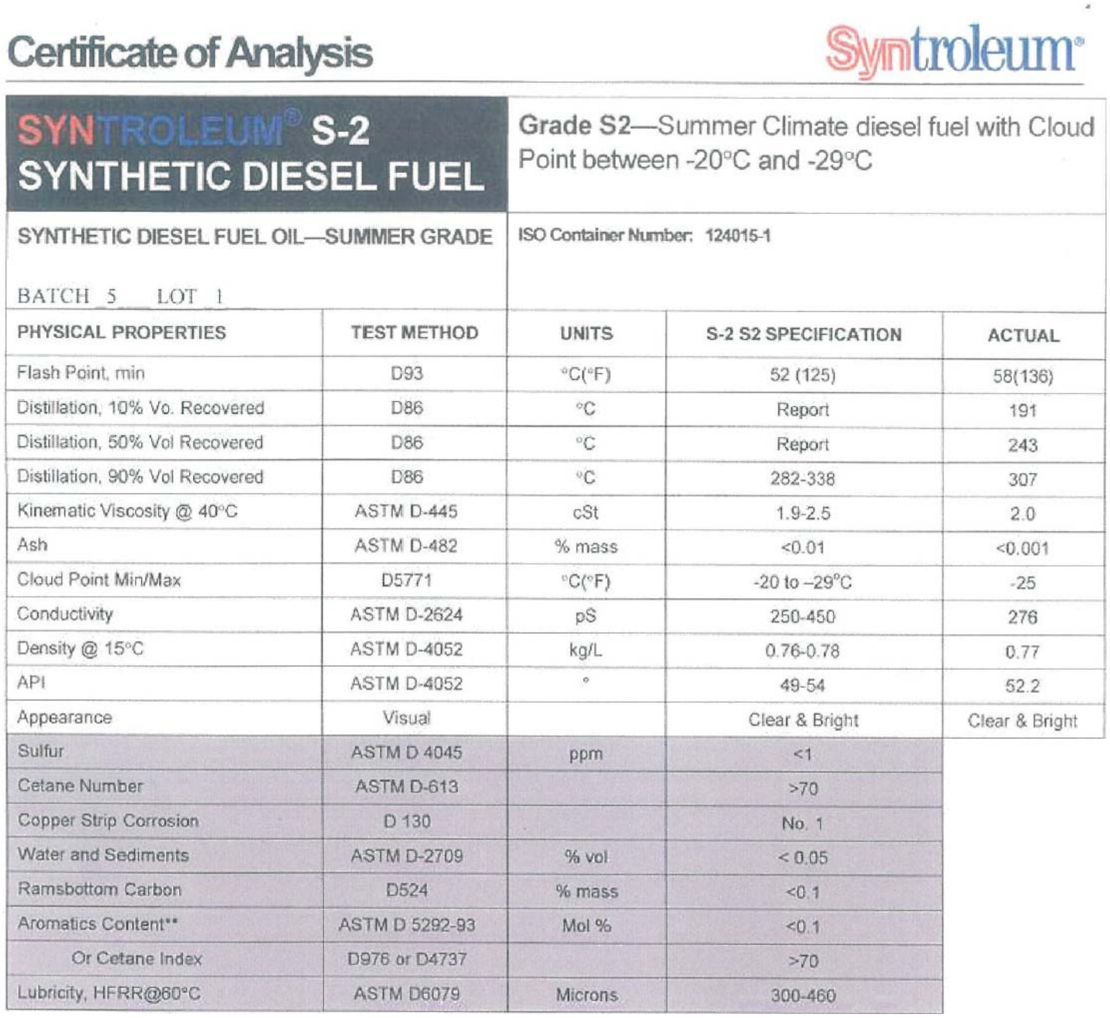
Property	Test Method*	Low Sulfur No. 1-D	No. 1-D	Low Sulfur No. 2-D	No. 2-D	No. 4-D
Flash point, °C, min	D 93	38	38	52	52	55
Water and sediment, % vol, max	D 2709 D 1796	0.05	0.05	0.05	0.05	 0.50
Distillation temperature, °C, 90% vol recovered min max	D 86	 288	 288	 282 338	 282 338	
Kinematic viscosity, 40°C, cSt min max	D 445	 1.3 2.4	 1.3 2.4	 1.9 4.1	 1.9 4.1	 5.5 24.0
Ash, % mass, max	D 482	0.01	0.01	0.01	0.01	0.1
Sulfur, % mass, max	D 2622	0.05	0.50	0.05	0.50	2.00
Copper strip corrosion, 3 hr at 50°C, max rating	D 130	No. 3	No. 3	No. 3	No. 3	
Cetane number, min	D 613	40	40	40	40	30
One of the following: 1) Cetane index, min 2) Aromaticity, % vol, max	 D 976 D 1319	 40 35		 40 35		
Ramsbottom carbon residue on 10% distillation residue,	D 524	0.15	0.15	0.35	0.35	

* All "Dxx" methods are ASTM standards.

Table 6.3. ASTM D 975 requirements for diesel fuel oils

While the zero sulfur content of the S-2 FT fuel provides a number of benefits in terms of particulate emissions reduction and improved compatibility with exhaust aftertreatment systems, the absence of the sulfur also reduces the lubricity properties of the fuel, which may have deleterious effects on the fuel injection system. In order to improve the lubricity properties of the fuel, 300 PPM of a lubricity additive manufactured by Lubrizol was blended with the fuel prior to shipping to MIT. The Lubrizol additive is not believed to significantly affect the combustion or emissions characteristics of the S-2 fuel.

The diesel fuels produced as a result of the Syntroleum Process ^{TM} exhibit a number of chemical and physical properties attributed to reduced emissions levels, namely zero sulfur content, low aromatics and olefins content, high cetane rating (74.4), and reduced density. In addition, S-2 diesel has a viscosity similar to that of standard No. 2 diesel, allowing the fuel to be used in current technology engines with no modifications to the fuel handling and injection system. Furthermore, FT diesel is completely miscible with conventional diesel making it an ideal candidate as both a blending agent with and eventual replacement for conventional petroleum-based diesel fuels. Additional fuel properties provided by Syntroleum for the two batches of S-2 FT fuel used during this study are presented in Table 6.4 and 6.5.



Certificate of Analysis

Syntroleum®

SYNTROLEUM® S-2
SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

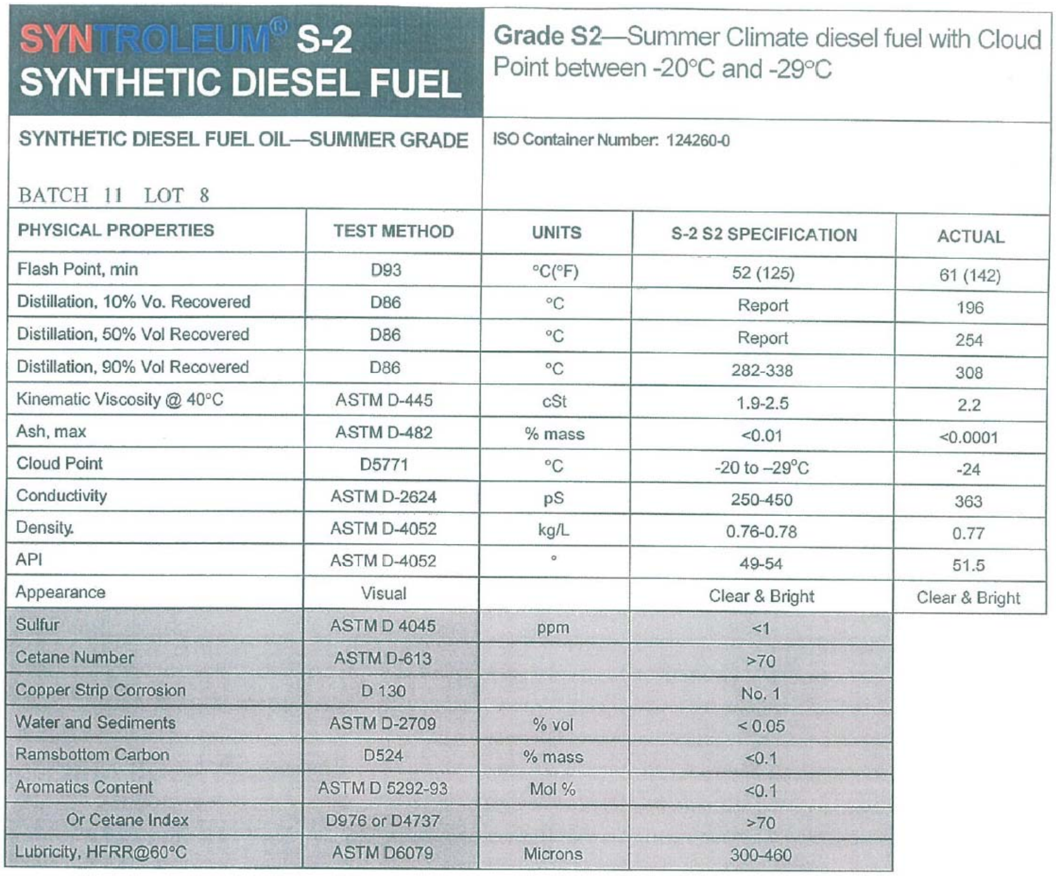
BATCH 5 LOT 1

ISO Container Number: 124015-1

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	58(136)
Distillation, 10% Vo. Recovered	D86	°C	Report	191
Distillation, 50% Vol Recovered	D86	°C	Report	243
Distillation, 90% Vol Recovered	D86	°C	282-338	307
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.0
Ash	ASTM D-482	% mass	<0.01	<0.001
Cloud Point Min/Max	D5771	°C(°F)	-20 to –29°C	-25
Conductivity	ASTM D-2624	pS	250-450	276
Density @ 15°C	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	52.2
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content**	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

Table 6.4. S-2 fuel properties for the first batch of Fischer-Tropsch diesel tested

Aside from minor variations in physical properties such as flash point, kinematic viscosity, and distillation there were no major differences between the two batches of Syntroleum S-2. Furthermore, the differences in physical properties are so small that their effect on the combustion and emissions behavior of the fuels is negligible.



SYNTROLEUM® S-2
SYNTHETIC DIESEL FUEL

Grade S2—Summer Climate diesel fuel with Cloud Point between -20°C and -29°C

SYNTHETIC DIESEL FUEL OIL—SUMMER GRADE

BATCH 11 LOT 8

ISO Container Number: 124260-0

PHYSICAL PROPERTIES	TEST METHOD	UNITS	S-2 S2 SPECIFICATION	ACTUAL
Flash Point, min	D93	°C(°F)	52 (125)	61 (142)
Distillation, 10% Vo. Recovered	D86	°C	Report	196
Distillation, 50% Vol Recovered	D86	°C	Report	254
Distillation, 90% Vol Recovered	D86	°C	282-338	308
Kinematic Viscosity @ 40°C	ASTM D-445	cSt	1.9-2.5	2.2
Ash, max	ASTM D-482	% mass	<0.01	<0.0001
Cloud Point	D5771	°C	-20 to –29°C	-24
Conductivity	ASTM D-2624	pS	250-450	363
Density.	ASTM D-4052	kg/L	0.76-0.78	0.77
API	ASTM D-4052	°	49-54	51.5
Appearance	Visual		Clear & Bright	Clear & Bright
Sulfur	ASTM D 4045	ppm	<1	
Cetane Number	ASTM D-613		>70	
Copper Strip Corrosion	D 130		No. 1	
Water and Sediments	ASTM D-2709	% vol	< 0.05	
Ramsbottom Carbon	D524	% mass	<0.1	
Aromatics Content	ASTM D 5292-93	Mol %	<0.1	
Or Cetane Index	D976 or D4737		>70	
Lubricity, HFRR@60°C	ASTM D6079	Microns	300-460	

Table 6.5. S-2 fuel properties for the second batch of Fischer-Tropsch diesel tested

The lower heating value of Syntroleum S-2 was calculated using data provided by Syntroleum and values listed in Table 6.4 and Table 6.5. The product literature for Syntroleum S-2 gives a lower heating value of $Q_{LHV,S\text{-}2}$ = 121,500 Btu/gal. The lower heating value was then converted to SI units and a mass basis using the S-2 density listed as $\rho_{S\text{-}2}$ = 775 kg/m^3. The resulting lower heating value of $Q_{LHV,S\text{-}2}$ = 43.7 MJ/kg is substantially greater than that of the baseline fuels on a mass basis. However, the significantly lower density of the S-2 fuel results in a reduction in the lower heating value on a volumetric basis by approximately 6.0% as compared to the baseline fuels.

6.2.2 Syntroleum FT Diesel Combustion Equation

Syntroleum provided additional S-2 fuel properties and specifications necessary to carry out the combustion calculations. The molecular weight of the FT fuel is 205 g/mol, and the fuel is composed primarily of 84.9% carbon and 15.1% hydrogen. No significant quantities of impurities such as oxygen or nitrogen were detected in the fuel. Based on the fuel composition data provided by Syntroleum, the reduced chemical H:C ratio for the S-2 diesel fuel is 2.12. Based on the simplified fuel composition, the ideal combustion equation for Syntroleum S-2 is:

Equation 6.3

$$14.49CH_{2.12} + \frac{22.17}{\phi}\left(O_2 + 3.773N_2\right) \rightarrow 14.49CO_2 + 15.36H_20 + 22.17\left(\frac{1}{\phi} - 1\right)O_2 + \frac{83.65}{\phi}N_2$$

Equation 6.3 yields an air/fuel ratio of 14.95:1 for the stoichiometric combustion of Syntroleum S-2 diesel.

6.3 Fuel Blends

In addition to the three neat fuels, fuel blends were studied in order to gain a better understanding of how varying fuel properties affect emissions reductions. Furthermore, this allowed direct quantification of the effect of fuel sulfur level on particulate emissions as well. A blend of 25% FT diesel and 75% low sulfur and ultra-low sulfur diesel were used in order to realize the greatest benefit of using the FT fuel as a blending agent.

6.3.1 25% FT - 75% No. 2 Diesel Blend

These blends were studied to determine whether or not the major advantages of FT fuel could be realized if the FT fuel comprised only a small portion of the engine's fuel. Previous studies have demonstrated that the effect on the emissions trends of FT/D-2 blends is not linear with respect to the portion of FT in the blend, with most of the benefit realized with less than 50% FT in the blend by volume [28, 35]. In order to realize the greatest benefit of using the FT fuel as a blending agent, a 3:1 by volume LSD and ULSD to FT fuel blending ratio was chosen.

The lower heating value and ideal combustion equation for the blend were determined from the figures for the baseline LSD and FT fuel properties presented above in Section 6.1.1 and Section 6.2.1. The conversion of 25% by volume FT fuel to a mass basis yielded 23.5% FT fuel by mass, giving a fuel density for the blend of 824 kg/m^3. Using the calculated fuel density, the lower heating value for the blend was calculated to be $Q_{LHV,\ BL}$ = 43.1 MJ/kg. Furthermore, the 25% molar fraction of FT gave a simplified chemical composition for the blend of $CH_{1.9}$. Based on the simplified chemical composition, the ideal combustion equation is given as:

Equation 6.4
$$12.88CH_{1.9}+\frac{19.0}{\phi}\left(O_2+3.773N_2\right)\rightarrow 12.88CO_2+12.24H_20+19.0\left(\frac{1}{\phi}-1\right)O_2+\frac{71.69}{\phi}N_2$$

From Equation 6.4, the stoichiometric air-fuel ratio for the blend is 14.61:1, which lies between the calculated air/fuel ratio for the baseline fuels and FT diesel, as could be expected.

6.4 Fuels Analysis

In order to verify the fuel properties provided by the manufacturers, and provide further insight into the observed combustion and emissions differences between the fuels, a sample of each of the fuels tested was sent to Syntroleum for analysis. A specific comparison of the fuel properties analyzed by Syntroleum is presented in Table 6.6.

	Fleetline Fuel LSD (400ppm)	Fleetline Fuel ULSD (15ppm)	Syntroleum S-2
Flash point, °F	130	139	142
Viscosity @40°C	2.777	2.288	2.2
Cloud Point, °C	-13	-24	-25
Freezing Point,°C	-10.5	-18.5	---
Density,15°C	0.851	0.82	0.7701
Sp Gr, 15°C	0.855	0.824	0.775
API, 60°F	33.95	40.16	51.06
Distillation Data			
D2887,IBP °F	225	254	246
D2887, 5%	335	321	330
D2887,10%	369	343	357
D2887,20%	409	368	400
D2887,30%	442	389	435
D2887,40%	473	410	467
D2887,50%	502	428	498
D2887,60%	534	449	528
D2887,70%	576	467	561
D2887,80%	622	491	594
D2887,90%	673	517	640
D2887,95%	703	540	675
D2887,FBP	758	652	741

Table 6.6. Fuel properties comparison as determined from the analysis carried out by Syntroleum

The results of the Syntroleum analysis match the data provided by Fleetline reasonably well, however the values provided by Fleetline are only the results of typical values computed from an average of a number of samples, and minor variations are to be expected.

Of specific interest to this study is the distillation data presented in the chart comparing the distillation curves for the three different fuels in Figure 6.2. It is quite clear from the chart that the distillation curve for the FT fuel is very similar to that of the low sulfur (400 PPM) diesel. Furthermore, the ultra-low sulfur diesel (15 PPM) contains a significantly greater amount of the lower boiling point (higher volatility) fraction, especially near the back end.

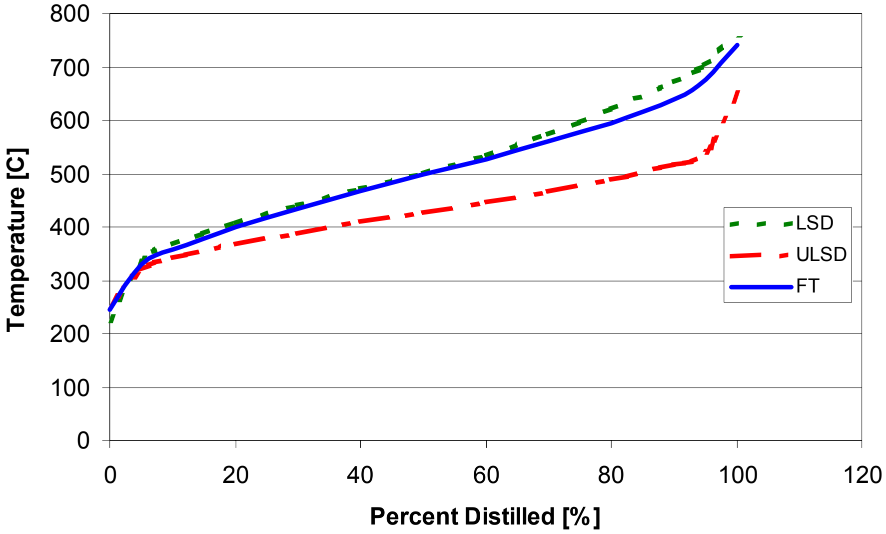


Figure 6.2. Distillation curves for each of the three fuels tested

In addition to verifying the distillation curves, Syntroleum also analyzed the fuel samples using gas chromatography. The gas chromatograms present the results of their analysis and are shown Figure 6.3 and Figure 6.4.

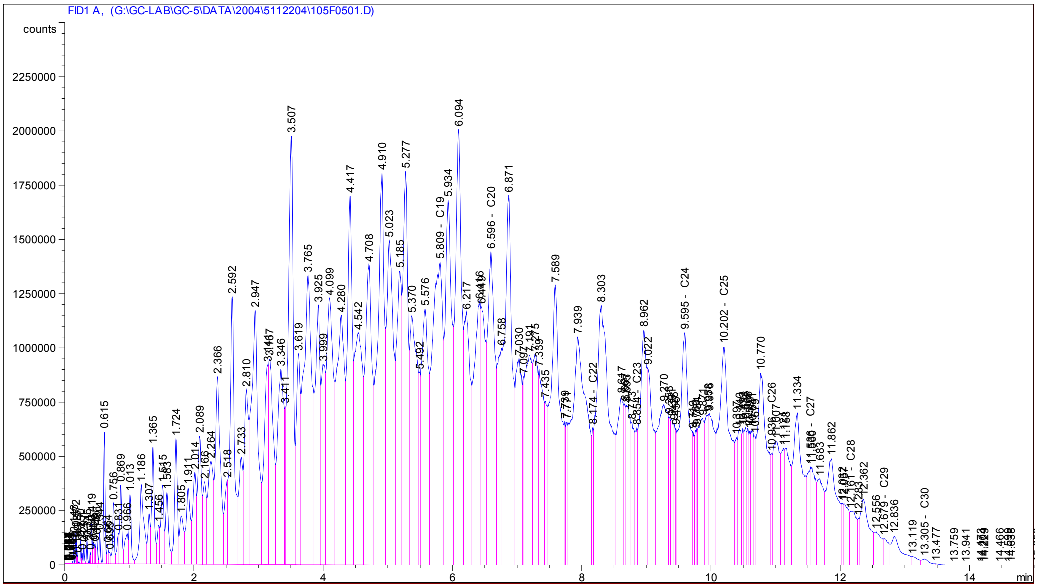


Figure 6.3. GC trace for the 400 PPM low sulfur diesel

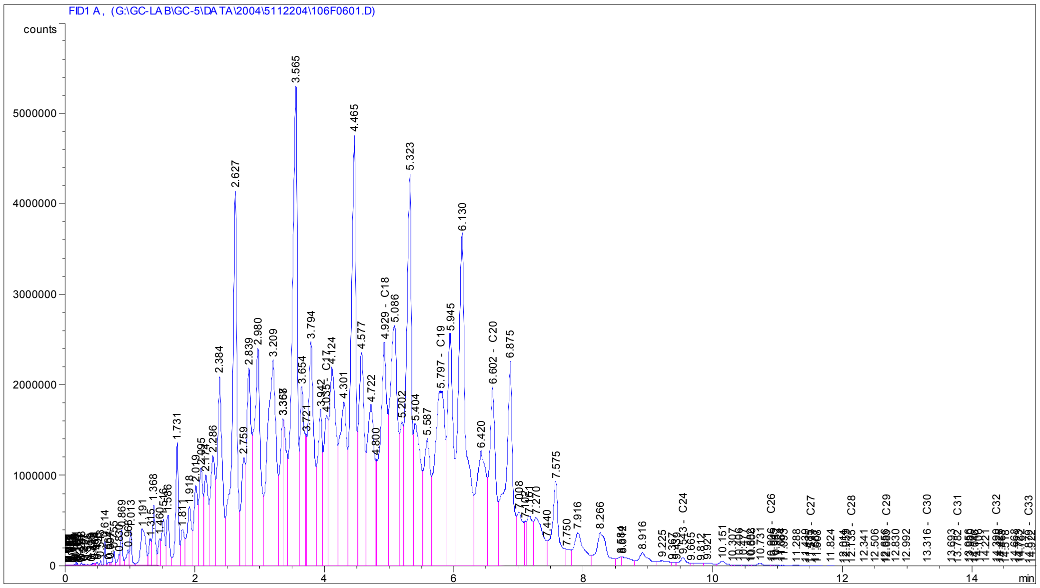


Figure 6.4. GC trace for the 15 PPM ultra-low sulfur diesel

Unfortunately the gas chromatograms for Syntroleum's S-2 fuel were not available prior to the conclusion of this study, however based on the distillation curves presented in Figure 6.2, the GC trace for the FT is expected to be similar to that of the LSD with a slightly lower heavy hydrocarbon concentration near the back end. From the two gas chromatograms for the low sulfur and ultra-low sulfur diesel, it is apparent that the ULSD contained a significantly greater portion of light hydrocarbons, a trend that was observed in the distillation curves for the two fuels as well. The lack of peaks on the right side of the spectrum for the ULSD indicate the absence of an appreciable number of heavy hydrocarbons (high carbon number compounds). Heavier compounds elute from the column more slowly, and, thus, appear toward the latter end of the spectrum. The distribution of hydrocarbon compounds in the LSD was much more uniformly distributed over the entire range of the GC trace and included a wide range of both light- and heavy-hydrocarbons, as indicated by the large number of peaks at later elusion times.

7.0 EXPERIMENTAL TEST MATRIX AND PROCEDURE

The specific engine operating conditions, fuels tested, and experimental procedures varied significantly for each reporting period as the investigation progressed through each of the three major tasks. With the exception of a summary of the engine operating conditions and test matrices for each reporting period, this chapter focuses on the experimental procedures and test matrix for the third and final reporting periods. For a detailed description of the experimental test matrix and fuels tested during each stage of the study, the reader is referred to the respective annual reports.

7.1 Engine Operation

Throughout the duration of the study, the stock 300 horsepower calibration provided by Cummins was uploaded into the ECM in order to ensure the engine would run on the 2002 EPA-emission-certified performance maps. In order to assess the impact of specific engine control parameters and the Fischer-Tropsch fuel on emissions, a number of engine control parameters were modified during the first two reporting periods. The most important parameters modified in the experiments include the start of main injection and EGR fraction. However, beginning at the start of the third reporting period and continuing through the duration of this study, no modifications to any engine control parameters were made and the engine was run using the stock calibration.

In some cases it was, however, necessary to override the stock control settings during engine warm-up, as the engine would shift from the stock control algorithm to a condensation protection algorithm. Cummins monitors intake manifold temperature, intake manifold pressure, airflow, EGR flow, and a number of other parameters to infer if water may be condensing in the intake manifold or EGR system. When the engine is first started and the intake manifold temperature is excessively cold as the charge air cooler is still warming up, oftentimes the engine control algorithm would switch to the condensation protection mode. As a result, the EGR valve closed completely to prevent excessive corrosion of the aluminum components, and the engine switched to a completely different set of operating tables. However, since the engine was operated in a controlled laboratory environment, this was often not the case. To expedite engine warm-up, the condensation protection algorithm was oftentimes manually overridden to return the engine to the stock control settings. The testing was carried out using the stock calibration to provide the worst-case scenario for a modern engine that switches to FT fuel without properly calibrating the ECM to account for the change in fuel properties.

7.2 Experimental Test Matrix

As part of engine development, Cummins uses the European Stationary Cycle (ESC) outlined by the Euro-III directive that came into effect in October 2000 [26]. The Euro-III 13 mode test cycle is listed in Table 7.1. In general, high average load factors and very high exhaust gas temperatures, simulating actual on-road driving conditions quite well, characterize the ESC test. The engine speeds A, B, and C are defined by the following: 1) the high speed RPM, RPM_{high}, is defined by calculating the highest engine speed (above the rated speed) where 70% of the declared maximum net power occurs, 2) the low speed RPM, RPM_{low}, is defined by calculating the lowest engine speed (below the rated speed) where 50% of the declared maximum net power occurs, 3) the following formulas are then used to calculated each mode speed:

Equation 7.1 $$A = RPM_{low} + 0.25 * (RPM_{high} - RPM_{low})$$

Equation 7.2 $$B = RPM_{low} + 0.50 * (RPM_{high} - RPM_{low})$$

Equation 7.3 $$C = RPM_{low} + 0.75 * (RPM_{high} - RPM_{low})$$

Using the above equations with the torque and power curves of the test engine gives the following values for the three mode speeds: A = 1682 RPM, B = 2013 RPM, and C = 2345 RPM. Table 7.1 presents all of the ESC test modes.

Mode	Engine Speed	% Load	Weight Factor, %	Duration.
1	Low Idle	0	15	4 Minutes
2	A	100	8	2 Minutes
3	B	50	10	2 Minutes
4	B	75	10	2 Minutes
5	A	50	5	2 Minutes
6	A	75	5	2 Minutes
7	A	25	5	2 Minutes
8	B	100	9	2 Minutes
9	B	25	10	2 Minutes
10	C	100	8	2 Minutes
11	C	25	5	2 Minutes
12	C	75	5	2 Minutes
13	C	50	5	2 Minutes

Table 7.1. European Stationary Cycle (ESC) test modes [26]

7.2.1 Test Matrix: First Annual Report

Governing the design of the initial test matrix was the limited supply of the FT fuel during the first reporting period. A full timing and EGR sweep consisting of five timing points and four EGR rates was originally chosen to calculate the overall fuel consumption values to accomplish a full test-matrix sweep. The initial test matrix consisted of five timing points and three EGR rates, running the engine at the A speed (1682 RPM) and 25% load [A25 point], and at a nominal A50 point [1682 RPM, 53% load], with raw PM sampling methods.

The five timing points chosen to run injection sweeps consist of the stock timing for each mode point, the stock timing ± 3°, and the stock timing ± 7°. The maximum advance was determined from peak cylinder pressure considerations. An injection advance of 7° at the A50 condition increased in-cylinder pressures to values (~13.0 MPa) within 15% of safe maximum operating pressures (15.3 MPa). Further injection advances would increase peak cylinder pressure significantly. The three EGR rates chosen for the EGR sweep consist of the stock EGR rate and the stock EGR rate ± 10% of the total charge flow (i.e. if stock EGR rate was 20%, the sweep included 10%, 20%, and 30% EGR rates).

The operating conditions defined by these timing, EGR, and speed/load combinations were given shortened labels to simplify data presentation. The low load tests with No. 2 low sulfur diesel begin with the letter “L”, while the high load tests begin with the letter “H.” For the

S-2 FT diesel test, the low load tests are denoted by “FTL” while the high load tests are defined by “FTH.” Please see Table 7.2 for the naming convention that describes the speed/load, injection timing and EGR combination.

	Timing	Retard		Advance	
EGR	Stock	3°	7°	3°	7°
Stock	*1	*2	*3	*4	*5
-0.10	*6	*7	*8	*9	*10
+0.10	*11	*12	*13	*14	*15

Notes: * = Fuel type and load (L, H, FTL, FTH). L/H = No. 2 diesel, FTL/FTH = FT diesel
Timing in Cummins ECM given as °bTDC.
EGR rates are 10% of total charge flow from stock setting.

Table 7.2. Definitions of engine operating conditions in the first reporting period. Shortened label provides load, timing, and EGR information.

7.2.2 Test Matrix: Second Annual Report

While the initial test matrix was constrained by fuel availability, such problems were not predicted for the second reporting period, and as such, the test matrix was modified to represent a larger portion of the engine’s operating range.

Condition	RPM	BMEP	EGR	Timing Sweep				
A25	1682	470	Stock	-7	-3	Stock	+3	+7
			+10%	-7	-3	Stock	+3	+7
			+20%	-7	-3	Stock	+3	+7
B50	2011	950	Stock	-7	-3	Stock	+3	+7
			+10%	-7	-3	Stock	+3	+7
B75	2011	1400	Stock	-7	-3	Stock	+3	+7

Table 7.3. Test matrix for the second reporting period

This test matrix was designed to complement the data previously collected and extend the scope of the work to cover a representative sample of engine operating conditions.

As noted in the 2003 report, FT fuel reduces PM output significantly, thereby avoiding the so-called PM-NOx tradeoff typical in emissions control strategies. Essentially, FT should allow EGR to be pushed to the practical limit, allowing for significant reduction in NOx with little (or no, in an optimized system) PM increase. As such, the EGR sweep for the A25 points was adjusted to include stock+20% absolute EGR rate in lieu of the –10% point.

A25-	Timing				
EGR	Stock	-3	-7	+3	+7
Stock (20%)	**01**	**02**	**03**	**04**	**05**
30%	**06**	**07**	**08**	**09**	**10**
40%	**11**	**12**	**13**	**14**	**15**

B50-	Timing				
EGR	Stock	-3	-7	+3	+7
Stock (18%)	**01**	**02**	**03**	**04**	**05**
23%	**06**	**07**	**08**	**09**	**10**

B75-	Timing				
EGR	Stock	-3	-7	+3	+7
Stock (18%)	**01**	**02**	**03**	**04**	**05**

Table 7.4. Definitions of operating conditions and data set labeling convention

Data sets recorded in the experiments and presented here adhere to a prescribed naming convention that indicates fuel used and engine operating parameters. Excepting data for the 15 PPM baseline fuel, a 2 to 3 letter prefix indicates the type of fuel for the data set. FT, BL and HS represent Fischer-Tropsch, FT/15 PPM blend, and 400 PPM fuel respectively. There is no prefix for the 15 PPM fuel, and ancillary blends used in one experiment also get a digit (e.g., BL2). Following the fuel specification, the general operating condition is indicated by the letter corresponding to the speed and two digits representing the percent load for that speed, as outlined in Table 7.4. Following the load/speed information is a hyphen and another pair of digits indicating the timing and EGR rates, relative to stock. For example, BLA25-03 is for 25% load (224 N-m) at the A speed (1682 RPM) with FT/15 PPM blended fuel, stock EGR rate and timing retarded 7 degrees.

7.2.3 Test Matrix: Third Annual Report

Table 7.5 below shows the original test matrix from the first reporting period, which formed the basis for the initial tests carried out at the beginning of the third reporting period.

Mode	Speed [RPM]	Load [N-m]	BMEP [kPa]
A25	1682	224	477
A50	1682	470	1001
B50	2013	447	952
*A50 is actually 53% load			

Table 7.5. Initial test matrix for the third reporting period

The test matrix shown above represents the three steady-state speed and load points that were used to evaluate the fuel effects on engine-out emissions. The A50 test point at 53% load was retained from the initial reporting period to allow for direct comparison of the results. The initial test matrix was chosen for the following two reasons: first, to verify the initial results observed in the first reporting period for the fuel blends and, second, to reduce dilute particulate collection times, as the test points represent operating conditions producing a relatively large amount of particulate emissions.

Following the initial round of testing, the test matrix was expanded to 10 steady-state speed-load points for each fuel to represent a larger portion of the engine's operating range. Similar to the initial test matrix, the expanded test matrix is comprised of a subset of the Euro III 13-mode test cycle. The specific operating conditions are listed in Table 7.6.

Mode	Speed	Load	BMEP
	[RPM]	[N-m]	[kPa]
Z25	1200	180	383
A25	1682	224	477
A50	1682	470	1001
A75	1682	671	1429
B25	2013	223	475
B50	2013	447	952
B75	2013	669	1425
C25	2345	217	462
C50	2345	433	922
C75	2345	650	1384
*A50 is actually 53% load			

Table 7.6. Expanded test matrix to evaluate combustion characteristics

Due to the lengthy sampling times necessary to collect a significant amount of dilute particulates for gravimetric analysis, combined with the fact that diesel particulate emissions are fairly well documented in the literature [3, 36, 37] and the previous reporting periods, detailed exhaust emission measurements were not continued with the expanded test matrix, and the focus of the study was shifted to a comprehensive combustion analysis.

This test matrix was designed to complement the data previously collected in several ways. As can be seen in Tables 7.5 and 7.6, there is significant overlap in the A25, A50, and B50 conditions. The purpose of this is two-fold: to provide an opportunity to correlate results of the combustion analysis with previous emissions data and to allow a direct comparison of the 400 PPM and 15 PPM sulfur fuel to the FT fuel. This expanded test matrix extends the scope of the work to cover a full range of engine operating conditions, and encompasses relatively high speed and load test conditions not covered in the last two reporting periods.

Data sets presented here adhere to a prescribed naming convention that indicates fuel used and engine operating parameters. A two to four letter prefix indicates the type of fuel for the data set. FT, BL, LSD, and ULSD represent Fischer-Tropsch, FT/400 PPM blend, low sulfur diesel (400 PPM), and ultra-low sulfur diesel (15 PPM) respectively. Following the fuel specification, the general operating condition is indicated by the letter corresponding to the speed and two digits representing the percent load for that speed, as outlined in Table 7.6. For the sake of clarity, the type of blend (FT/LSD or FT/ULSD) is always explicitly stated in the results.

7.3 Particulate Matter Sampling Conditions

Due to time and fuel constraints, most of the particulates sampled in the first two reporting periods, were sampled raw, without the use of the dilution tunnel. However in the third and final reporting periods all particulates collected were sampled from the exhaust stream after passing through the mini-dilution tunnel, and raw particulate samples were no longer collected. Although the sampling times required to collect a comparable amount of dilute particulates are approximately 6 times longer when compared with the raw sampling method, only dilute particulates were sampled during the last two reporting periods in order to reduce the error and uncertainty inherent to the raw sampling method.

Before each test, the Pallflex filter papers were placed in individual plastic petri dishes and allowed to condition for at least 56 hours in accordance with protocol recommended by the EPA [38]. All filter preparation, conditioning, and settling were done in an air-conditioned room where the temperature was between the EPA mandated range of 68° – 86° and relative humidity of 30% – 70%. However, it was found that daily variation in room conditions had a substantial effect on filter mass, in some cases on the order of the entire particulate mass sampled. To correct for this, a set of "control" filters were kept in the sample room at all times so that a correction could be calculated based on the variation of the control filters in the period between filter weighing.

7.3.1 Dilute Exhaust Sampling

Dilution ratios were generally kept between 7 and 12, and verified by measuring the CO_2 concentration in both the raw and dilute exhaust stream. Additional checks of the dilution ratio were made by measuring the dilute and raw NOx concentrations as well. The goal was to dilute the exhaust just enough to reduce the sample temperature below the mandated 52 °C, and not too much more. This helped to keep sample times reasonable. With the Gast rotary vane pump installed, sample times were typically around 30 minutes to collect at least 2 mg of sample. It was observed that filters sitting idle in the climate controlled conditioning room could vary in weight by $\pm$ 0.5 mg. Even though measures were taken to correct for this, the best way to improve data quality was to collect as much sample as possible.

As mentioned in the previous section, new filter papers were allowed to condition in a climate controlled room for at least 56 hours prior to use. After the conditioning period, four PM samples were taken consecutively in order to collect a large enough sample to calculate a meaningful average. After the filter papers were loaded, they were again allowed to sit for at least 56 hours in the climate controlled room in order to dry the paper and settle the particulates.

7.3.2 Raw Exhaust Sampling

While some raw particulate samples were collected in the previous reporting periods due to time constraints, it typically shows lower PM output than dilute sampling and was not continued after the second reporting period. Since the raw exhaust is sampled hot and undiluted, the driving forces for nucleation and adsorption of condensable gas species are severely reduced, thus significantly reducing the extractable fraction. Therefore, the raw PM emission levels are much less than a comparable sampling run with a dilute sample for the same operating point.

Generally, the dilute sampling produced more consistent results, and was the only sampling method that ensured the sample stream was cooled to below 52 °C in accordance with the EPA particulate sampling guidelines. Despite this fact, the dilute sampling method still leaves much room for improvement. Of primary concern is the filter conditioning pre- and post-weighing.

7.4 Engine Operation during Experiments

Before beginning each round of experiments, the CAI Models 300-HFID, 400 HCLD, and 602P NDIR gas analyzers were calibrated with zero and span gases covering the instrument's expected operating range. All analyzers were allowed to warm up for approximately one hour prior to calibration. After the instrumentation was properly calibrated, the engine was then started and allowed to idle for a few minutes as the National Instruments and CalTerm software programs were started and the dynamometer idle torque offset settled. After all the computers and gas analyzers were ready for use, the ECM settings were left in stock form while the voltage output from the Watlow controller was slowly increased until the appropriate load condition was reached. The engine was run at the predetermined test condition until normal operating oil and coolant temperatures were reached before initial testing was initiated. This time also allowed the filter holders and sampling apparatus to reach operating temperature. As mentioned in Section 7.1, the condensation protection control algorithm was occasionally overridden to expedite the warm-up process; however all engine control parameters were returned to their stock settings before any measurements were taken.

Once the engine reached a steady-state condition, a 60-second scan of all slow-speed engine data including fuel flow was taken. After this, two 30-second scans of the gas analyzers were run and CO_2 data was manually recorded in a lab book. During these runs, the engine's fuel was drawn from the fuel beaker instead of the tank, which provided fuel flow figures for the conditions. Once the emissions scans had finished, the first filter sample was begun. During the particulate sampling, the data acquisition system recorded the flow through the filter for calculation of actual engine out data. Between the four particulate samples, another round of emissions data was taken and the particulate sampling process repeated. All in all, four particulate samples were taken in between five sets of emissions and fuel consumption data. Finally, after all particulate samples were taken at a particular test condition, a final scan of all data was taken, along with a 100-cylce high-speed scan to record in-cylinder pressure data. The 100-cycle scan was taken at the end of all tests (approximately 2.5 hours after the first slow speed scan) since this ensured ample time for all operating parameters to reach a steady state.

It should be noted that the detailed particulate and emissions measurements were not continued for the expanded test matrix. During these tests only the 60-second scan of all slow-speed engine data, including fuel flow, was taken. Following the slow-speed data, the 100-cycle high speed in-cylinder pressure measurements were taken. This process (alternating slow- and high-speed scans) was repeated four times for each test condition in order to collect enough data to calculate meaningful averages for each test condition.

7.4.1 Fuel Change Procedure

Fuel changes were initiated following the completion of a full round of testing for each fuel under investigation. Testing began with the FT fuel (zero sulfur content) and subsequent fuel tests were carried out in the order of increasing fuel sulfur content. The fuels were tested in this order for the purpose of reducing the potential for residual fuel sulfur in the fuel system leftover from a high sulfur fuel to contaminate the ultra-low sulfur and FT fuels.

In order to minimize cross-contamination of the FT and standard No. 2 diesel fuels, the engine is equipped with two separate ATL fuel cells. Despite this fact, a number of additional precautions were taken when switching from one fuel to another. First, the supply and return valves on the bulkhead controlling fuel routing were switched to the desired fuel source. In addition, the bypass valve was opened and the engine's electronic fuel lift pump was run to purge any remaining fuel from the supply-side of the system. At this point, the engine's fuel filter was removed and replaced to prevent any cross-contamination of fuel sulfur. In order to purge any remaining fuel from the return side of the system, the lift pump was again run with the return line disconnected from its respective tank, and all fuel routed to a waste fuel container. As a further precaution, the return line was left connected to the waste fuel container for the first few minutes of engine operation with the new fuel to fully eliminate the possibility of any cross-contamination.

7.4.2 Oil Change Procedure

All engine tests for the current reporting period were carried out using a standard 15W-40 heavy-duty diesel oil as recommended by Cummins. Routine oil and filter changes were carried out at the manufacturer's prescribed maintenance intervals. Furthermore, new and used oil samples were collected and sent to the emissions-chemistry laboratory of a major engine manufacturer for analysis.

7.5 Data Processing and Reduction

All gaseous and particulate emissions values reported in this study were normalized in units of power and time (g/hp-hr) to allow for direct comparison of the various fuels over a wide range of engine operating conditions. Furthermore, as not all gaseous emissions were measured on the same basis (wet or dry), the conversion of the emissions values to the same basis required a significant amount of data processing.

7.5.1 Gaseous Emissions Data Processing

Since the HC, NO, and NOx emissions were measured wet and the CO, CO_2, and O_2 emissions were measured dry, with any water in the exhaust removed via the sample chiller, the CO, CO_2, and O_2 concentrations were all converted to a wet basis. This also enabled direct comparison with the Cummins ESC data, which was reported on a wet basis as well. In order to convert all of the emissions values measured on a dry basis to a wet basis, the water content in the intake and exhaust had to be estimated.

The conversion of the emissions values measured on a dry basis to a wet basis is as follows. If the average molecular formula of the fuel is defined as $(CH_y)_\alpha$, where y is the molar H/C ratio of the fuel, then the molecular weight, M_f, of the fuel is given by [34]:

Equation 7.4
$$M_f = \alpha(12 + y)$$

where α is the coefficient used to multiply the average molecular weight of the simplified chemical composition to equal M_f. Since the Cummins ISB employs a cooled EGR system to reduce NOx emissions, a fraction of the exhaust gasses is routed back into the intake manifold where it is mixed with the fresh intake charge. The moles of the major species in the intake mixture with EGR can be estimated via the following equation written per mole of O_2 [34]:

Equation 7.5
$$(1 - x_b)\left[\frac{4}{M_f}(1 + 2\varepsilon)\phi(CH_y)_\alpha + O_2 + \psi N_2\right] + x_b(n_{CO_2} + n_{H_2O} + n_{CO} + n_{H_2} + n_{N_2} + n_{O_2})$$

where x_b is the burned gas fraction, ε is defined as 4/(4+y), ϕ is the fuel/air equivalence ratio, n_i is the number of moles of species *i* per mole of O_2, and ψ is the molar N/O ratio (3.773 for air). The mole fractions of the individual species are obtained by dividing by the total number of moles of unburned mixture, n_u, [34].

Equation 7.6
$$n_u = (1 - x_b)\left[\frac{4(1+2\varepsilon)\phi}{M_f} + 1 + \psi\right] + x_b n_b$$

where n_b, the total number of moles of burned mixture, is given by the following equation for a lean mixture [34]:

Equation 7.7
$$n_b = (1 - \varepsilon)\phi + 1 + \psi\ .$$

Since the engine is turbocharged, it is assumed that the residual gas fraction is negligible in the equations presented above. However, since the engine employs EGR, x_b, was initially set equal to the EGR fraction, which was computed from the measured CO_2 concentrations in the intake manifold and exhaust system [28].

Once the correct water content in the intake mixture (air, fuel, and burned gas fraction) was calculated, the water vapor mole fraction in the exhaust was found from the ideal combustion equations for each fuel. The equations presented above were then iterated with the newly determined EGR fraction until a steady-state value was reached. Based on the water vapor mole fraction in the exhaust, the dry-basis CO, CO_2, and O_2 values were converted to a wet basis as follows:

Equation 7.8
$$\tilde{x}_i = (1 - \tilde{x}_{H_2O})\tilde{x}_i^*$$

where $\tilde{x}_i$ is the wet mole fraction of species *i*, and $\tilde{x}_i^*$ is the dry mole fraction of species *i*, [34]. As an additional check of the accuracy of the calculations presented above, the measured air/fuel ratio based on the air and fuel flow measurements was compared against the air/fuel ratio computed using the exhaust emissions measurements and the two were found to be in good agreement.

7.5.2 Particulate Emissions Data Processing

Only a portion of the raw exhaust was diverted into the mini-dilution tunnel and collected via the particulate sampling system. Therefore, the mass of the particulates collected on the filter papers had to be converted to a total engine-out PM emissions rate. This was accomplished by using the measured sample flow data recorded from the Omega FVL-1611 volumetric flow meter and the dilution ratio computed from the CO_2 concentrations measured in the dilution tunnel and exhaust system.

The PM sample flow rate data was averaged over the entire sampling period, since the flow rate decreased with time as the filters were loaded. The sample flow rate across the filter was then used to compute the actual particulate emissions from the engine normalized in units of power and time (g/hp-hr) to allow for direct comparison over a range of operating conditions.

7.6 Heat Release Analysis

The major thermodynamic indicators used in this study to quantify the specific aspects of the combustion process were calculated via a simple single-zone heat release analysis. The analysis is based on the First Law of Thermodynamics and assumes a single zone of uniform products in a closed system between intake valve closing (IVC) and exhaust valve opening (EVO). The gas properties in the cylinder are calculated using the ideal gas relationships and the gas constant for air. Due to the nature of this simple single zone model, heat loss through crevice effects and non-uniformities within the cylinder, the model can only produce approximate results. The following form of the First Law forms the basis of the model:

Equation 7.9
$$dU_{\text{int}ernal} = \delta Q_{chemical} - \delta Q_{HT} - \delta W$$

where $\delta Q_{\text{chemical}}$ is the calculated energy of the fuel, δQ_{HT} is the energy lost through heat transfer and δW is the work term. In order to apply the First Law directly to in-cylinder pressure data, the following form is used:

Equation 7.10
$$\frac{\delta Q_{chemical}}{d\theta} = \frac{1}{\gamma - 1} V \frac{dP}{d\theta} + \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{\delta Q_{HT}}{d\theta}$$

where V is the cylinder volume, P is the cylinder pressure, and γ is the ratio of specific heats. The differential forms of some of the terms are written on a crank-angle basis, since pressure and volume data are recorded referenced to a signal from the crank-angle encoder. The heat transfer term was determined from a Nusselt-Reynolds number correlation analogous to that used for steady turbulent pipe flow. See Reference [39] for further information on the heat transfer model for its implementation in the heat-release analysis code.

7.6.1 In-Cylinder Pressure Signal and Data Processing

The in-cylinder pressure signal from the crank angle encoder was first processed using a 10 kHz hardware filter in the National Instruments SCXI data acquisition module. The 10 kHz filter setting was selected to filter some noise, while at the same time preventing the possibility of introducing phase-shift errors in the pressure signals due to poor low-pass filter response [28].

In addition to the hardware filtering, a simple software filter was created in MatLab to further process the data prior to carrying out the heat release and combustion analysis. This code essentially employs a Discrete Fourier Transform to convert between the time and frequency domains and computes and filters the signal at and above the Nyquist frequency to eliminate the problem of alias frequencies. Furthermore, all in-cylinder pressure data was averaged over 100 cycles to eliminate the effects of cycle-to-cycle variation.

The filtered output from the MatLab code was then input into the FORTRAN heat release program to calculate the various thermodynamic indicators of interest. The heat release program employs the simple First Law model presented in Section 7.6 to calculate a number of thermodynamic indicators to characterize the combustion process. In addition to the pressure data filtered using the MatLab program described above, a second data file containing specific fuel properties and engine operating parameters was also input into the heat release program.

7.7 Particulate Trap Loading

In order to ensure consistent and repeatable trap loading conditions, each set of traps was loaded at the same steady state engine operating condition. The engine was operated at 1682 rpm and 224 N-m, 25% load, for the duration of the study. This operating condition was chosen for two reasons. First, it produced a relatively large amount of particulates thus reducing trap loading times, and, second, this test condition overlapped with previous studies on the same engine allowing for simple verification of emissions measurements.

For each round of testing, the engine was brought to the specified speed-load point and allowed to settle in to steady-state operation following which data acquisition was initiated. An initial round of high-speed data was collected for each operating condition to verify that no significant differences in engine operation existed between each round of testing. Following the high-speed data acquisition, slow speed engine data was collected as well. Gaseous emissions were sampled before and after the trap every hour, and particulate emissions sampled every two hours. Furthermore, trap pressure and temperature data were recorded every hour as well. All particulate samples were collected simultaneously from the raw exhaust before and after the trap, and the sample filters were loaded for 10 minutes each. Gaseous emissions measurements were sampled from the raw exhaust for one minute each between particulate samples for a total of two sets of gaseous emissions measurements per particulate sample. Following the emissions measurements, another set of slow-speed engine data was recorded to accurately monitor any changes in fuel consumption due trap loading and increased backpressure. Each set of traps was loaded for 25 hours at the same steady state engine operating condition with each fuel, and the procedure above repeated every two hours. At the end of the 25 hour trap loading period with the LSD, the traps were removed from the engine, new traps were installed, and the process was repeated with the FT fuel. Only the LSD and FT fuels were tested with the particulate trap in order to realize the greatest benefit of using the FT fuel.

8.0 Experimental Results and Discussion: Task 1

The major objectives of Task 1 were as follows: to assess how gas-to-liquid fuels impact engine performance and emissions, directly and in blends; to evaluate tradeoffs among fuel properties and blending ratios; to evaluate engine modifications in further improving engine emissions; and to determine combustion and emission characteristics. This chapter presents the results of the combustion and emissions measurements, along with the detailed particulate analysis. The results provide considerable insight into the major factors influencing the observed emissions trends.

8.1 Emissions Characteristics

Due to the overall lean operation of diesel engines, in addition to the advanced subsystems and combustion strategy of the Cummins ISB, emissions of carbon monoxide are fairly low. The compression of only air during the compression stroke eliminates several major sources of unburned hydrocarbons, thus HC emissions from diesel engines are usually within acceptable levels. Therefore, the focus of the following discussion is primarily on the NO_x and PM emissions trends; however, some experimental data covering other emissions of interest are presented as well.

8.1.1 Particulate Emissions

The specific particulate emissions rates for the three initial test conditions under investigation are shown in Figure 8.1.

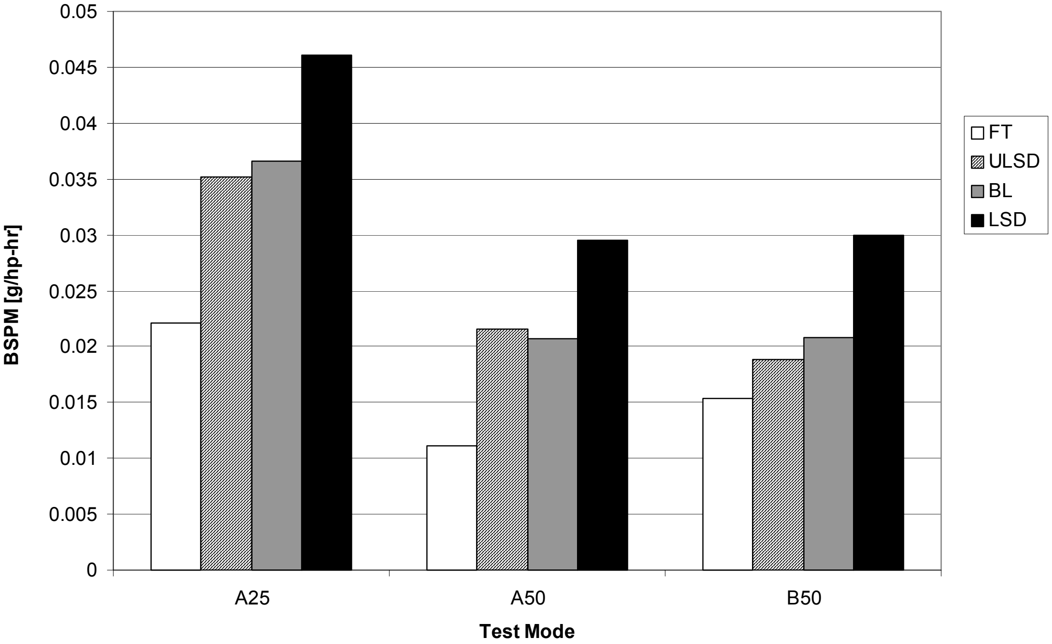


Figure 8.1. Specific particulate emissions

The amount of particulate matter that exits the engine is due to two competing processes: the extent of particulate formation and oxidation. Both the FT fuel and the blends reduced regulated emissions for each test condition. The fuel effects were most pronounced in regards to particulate emissions, where the FT fuel alone reduced particulate emissions by 54% on average as compared to the baseline fuel over all three test conditions. The blend performed nearly as well as the ultra-low sulfur diesel in reducing particulate emissions, with both fuels reducing particulates by an average of 28% compared to the baseline fuel. The fact that the blend produced approximately half the particulate reduction of using neat FT fuel alone suggests a more than proportional benefit of using the blend.

8.1.2 NOx Emissions

It is well understood that the principle factor driving NO_x formation is in-cylinder temperature during combustion. The extended Zeldovich mechanism is very sensitive to temperature, and NO_x control techniques typically attempt to lower peak cylinder temperatures. Based on this fact, it is not surprising that the fuel effect on NOx emissions is much less pronounced. The greatest reduction in NOx emissions was observed with the FT fuel, which reduced NOx by approximately 12% as compared to the low sulfur diesel. The blend and ultra-low sulfur diesel reduced NOx emissions only slightly, on the order of 2% and 4% respectively. The specific NOx emissions rates for the three initial test conditions are depicted in Figure 8.2.

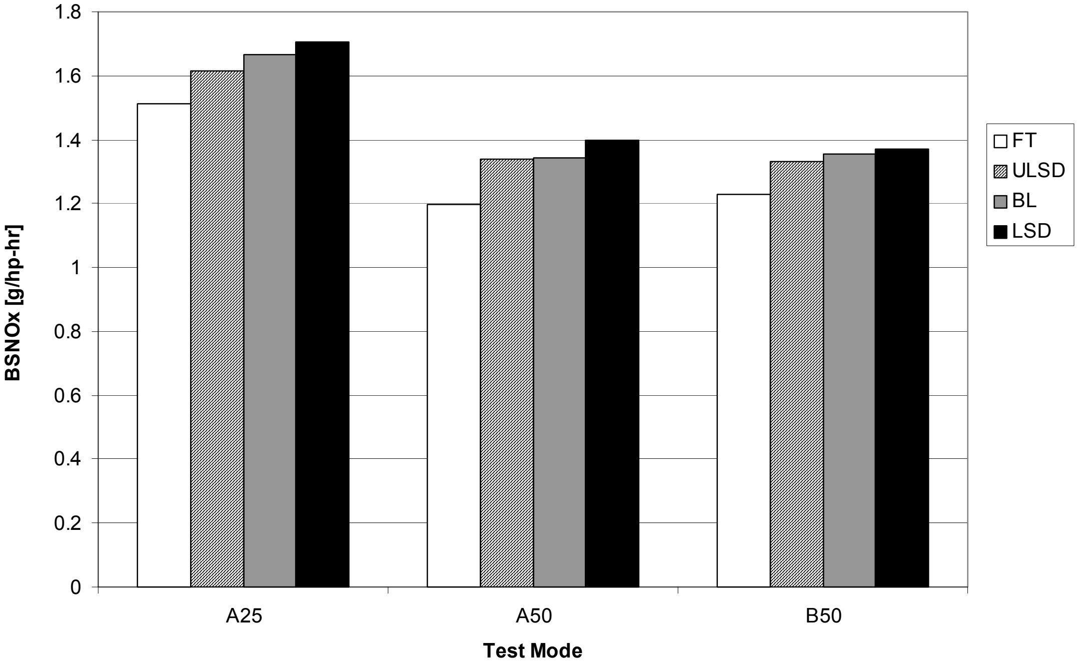
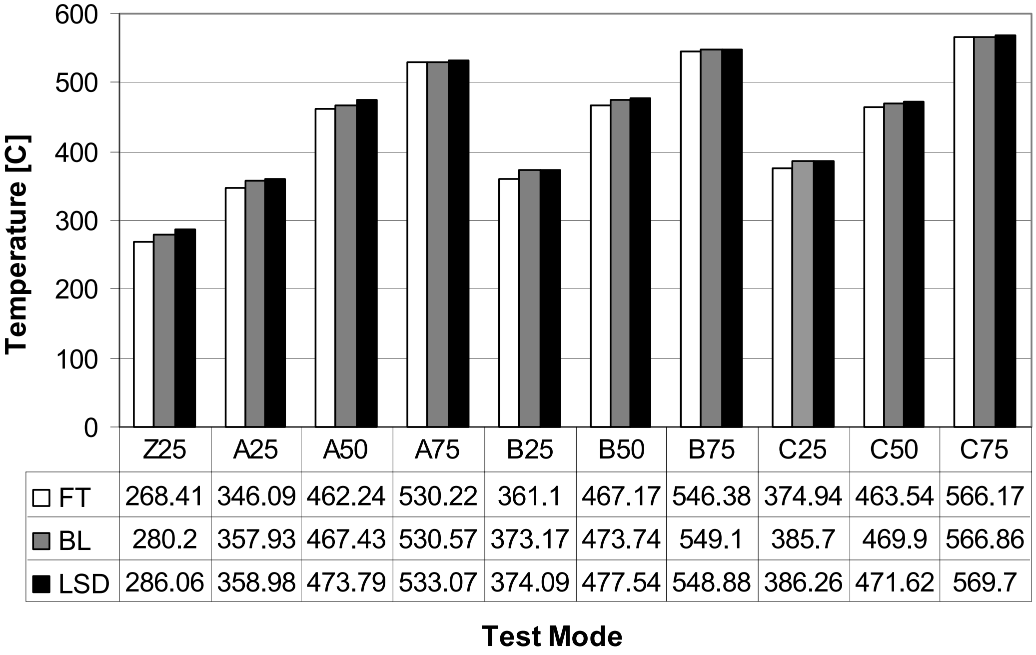


Figure 8.2. Specific NOx emissions

The average exhaust temperatures measured from thermocouples located just outside each exhaust port are plotted in Figure 8.3.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	268.41	346.09	462.24	530.22	361.1	467.17	546.38	374.94	463.54	566.17
▨ BL	280.2	357.93	467.43	530.57	373.17	473.74	549.1	385.7	469.9	566.86
■ LSD	286.06	358.98	473.79	533.07	374.09	477.54	548.88	386.26	471.62	569.7

Figure 8.3. Average measured exhaust temperature

The FT fuel exhibited a slightly lower exhaust temperature for each test condition, with values ranging from a maximum temperature reduction of 17.6°C to a minimum reduction of 2.5°C. The blend exhibited only a slight decrease in exhaust temperature relative to that of the baseline fuel.

The effect of the FT fuel and blend on reducing the measured exhaust and corresponding cylinder temperatures is most likely the primary factor contributing to the reduction in NOx emissions. This observation confirms the temperature sensitivity of the extended Zeldovich mechanism as primarily responsible for the majority of the NOx formation in the power cylinder.

8.1.3 Hydrocarbon Emissions

As can be seen from Figure 8.4, the effect of the fuels on hydrocarbon emissions was varied.

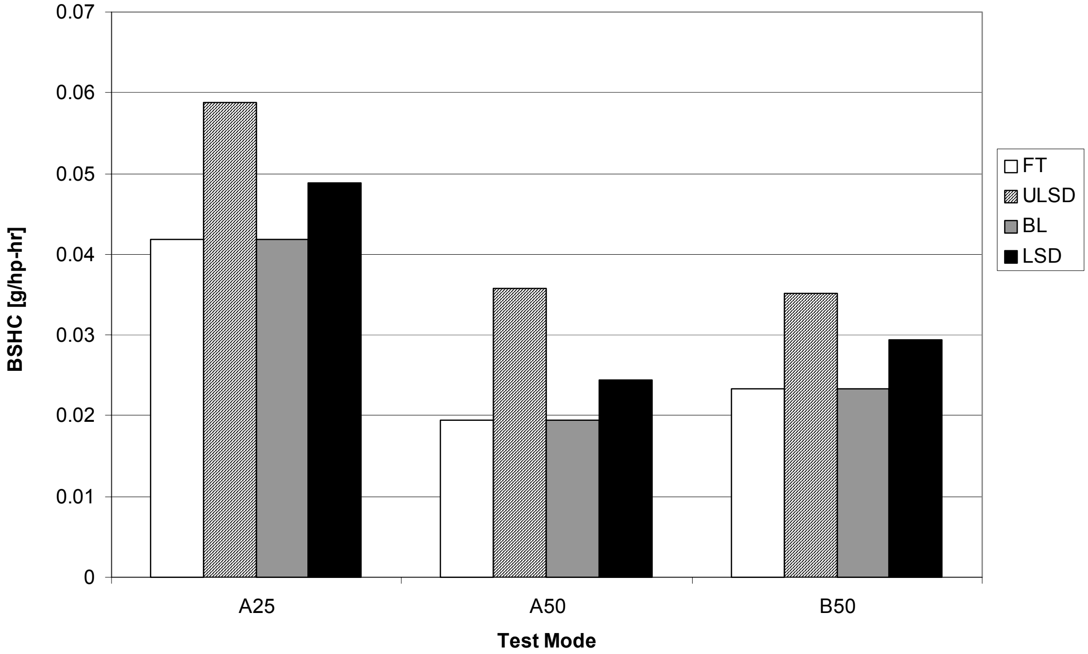


Figure 8.4. Specific hydrocarbon emissions

The FT and blend yielded approximately the same reduction in HC emissions, while the ULSD increased hydrocarbon emissions by nearly 15% on average when compared with the baseline low sulfur diesel. Hydrocarbon emissions are the product of a number of factors related to fuel properties, cylinder geometry, combustion characteristics, and a multitude of additional factors. It is, therefore, quite difficult to attribute the observed differences in HC emissions to any one specific factor. While a number of fuel property interactions may be responsible for the trend, the most likely cause is due to the higher volatility of the ULSD, as depicted by the distillation curves shown in Figure 6.2.

8.1.4 Detailed Emissions Summary

Following the initial round of testing, a more detailed emissions sweep was carried out over a much wider range of engine operating conditions. The engine operating conditions covered nearly all modes of the Euro-III 13-mode test cycle, with the exception of the 100% load points. In addition to the gaseous emissions measured in the previous round of testing (CO, CO_2, O_2, HC, NO, and NOx), measurements of the SO_2 concentration in the exhaust were carried out as well. However, unlike the previous round of testing, the complete emissions mapping was conducted only with the low sulfur diesel and Fischer-Tropsch diesel. The percent difference between the emissions levels for the FT and LSD are presented in Table 8.1.

	CO_2	H_2O	O_2	N_2	CO	HC	NO	NO_2	H_2	SO_2	NOx	PM
Test Condition	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
A25	-9.3	20.6	-9.5	-4.1	10.2	-31.9	-25.8	-25.0	46.5	-99.9	-25.8	-56.0
A50	-4.4	8.8	-1.9	0.0	22.5	-32.9	-20.4	-27.9	39.5	-100.1	-20.8	-40.6
A75	-3.0	9.3	-1.0	1.0	-37.0	-21.1	-22.3	56.4	-29.1	-98.1	-20.1	-24.3
B25	-3.2	9.6	-0.3	0.6	33.3	-45.7	-11.6	-6.0	51.0	-97.7	-10.9	-50.1
B50	-3.9	7.0	2.2	1.4	33.9	-47.9	-9.0	-4.3	49.2	-98.1	-8.6	-56.0
B75	-2.2	7.0	-0.6	0.8	-37.9	-31.6	-19.3	31.1	-32.1	-97.0	-16.8	-45.7
C25	-5.5	6.4	-0.7	-0.7	26.5	-49.2	-15.5	2.2	42.4	-95.1	-12.9	-53.8
C50	-5.5	4.4	2.1	0.3	51.7	-53.2	-10.4	40.3	67.4	-96.4	-6.6	-58.9
Z25	-13.0	1.9	-1.6	-3.4	6.8	-48.8	-8.8	5.6	25.1	-93.1	-8.0	0.0
Average	**-5.56**	**8.33**	**-1.27**	**-0.46**	**12.21**	**-40.27**	**-15.90**	**8.05**	**28.88**	**-97.28**	**-14.51**	**-48.16**

Table 8.1. Difference in measured and calculated exhaust constituents for the Fischer-Tropsch and low sulfur diesel fuel

Negative values in the table indicate a decrease in emissions with the FT fuel, whereas positive values indicate an increase. The NO_2 emissions values used in the calculations presented in the table were determined from the difference in the measured NOx and NO emissions values. Furthermore, the water content in the exhaust was estimated using the procedure outlined in Section 7.5.1, and concentrations of all other gaseous species that were not measured in the exhaust directly (N_2 and H_2) were calculated from the actual combustion equation for the appropriate fuel.

Consistent with the emissions trends observed during the initial round of testing, the data shows an average reduction in PM emissions with the FT fuel of nearly 50% as compared to the baseline low-sulfur diesel. Emissions of sulfur dioxide for the FT fuel were on average 97% lower than with the LSD. The large reduction in SO_2 emissions is due to the fact that FT diesel contains zero sulfur, whereas the LSD contains 400 PPM sulfur. The low levels of SO_2 emissions that were measured for the FT fuel are attributed to the sulfur contained in the lubricant oil. NOx and HC emission agree well with those reported for the initial round of testing, with reductions in NOx and HC by 15% and 40% on average. Furthermore, emissions of CO_2 decreased with the FT fuel by approximately 5% on average. Although an average increase in CO levels of 12% was observed with the FT, the CO levels measured with both fuels were extremely low, near the lower detection limit of the analyzer, and the increase in CO levels with the FT warrants further investigation.

8.2 Particulate Analysis

In order to determine more precisely the effect of various fuels on particulate composition, all particulate samples were sent to the emission/chemistry laboratory of a major engine manufacturer for detailed analysis. Prior to analysis, all samples were conditioned and reweighed in a strictly controlled environment at the engine manufacturer's emission/chemistry laboratory to confirm the particulate mass values determined at MIT. Following the conditioning and weighing, the samples were analyzed to determine the contribution of sulfates (SO_4), nitrates (NO_3), and soluble organic fraction (SOF) to the total particulate mass (TPM). As nitrates are not of primary interest, and since the nitrate levels were extremely low, their contribution to the TPM is neglected in the following sections. Once total SOF and SO_4 were known, and neglecting the contribution of the nitrates, the SOL (non-soluble fraction or soot) was calculated from the total particulate mass as follows:

Equation 8.1 $$TPM = SOL + SOF + SO_4$$

The SOL is important as it consists of the basic solid carbonaceous particles formed during combustion [36]. The following sections present the results of the detailed PM analysis.

8.2.1 PM Constituent Distribution

An overview of the results of the particulate analysis for each of the three test conditions is presented in Figures 8.5 through 8.7.

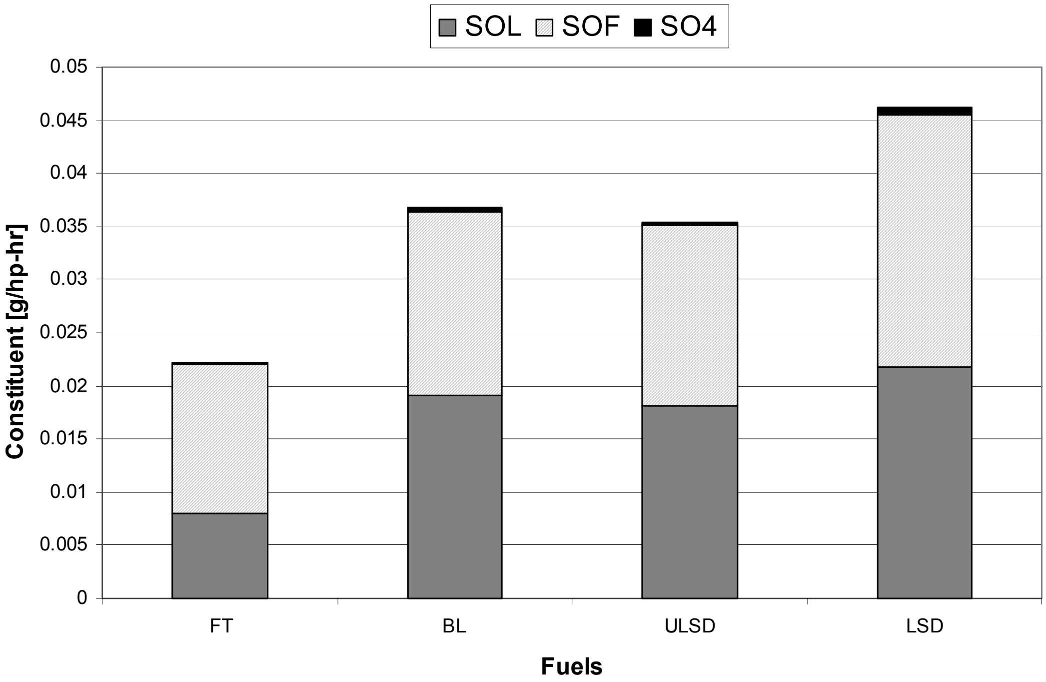


Figure 8.5. Distribution of particulate constituents collected at an engine operating condition of 1682 rpm, 474 kPa BMEP

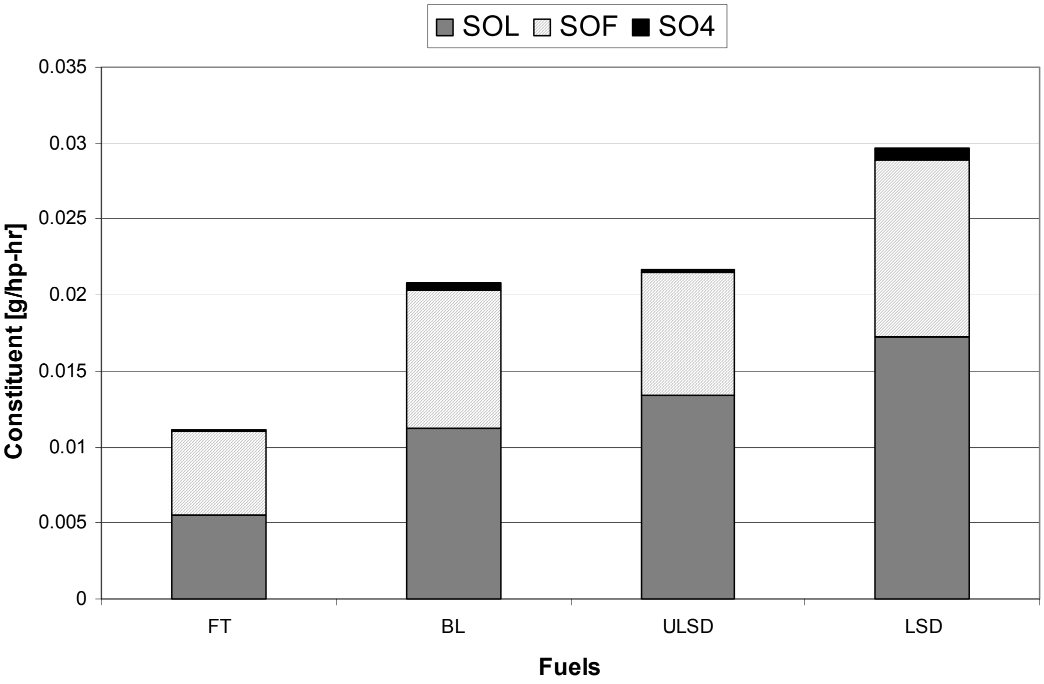


Figure 8.6. Distribution of particulate constituents collected at an engine operating condition of 1682 rpm, 1000 kPa BMEP

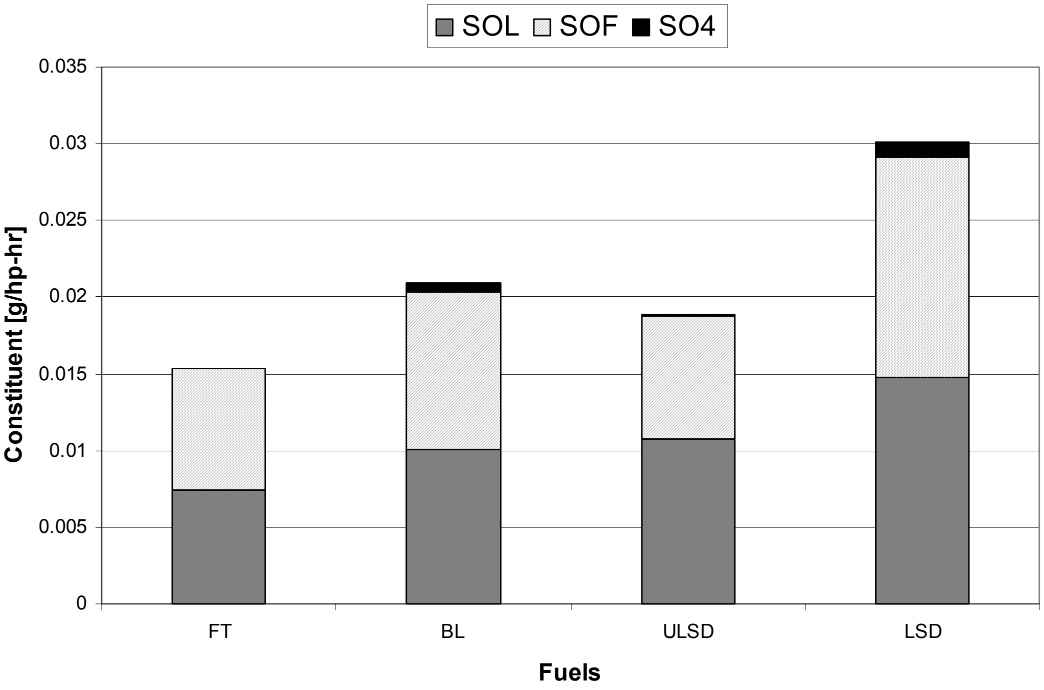


Figure 8.7. Distribution of particulate constituents collected at an engine operating condition of 2011 rpm, 947 kPa BMEP

Of particular interest is the apparently small contribution of sulfate to the total particulate mass, which ranged from a minimum of 0.64% to a maximum of 3.05% of the TPM. A simple calculation of the fuel sulfur to sulfate conversion rate, based on the known fuel sulfur content and fuel consumption rate, yielded a range from a low of 0.22% for the FT/LSD blend to a high of 1.94% for the ULSD. Furthermore, the sulfur to sulfate conversion rates of the blend and low sulfur diesel comprised the low end of the range (0.22% to 0.43%) while the ultra-low sulfur diesel made up the high end (0.52% to 1.94%). These values are suspect as previous studies have shown that the amount of fuel sulfur converted to PM is at least 1-2% of the fuel sulfur content irrespective of the total fuel sulfur level or engine type [18]. Despite this discrepancy, the relative trends observed in the data still hold considerable merit.

The fuel sulfur to sulfate conversion rates were observed to vary directly with load, however the trends differed for each of the fuels tested. The fuel sulfur to sulfate conversion rates for both the blend and low sulfur diesel tended to increase with increasing load, while the conversion rates for the ultra-low sulfur diesel exhibited the opposite behavior.

In general, the contribution of the SOF to the total particulate mass decreased with increasing load, while SOL and SO_4 increased. This trend is consistent with other published reports in the literature [40].

8.2.2 Non-Soluble Fraction and Soot

The SOL contribution to the total particulate mass ranged from 43.7% for the FT fuel to 54.4% for the ULSD. On average, over all of the test conditions, the FT fuel reduced SOL by 60.6%, the ULSD reduced SOL by 22.1%, and the blend reduced SOL by 26.16% as compared to the baseline low-sulfur diesel. A comparison of the solid fraction for each of the fuels over all of the test conditions is shown in Figure 8.8.

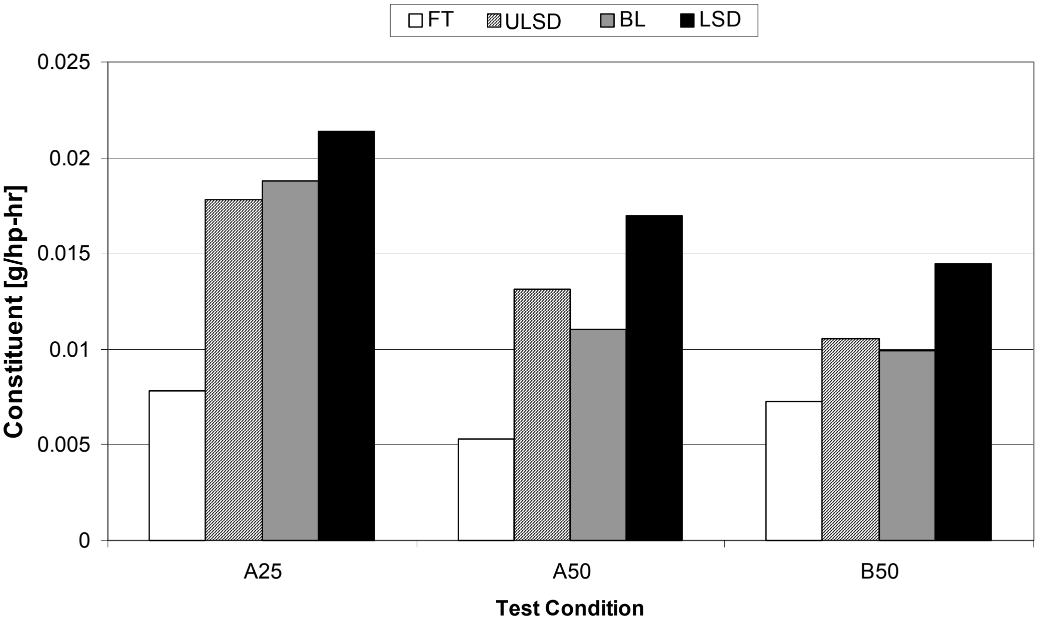


Figure 8.8. Comparison of solid non-soluble fraction

Estimates based on the simplified chemical composition of the fuels, molecular weight, and carbon content provided by the manufacturers gives a lower carbon content of 9.8% by weight for the FT fuel as compared to the LSD. As demonstrated in the figure above, the blend yielded a more than proportional reduction in SOL by approximately 43.0% as compared to the reduction obtained with the FT fuel alone.

8.2.3 Soluble Organic Fraction

The soluble organic fraction was determined via supercritical fluid extraction using CO_2 as the working fluid. This method is believed to produce more consistent results than those achieved by performing the soxhlet extraction using dichloromethane. The trends observed in the SOF are very similar to those presented in the previous section for the SOL. The SOF contribution to the total particulate mass ranged from 41.8% for the ULSD to 55.7% for the FT fuel. While the FT fuel yielded proportionally the greatest contribution of SOF to the TPM, it still produced an average reduction in SOF of 46.0% as compared to the baseline LSD. The blend and ULSD both yielded average reductions in SOF of 26.2% and 34.2% respectively, over the baseline fuel.

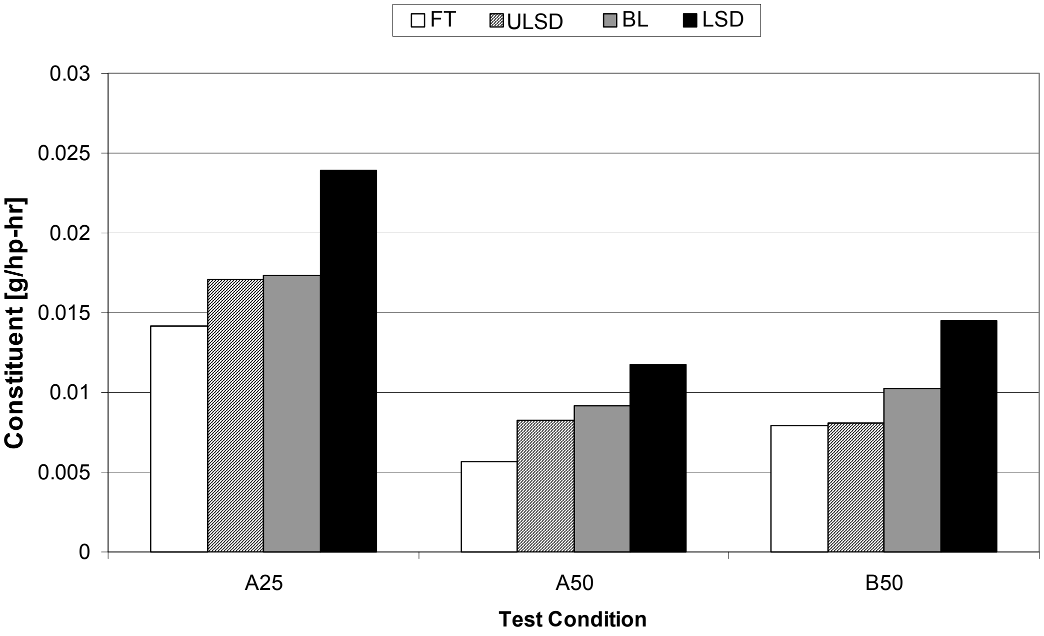


Figure 8.9. Comparison of soluble organic fraction

As shown in Figure 8.9, the blend yielded a more than proportional reduction in SOF, by approximately 56.9%, when compared with the reduction obtained using the FT fuel alone.

8.2.4 Sulfates

The sulfate contribution to the TPM was determined via ion chromatography. As discussed in Section 8.2.1, the low absolute magnitudes of the SO_4 values (between 0.22% and 3.05% of the TPM) are suspect, as they do not correlate well to the accepted fuel sulfur to sulfate conversion rates presented in the literature. Nonetheless, the relative trends are still quite valid. As was expected, the FT fuel and ULSD contributed least to the SO_4, as these fuels contained little to no sulfur. The blend and LSD, on the other hand, contained considerably more sulfur, 305.9 PPM and 400 PPM sulfur by weight respectively. Figure 8.10 presents the particulate sulfate levels generated by each of the fuels.

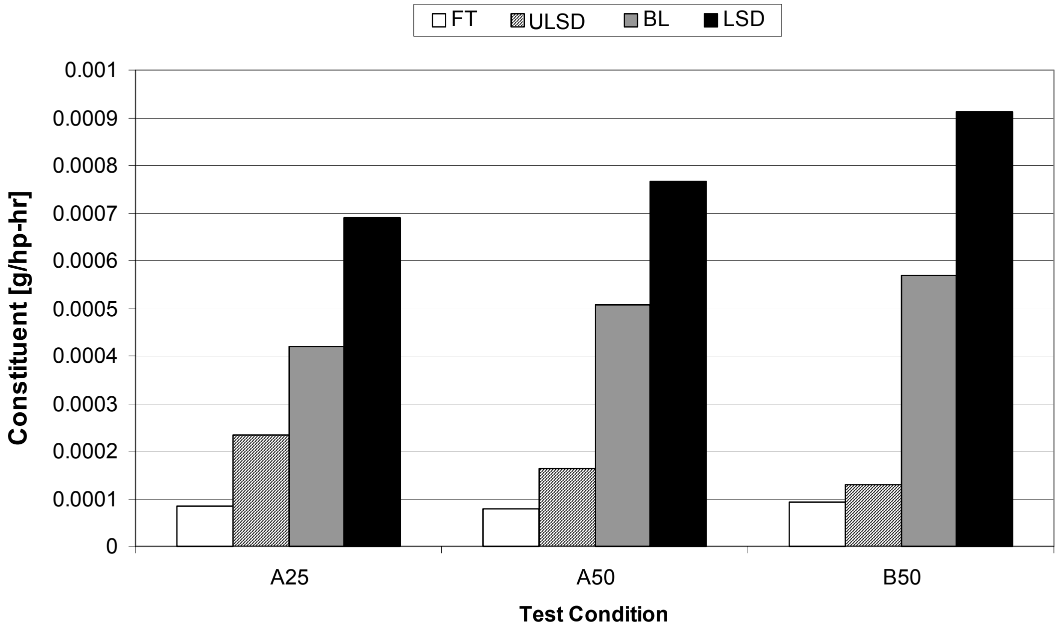


Figure 8.10. Comparison of sulfate contribution to TPM

On average, the FT fuel reduced SO_4 by 89.1%, the ULSD reduced SO_4 by 76.9%, and the blend reduced SO_4 by 37.0% as compared to the baseline low-sulfur diesel. As demonstrated in Figure 8.10, the blend yielded a more than proportional reduction in SO_4 by approximately 41.5% as compared to the reduction obtained with the FT fuel alone. Despite these significant reductions in SO_4, the impact to the overall particulate mass was nearly negligible due to the small contribution of the SO_4 to the TPM.

The contribution of sulfur in the engine lube oil to the total particulate sulfate is depicted in Figures 8.11 through 8.13 for each of the three test conditions.

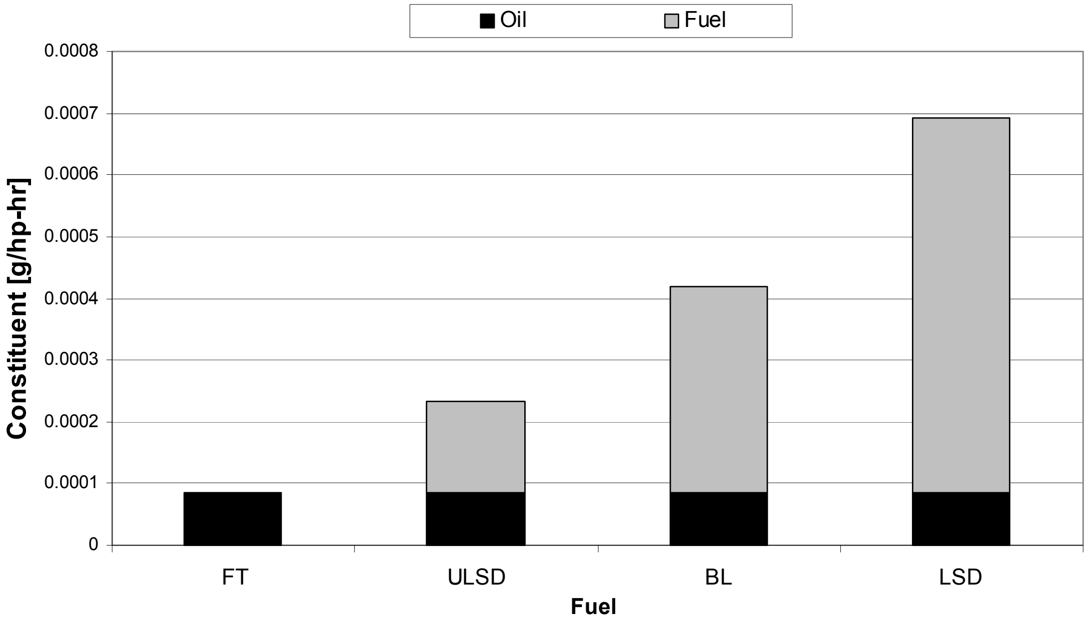


Figure 8.11. Comparison of lubricant oil and fuel contribution to particulate sulfate at a test condition of 1682 rpm, 474 kPa BMEP

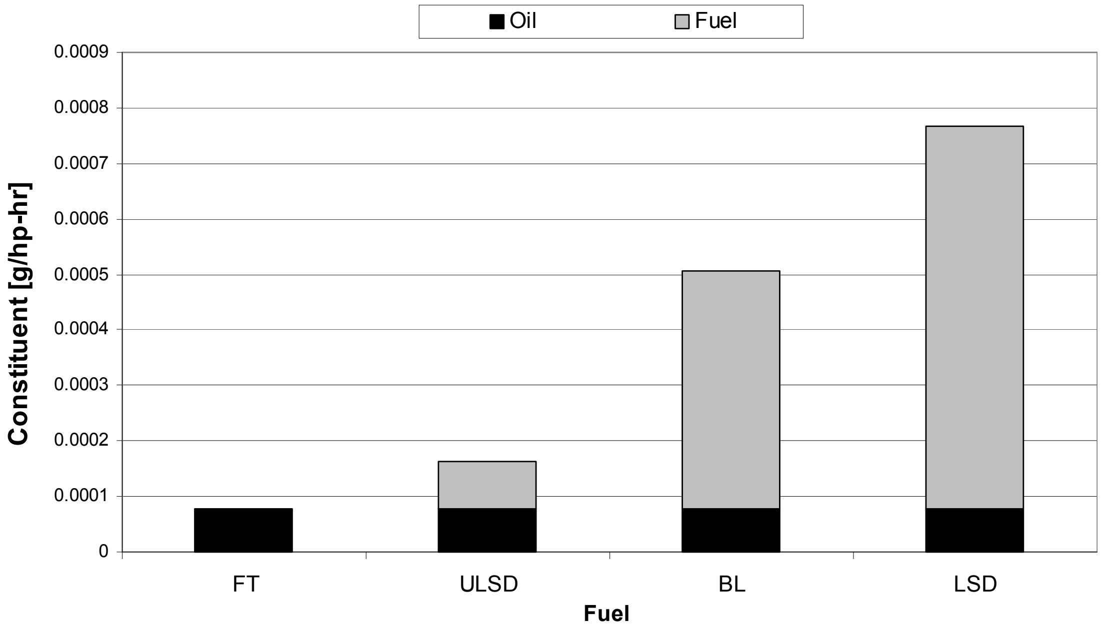


Figure 8.12. Comparison of lubricant oil and fuel contribution to particulate sulfate at a test condition of 1682 rpm, 1000 kPa BMEP

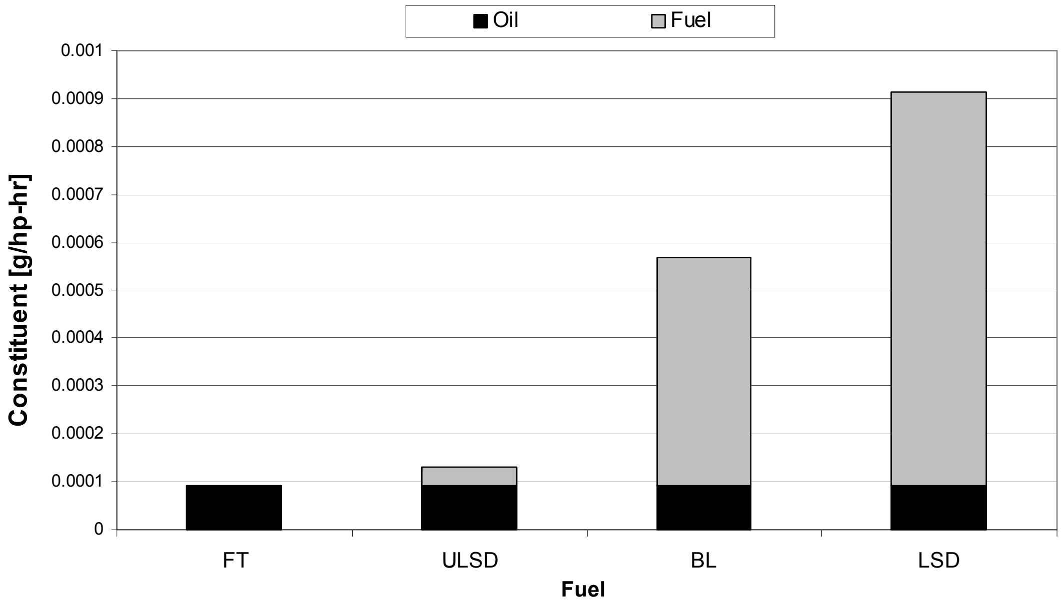


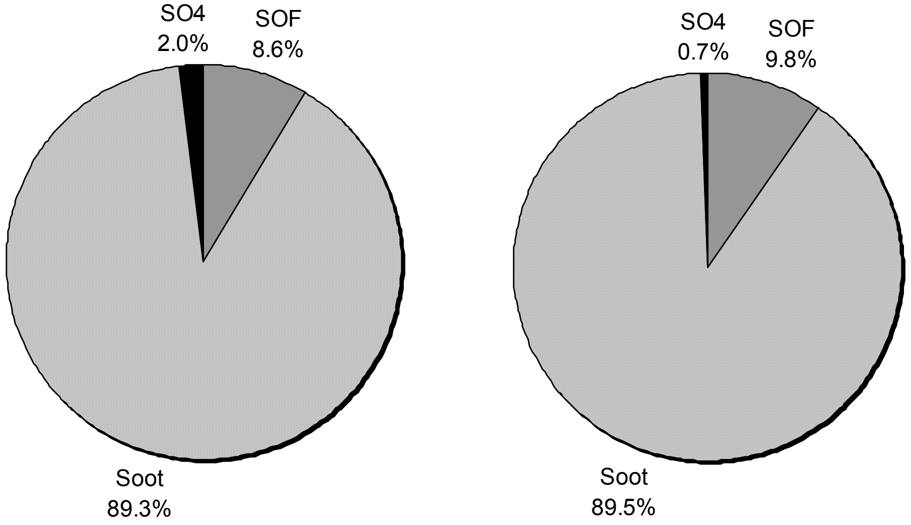
Figure 8.13. Comparison of lubricant oil and fuel contribution to particulate sulfate at a test condition of 2011 rpm, 947 kPa BMEP

The zero sulfur nature of the FT fuel allowed for the simple and straightforward determination of the lube oil contribution, as any SO_4 in the PM must be attributed to the lube oil. Although the absolute magnitude of the lube oil-derived SO_4 increased with increased engine speed and load, a result of the associated increase in lube oil consumption, the relative lube oil contribution to the total SO_4 declined as the increase in oil consumption was negated by the significantly larger increase in fuel consumption. On average the lube oil contributed between 13.9% and 24.9% of the SO_4 determined from the LSD PM emissions, between

63.3% and 74.3% of the SO_4 determined from the ULSD PM emissions, and between 17.9% and 35.7% of the SO_4 determined from the PM emissions observed from the blend.

8.2.5 Comparison to Raw Particulate Measurements

In order to verify the results of the first PM analysis, as well as to determine the effect of dilution ratio on PM composition, a second batch of particulate samples was sent to the same engine manufacturer's emission/chemistry laboratory for analysis. The average particulate composition is shown in Figure 8.14.



(a) **(b)**

Figure 8.14. Particulate composition for (a) low sulfur diesel, and (b) Fischer-Tropsch fuel. All particulate samples were collected from the raw undiluted exhaust at an engine operating condition of 1682 rpm, 474 kPa BMEP.

All of the samples in the second batch were collected from the raw exhaust without the use of the dilution tunnel. Furthermore, all of the paper filters used in the second batch were stored in glass Petri dishes, rather than the plastic dishes typically used to store the filters, as it was believed that some chemicals in the plastic could leach into the filter paper, potentially affecting the results of the analysis.

The results of the second analysis confirm the initial results with respect to the sulfate contribution to the total particulate mass. In the case of the FT particulates, the SO_4 content was reduced by nearly a factor of three when compared to the LSD particulates. However, as a result of the raw sampling, the soluble organic fraction is quite small in both cases, as the hot raw exhaust conditions are not conducive to the condensation of various gaseous species onto the PM. While the FT particulates do exhibit a slightly higher soluble organic fraction and a significantly lower overall sulfate content than the LSD particulates, due to the differences in fuel composition, the differences in the hot undiluted exhaust stream are minimal. In both cases the particulate composition is very similar, consisting primarily of non-soluble carbonaceous soot. Typically raw particulate samples contain a significantly higher portion of SOL than equivalent dilute PM samples due to the elevated temperatures at which the samples are collected [40].

8.2.6 Detailed Exhaust Sulfur Accounting

Based on the measured gaseous SO_2 emissions and the sulfate contribution to the total particulate mass, the total sulfur content of the exhaust (particulate and gaseous) was calculated and compared to the expected exhaust sulfur levels. The expected exhaust sulfur levels were computed using the known fuel and oil sulfur levels and fuel and oil consumption rates. While the fuel consumption rates were measured directly for each test condition, no direct measurements of oil consumption were made. The contribution of the sulfur in the lubricating oil to the total exhaust sulfur levels was estimated in two different ways. One means of estimating the lube oil sulfur contribution was to use the gaseous and particulate sulfur levels measured using the FT fuel. Since the FT diesel contains no sulfur, it was assumed that any SO_2 in the exhaust and any sulfates on the FT particulates were due to the lube oil sulfur. Table 8.2 lists the contribution of the gaseous and particulate sulfur levels to the total measured sulfur emissions with the FT fuel.

FT	Speed	BMEP	Sulfur: Gaseous SO_2	Sulfur: PM Sulfates	Total Sulfur (Oil Contribution)
	[rpm]	[kPa]	[g/hr]	[g/hr]	[g/hr]
A25	1681	477	0.00	0.03	0.03
A50	1684	955	0.00	0.03	0.03
A75	1684	1388	0.11	0.05	0.16
B25	2012	483	0.06	0.02	0.09
B50	2016	951	0.10	0.03	0.12
B75	2013	1407	0.21	0.05	0.26
C25	2344	456	0.16	0.03	0.19
C50	2351	901	0.21	0.02	0.24

Table 8.2. Breakdown of total sulfur emissions for the FT fuel

The second means of estimating the contribution of the lube oil sulfur to the total exhaust sulfur levels, was by using the oil consumption rates for the Cummins ISB determined in a thesis by Plumley (S.M. 2005). In this thesis, Plumley gives the measured oil sulfur concentration as 4,200 PPM_w and oil consumption rates for the A50 and B75 test conditions as 5.8 g/hr and 7.5 g/hr respectively for the Cummins ISB 300 [29].

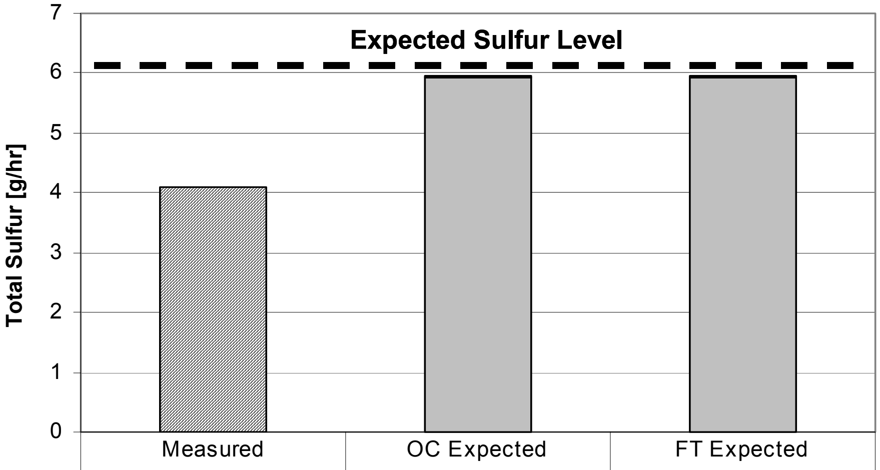
LSD	Speed	BMEP	Sulfur: Gaseous SO2	Sulfur: PM Sulfates	Total Measured Sulfur (Fuel +Lube)	Total Expected Sulfur (Fuel +Lube)	Percent Sulfur Accounted For
	[rpm]	[kPa]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	
A25	1679	483	2.23	0.17	2.40	3.68	65.1%
A50	1681	951	3.97	0.13	4.10	5.95	69.0%
A75	1686	1415	5.79	0.19	5.98	8.73	68.5%
B25	2012	476	2.84	0.13	2.97	4.63	64.1%
B50	2017	945	4.93	0.17	5.09	7.55	67.5%
B75	2013	1416	7.08	0.24	7.32	10.37	70.6%
C25	2342	457	3.25	0.16	3.41	5.57	61.2%
C50	2345	919	5.98	0.16	6.14	8.99	68.3%

Table 8.3. Breakdown of total sulfur emissions for the LSD

Once the expected lube oil sulfur emission rates were known, the total expected exhaust sulfur levels were calculated as the sum of the fuel and lube oil sulfur contributions. The breakdown of the total sulfur emissions for the LSD is given in Table 8.3. The contribution of the lube oil sulfur to the expected sulfur levels in the Table 8.3 was estimated from the FT sulfur data presented in Table 8.2. As can be seen from the table, only 65% to 70% of the expected exhaust sulfur could be accounted for based on the gaseous SO_2 and PM sulfate concentration measurements alone.

In order to verify the difference in the measured and expected exhaust sulfur levels, the estimated lube sulfur contribution based on the measured FT sulfur levels were compared with those calculated using the lube oil consumption rates given by Plumley. In both cases, the lube oil sulfur contribution to the total exhaust sulfur levels was extremely small due to the low lube oil sulfur content and small rate of engine oil consumption.

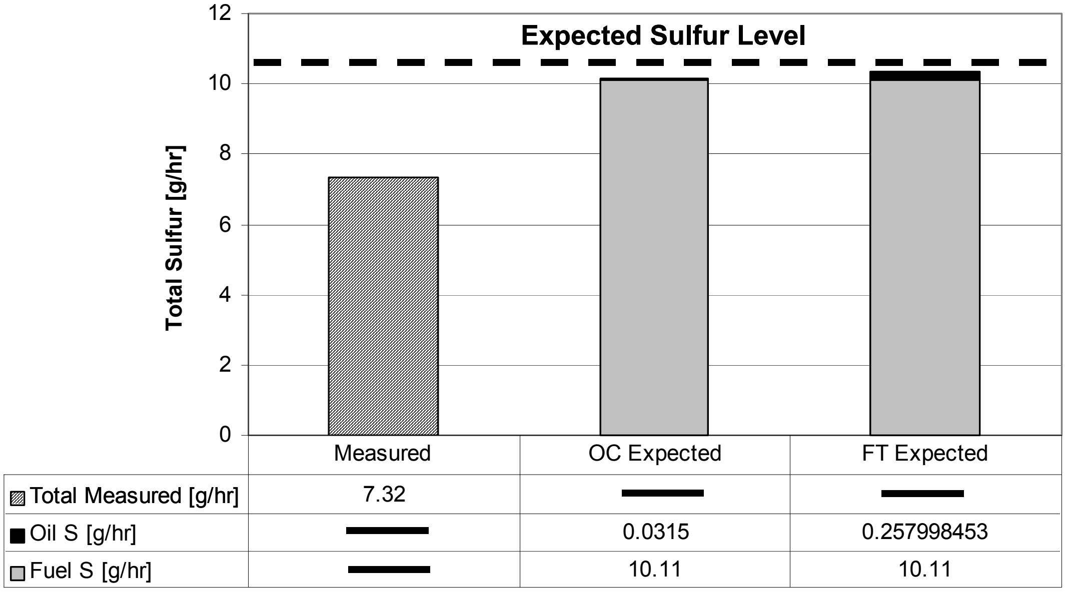
A comparison of the measured and expected exhaust sulfur levels for the A50 test condition is given in Figure 8.15. In this case, the sulfur contribution of the lube oil estimates based on the measured FT data and oil consumption data given by Plumley agree very well.



	Measured	OC Expected	FT Expected
▨ Total Measured [g/hr]	4.10	—	—
■ Oil S [g/hr]	—	0.02436	0.026929837
□ Fuel S [g/hr]	—	5.92	5.92

Figure 8.15. Measured and expected sulfur emissions with the 400 PPM low sulfur diesel at 1682 rpm and 951 kPa BMEP. FT corrected and OC corrected indicate lube oil sulfur contribution estimates based on the measured FT data and oil consumption rates given by Plumley respectively.

On the other hand, the sulfur contribution of the lube oil estimates based on the measured FT data and oil consumption data given by Plumley for the B75 test condition differ substantially as shown in Figure 8.16. However, once again, the contribution of the lube oil-derived sulfur is small in comparison to the fuel sulfur contribution.



	Measured	OC Expected	FT Expected
▨ Total Measured [g/hr]	7.32	—	—
■ Oil S [g/hr]	—	0.0315	0.257998453
□ Fuel S [g/hr]	—	10.11	10.11

Figure 8.16. Measured and expected sulfur emissions with the 400 PPM low sulfur diesel at 2013 rpm and 1416 kPa BMEP. FT corrected and OC corrected indicate lube oil sulfur contribution estimates based on the measured FT data and oil consumption rates given by Plumley respectively.

Despite differences in the estimation of the lube oil-derived sulfur, the measured exhaust sulfur levels are still 30% to 35% lower than the expected levels. This discrepancy is most likely due to a combination of one of the following causes:

- failure by the Antek SO_2 analyzer to convert and measure all of the gaseous sulfur (SO_2) in the exhaust,
- failure to measure all of the sulfur on the PM via ion chromatography,
- or deposition of the sulfur within the engine/exhaust system.

The first two reasons are the most likely causes, especially since the sulfur content measured on the PM was much smaller than expected. However, if the low PM sulfate content was the only source of the discrepancy, a total PM sulfate content of approximately 25% would be required to make up the difference between the measured and expected exhaust sulfur levels. Since this level of sulfate on the PM is on the high side for a 400 PPM fuel, low SO_2 readings by the Antek in conjunction with low sulfate measurements are the most likely causes. Nonetheless, deposition of sulfur within the engine/exhaust system is still a plausible factor contributing to the low exhaust sulfur measurements and will be the subject of further investigation.

8.3 Discussion of Fuel Effects

The lower density and near zero sulfur and aromatic content of the FT fuel contribute to the reduction in particulate emissions to a certain extent. Furthermore, Lee et al. showed that lower density diesel fuels increase the spray dispersion angle and achieve greater spray penetration in the cylinder, promoting better mixing of the charge and more complete combustion [16]. In addition, the lower C/H ratio of the FT fuel, due to its reduced aromatic content, reduces the amount of carbon in the cylinder and, thus, the amount of solid carbon in the particulates. This fact is further supported by the observed reduction in CO_2 emissions, along with a decrease in the solid fraction (SOL) of the particulates for the FT fuel.

While the reduction in fuel sulfur from 400 PPM in the low-sulfur diesel to 0 PPM in the FT diesel does have some effect in terms of overall PM reduction, the effect is believed to be small. Previous results, most notably reported by Lee at al. and Kwon et al., demonstrate that a reduction in fuel sulfur content below 0.05% yields little incremental benefit in terms of PM emissions reduction [16, 20]. The small overall sulfate content of the particulates, less than 4 % in most cases, further supports this observation. Therefore, a significant non-sulfur effect must be accounted for to explain the observed PM emissions trends.

Interestingly, the blend exhibited the same reduction in HC emissions as the neat FT fuel (Figure 8.4). A number of investigators have attempted to relate total hydrocarbon emissions to fuel properties and combustion characteristics with varying degrees of success. It is widely accepted that cetane number and density are the two fuel properties with perhaps the greatest influence on total hydrocarbon emissions [22]. However, a number of other factors such as mixing, flame quenching, fuel atomization, and combustion rate all play an important role in determining total hydrocarbon emissions as well. The fact that the ultra-low sulfur diesel has the greatest proportion of light hydrocarbons of all the fuels tested, may partially explain its higher HC emissions. Furthermore, the reduction in T90 and T95 from the LSD to the ULSD by 68°C and 72°C respectively, may also contribute to the large observed increase in HC emissions. A more detailed analysis taking into consideration all of the factors involved is warranted to determine the exact causes of the observed trends in HC emissions.

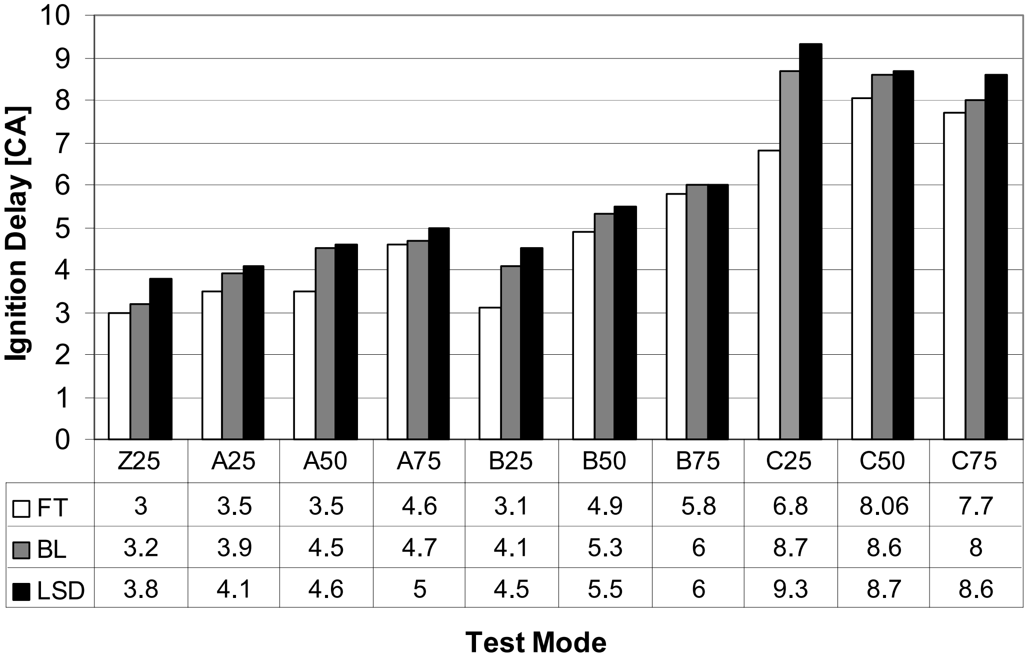
The detailed particulate analysis carried out by the emission/chemistry laboratory of a major engine manufacturer confirmed the initial observations of the more than proportional benefit of using the FT diesel blend in terms of overall PM reduction. However, since a more than proportional reduction in all of the PM constituents (SOL, SOF, and SO_4) was observed, little insight is gained into this trend based on fuel properties alone. Of interest is the extremely small, almost negligible, contribution of fuel sulfur to the TPM, and while the absolute magnitudes of the numbers are suspect, the observed trend does support the findings presented in [2]. Furthermore, lube oil-derived sulfur was seen to contribute significantly to the PM emissions of fuels containing less than 15 PPM sulfur, with the lube oil-derived sulfur contributing to between 63% to 74% of the SO_4 emissions observed from the ULSD and 100% of the SO_4 emissions for the FT fuel.

8.4 Combustion Characteristics

For the sake of clarity, the combustion data for the ultra-low sulfur fuel was not included in the figures comparing the combustion characteristics. It should be noted, however, that the ULSD exhibited very similar combustion characteristics to the standard low sulfur baseline fuel. Thus, the following discussion is focused on comparing the combustion characteristics of the neat FT fuel, low sulfur diesel, and blend of FT/LSD.

8.4.1 Ignition Delay

Figure 8.17 compares the ignition delay of the three fuels. The FT fuel yielded a shorter ignition delay over the range of operating conditions, with the blend exhibiting an ignition delay between that of the FT and LSD.



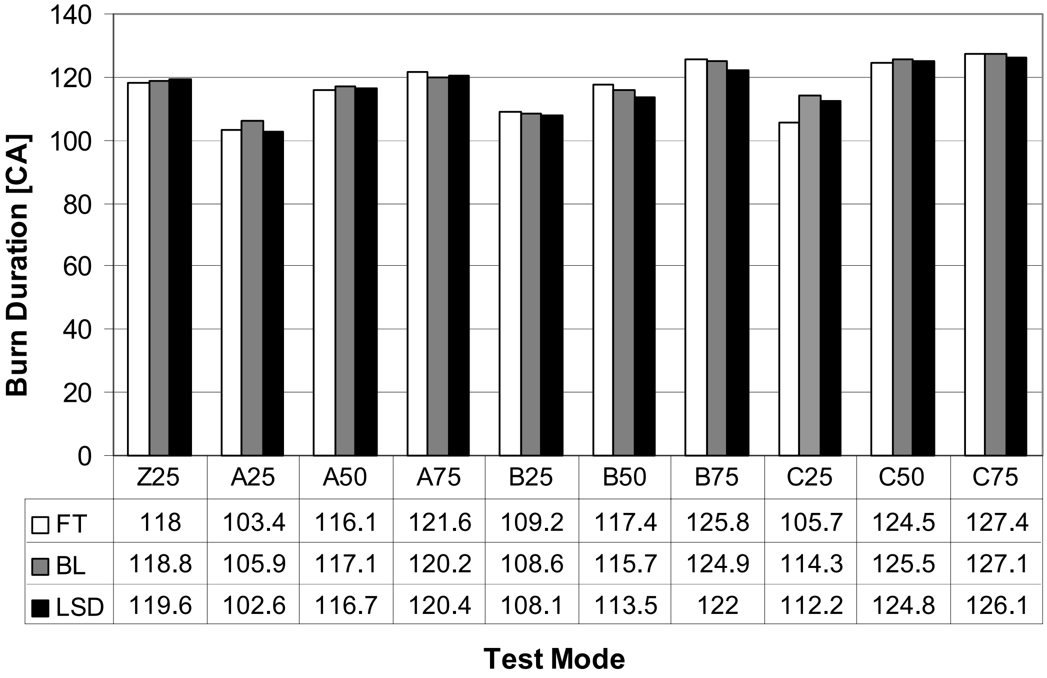
	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	3	3.5	3.5	4.6	3.1	4.9	5.8	6.8	8.06	7.7
▨ BL	3.2	3.9	4.5	4.7	4.1	5.3	6	8.7	8.6	8
■ LSD	3.8	4.1	4.6	5	4.5	5.5	6	9.3	8.7	8.6

Figure 8.17. Ignition delay

The decreased ignition delay for the FT and blend results in less fuel injected during the premixed combustion phase, yielding a more uniform and less rapid temperature rise within the cylinder. This is evidenced by the significantly lower heat release rate in the pilot injection (see Figure 8.21), however the heat release profile of the main injection seemed little affected by the reduced ignition delay.

8.4.2 Burn Duration

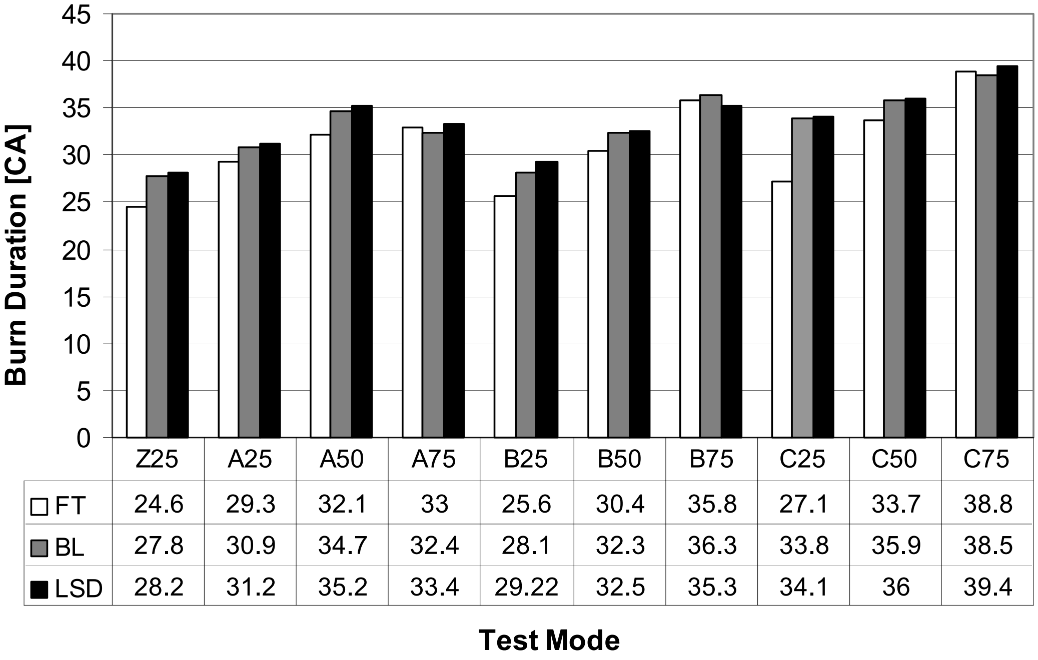
Figure 8.18 depicts the total time from the start of injection (SOI) to the end of combustion (EOC), which is nearly the same for both fuels. Despite the reduced ignition delay of the FT fuel and blend, the fact that the time from SOI to EOC varied little with the three fuels is attributed to the lower density of the FT fuel which results in more fuel injected per cycle (longer injection duration), as well as the slightly longer tale-end burn observed in the FT fuel and blend.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	118	103.4	116.1	121.6	109.2	117.4	125.8	105.7	124.5	127.4
▨ BL	118.8	105.9	117.1	120.2	108.6	115.7	124.9	114.3	125.5	127.1
■ LSD	119.6	102.6	116.7	120.4	108.1	113.5	122	112.2	124.8	126.1

Figure 8.18. Start of injection to 99% burn duration

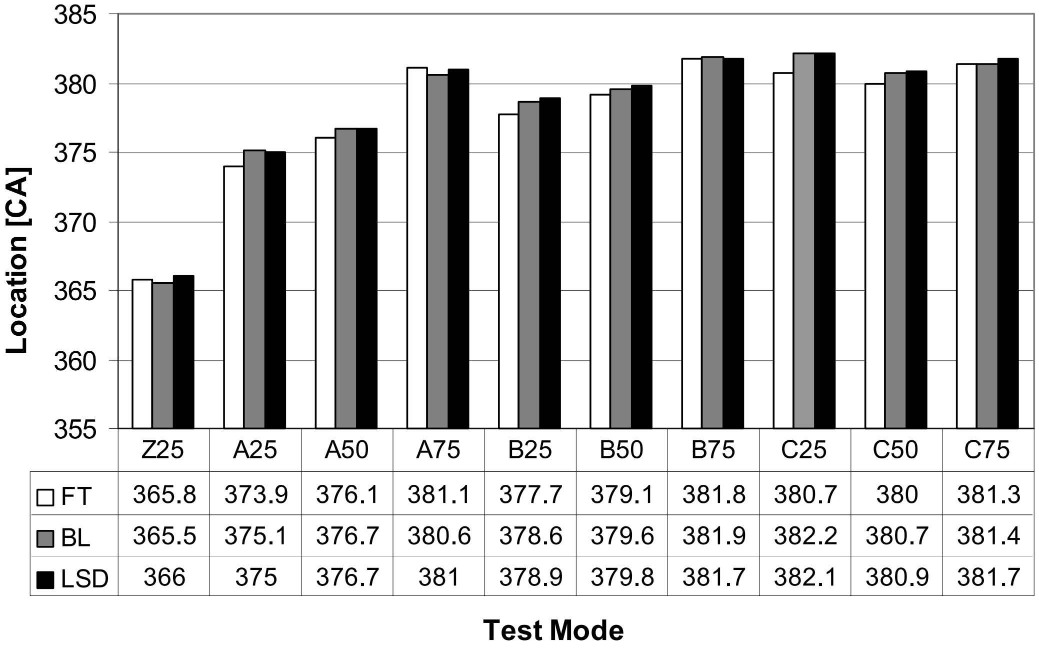
The FT fuel and the blend also exhibited reduced 50% to 90% burn durations, indicating a faster burn rate for the FT fuel during the latter part of the combustion process as shown in Figure 8.19. On average, the FT fuel reduced the diffusion burn duration by approximately 7.4%, with values ranging from a maximum reduction of 20.2% to a slight increase of 1.4% as compared to the low sulfur diesel.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	24.6	29.3	32.1	33	25.6	30.4	35.8	27.1	33.7	38.8
▨ BL	27.8	30.9	34.7	32.4	28.1	32.3	36.3	33.8	35.9	38.5
■ LSD	28.2	31.2	35.2	33.4	29.22	32.5	35.3	34.1	36	39.4

Figure 8.19. 50% to 90% burn duration

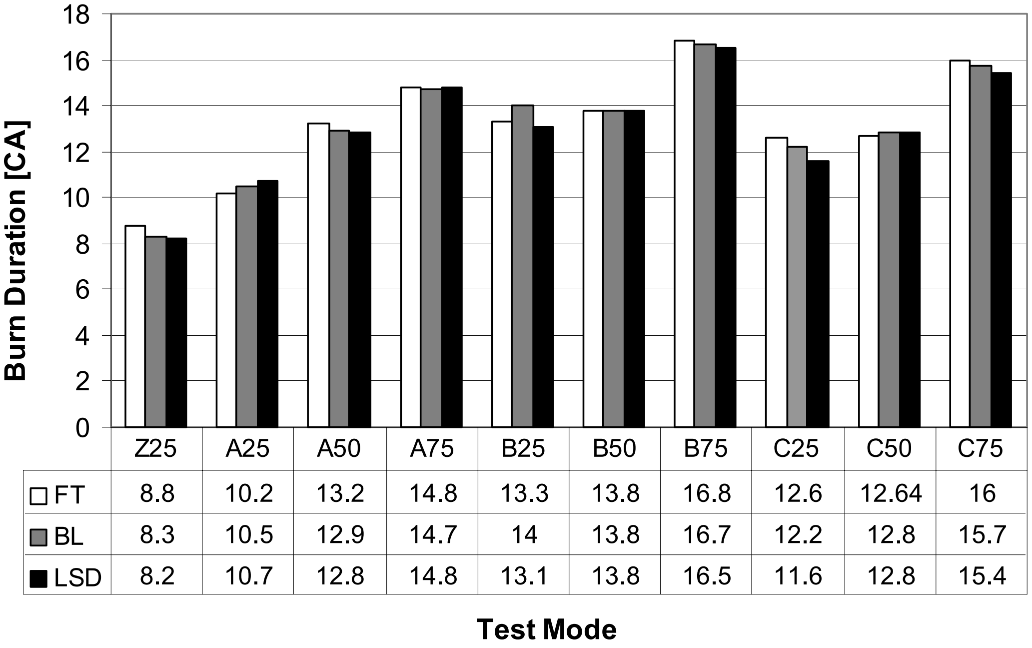
In addition to exhibiting a faster burn rate during the diffusion burn, the location of the 50% heat release occurred slightly earlier for both the FT and blend as shown in Figure 8.20. This observation is attributed primarily to the reduced ignition delay of the FT fuel and blend, essentially initiating the combustion process earlier and thus liberating more energy faster than the baseline fuel.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	365.8	373.9	376.1	381.1	377.7	379.1	381.8	380.7	380	381.3
▨ BL	365.5	375.1	376.7	380.6	378.6	379.6	381.9	382.2	380.7	381.4
■ LSD	366	375	376.7	381	378.9	379.8	381.7	382.1	380.9	381.7

Figure 8.20. Location of 50% heat release

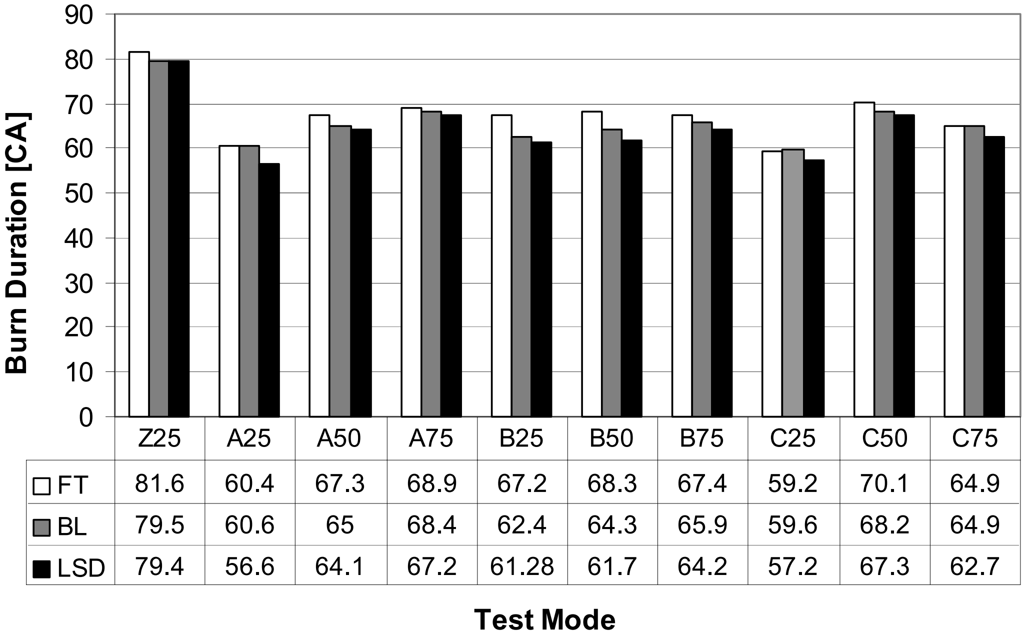
Figure 8.21 shows the initial 10% to 50% burn duration, which did not vary significantly for the three fuels. The reduced ignition delay for the FT fuel and blend, combined with the lower density of the FT fuel which reduces the amount of fuel injected for a given time interval, may lead to a reduction in the amount of fuel burned during the pre-mixed burn phase and thus contribute significantly to the observed reduction in PM emissions.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	8.8	10.2	13.2	14.8	13.3	13.8	16.8	12.6	12.64	16
▨ BL	8.3	10.5	12.9	14.7	14	13.8	16.7	12.2	12.8	15.7
■ LSD	8.2	10.7	12.8	14.8	13.1	13.8	16.5	11.6	12.8	15.4

Figure 8.21. 10% to 50% burn duration

On the other hand, the FT and blend tended to have a slightly longer tail-end burn as demonstrated in Figure 8.22. The tail-end burn for the FT fuel was approximately 5.3% longer on average, with values ranging from a maximum increase of 10.7% to a minimum of 2.5%. These values should only be taken as approximate, due to the difficulty associated with determining the location of the 99% heat release. In nearly all the cases, the blend exhibited combustion characteristics in between those of the two fuels.

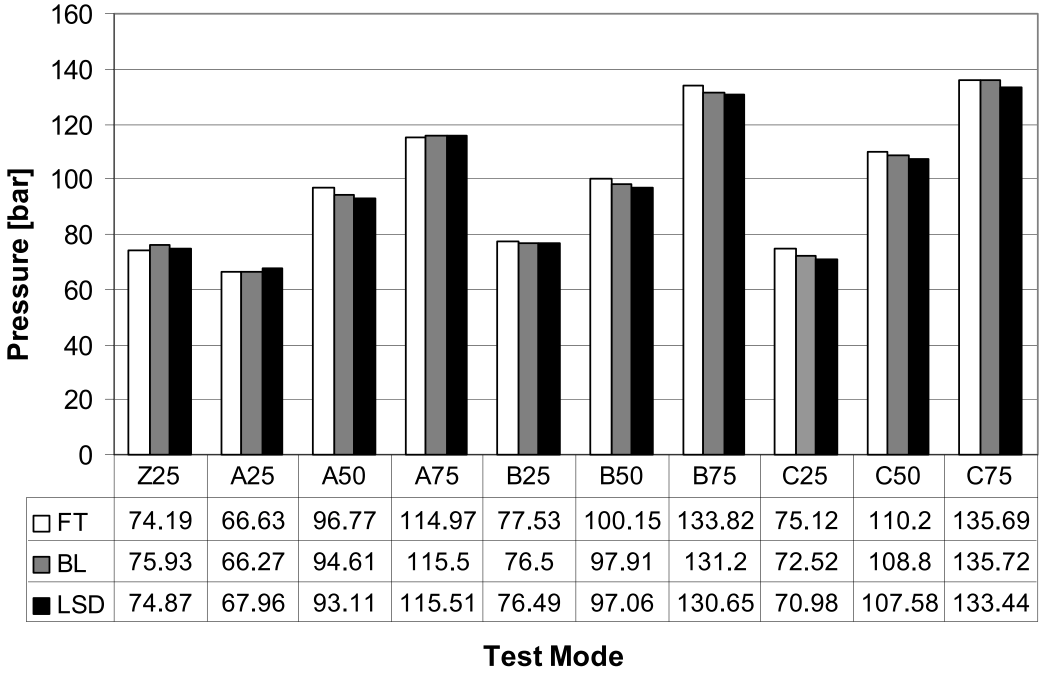


	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	81.6	60.4	67.3	68.9	67.2	68.3	67.4	59.2	70.1	64.9
▨ BL	79.5	60.6	65	68.4	62.4	64.3	65.9	59.6	68.2	64.9
■ LSD	79.4	56.6	64.1	67.2	61.28	61.7	64.2	57.2	67.3	62.7

Figure 8.22. Tail-end burn duration

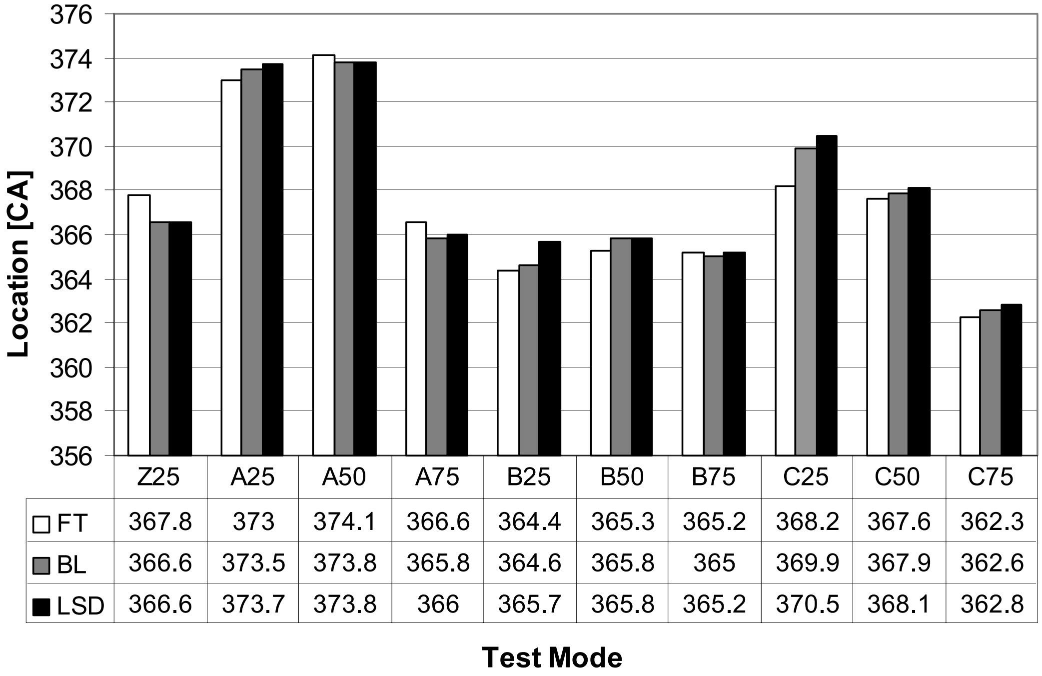
8.4.3 Maximum In-Cylinder Pressure and Location

Figures 8.23 and 8.24 compare the maximum in-cylinder pressure for each fuel and its associated location.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
☐ FT	74.19	66.63	96.77	114.97	77.53	100.15	133.82	75.12	110.2	135.69
▨ BL	75.93	66.27	94.61	115.5	76.5	97.91	131.2	72.52	108.8	135.72
■ LSD	74.87	67.96	93.11	115.51	76.49	97.06	130.65	70.98	107.58	133.44

Figure 8.23. Maximum in-cylinder pressure after start of injection



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
☐ FT	367.8	373	374.1	366.6	364.4	365.3	365.2	368.2	367.6	362.3
▨ BL	366.6	373.5	373.8	365.8	364.6	365.8	365	369.9	367.9	362.6
■ LSD	366.6	373.7	373.8	366	365.7	365.8	365.2	370.5	368.1	362.8

Figure 8.24. Location of maximum in-cylinder pressure after start of injection

Since torque was held constant at each test condition for each fuel, maximum cylinder pressure and its location remained fairly constant as well. Slight variations between the two fuels can be attributed to small differences in injection timing, which would affect the location and magnitude of the maximum pressure.

8.4.4 Pressure Trace and Heat Release Characteristics

Since the stock engine calibration employs a strategy of severely retarded injection timing to decrease in-cylinder temperatures and reduce NOx emissions, the maximum cylinder pressure for a number of test conditions occurred before TDC and before significant combustion had taken place. For these cases, the maximum cylinder pressure was taken at the 10% heat release location to provide a more representative value of the pressure actually experienced by the fuel [28]. An example of a typical pressure trace for a severely retarded injection timing condition is given in Figure 8.25.

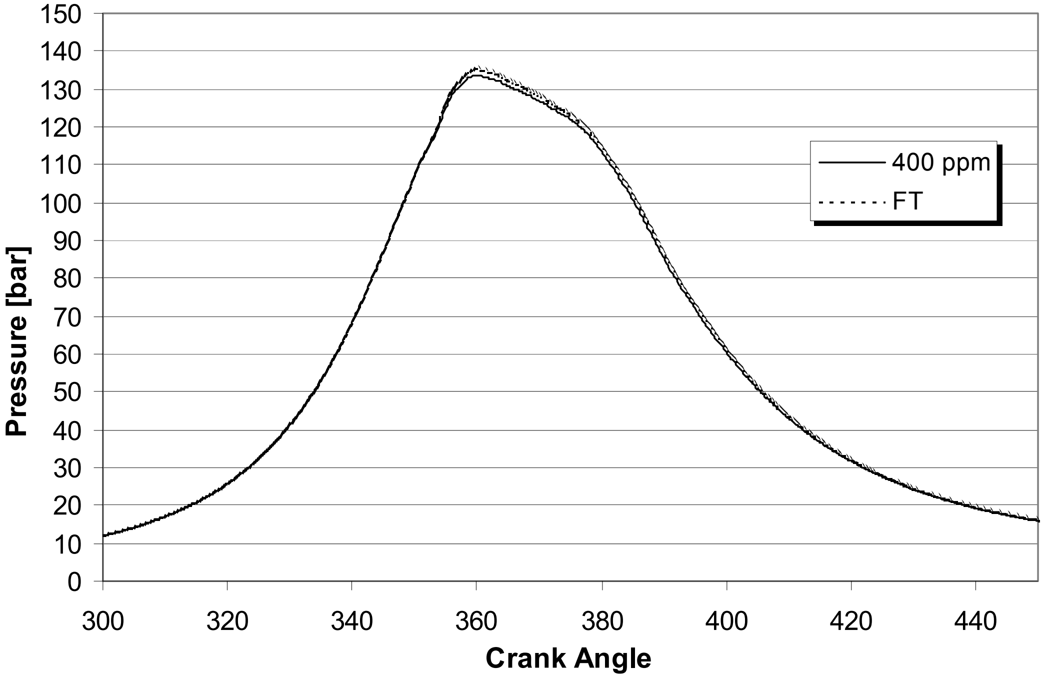


Figure 8.25. Pressure trace for severely retarded timing, 2013 rpm, 1611 kPa IMEP

Figure 8.26 presents the heat release curve corresponding to the pressure trace presented in Figure 8.25 above. The three distinct peaks correspond to the pre-, main-, and post-injection events and their associated heat release profiles.

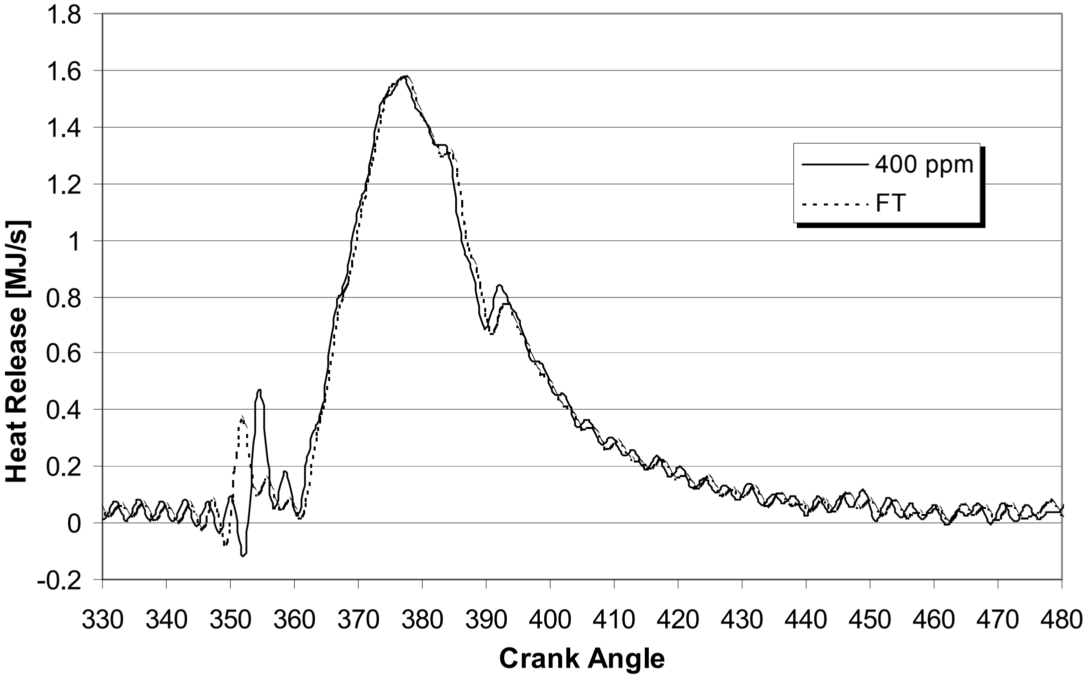
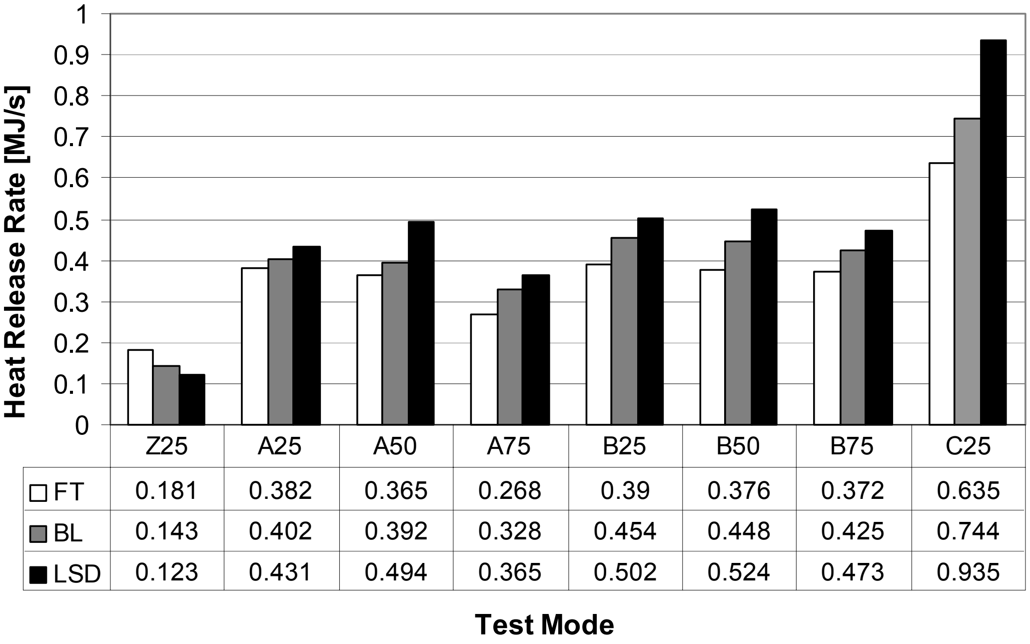


Figure 8.26. Heat release curves corresponding to severely retarded injection timing at an engine operating condition of 2013 rpm, 1611 kPa IMEP

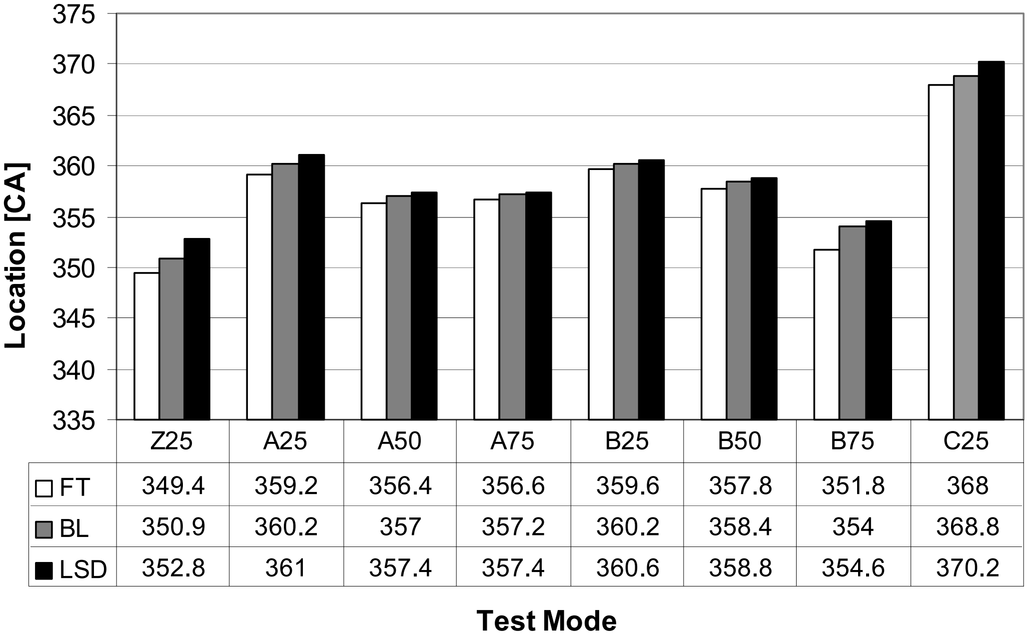
8.4.5 Pilot-Injection Maximum Heat Release Rates and Location

Figures 8.27 and 8.28 depict the maximum heat release rates and corresponding locations for each pilot injection event. In nearly all of the cases, the FT and blend exhibited a lower maximum heat release rate occurring slightly earlier than that of the low-sulfur diesel. The most significant difference between the heat release rates occurred for the pilot injection with the FT fuel. On average the FT reduced the maximum heat released by 24%, once again indicating a reduction in the amount of fuel burned during the pre-mixed combustion phase. The C50 and C75 test conditions were omitted in Figure 8.27 and Figure 8.28 due to the absence of a readily discernible heat release profile for the pilot injection event.



	Z25	A25	A50	A75	B25	B50	B75	C25
☐ FT	0.181	0.382	0.365	0.268	0.39	0.376	0.372	0.635
▨ BL	0.143	0.402	0.392	0.328	0.454	0.448	0.425	0.744
■ LSD	0.123	0.431	0.494	0.365	0.502	0.524	0.473	0.935

Figure 8.27. Pilot injection maximum heat release rate

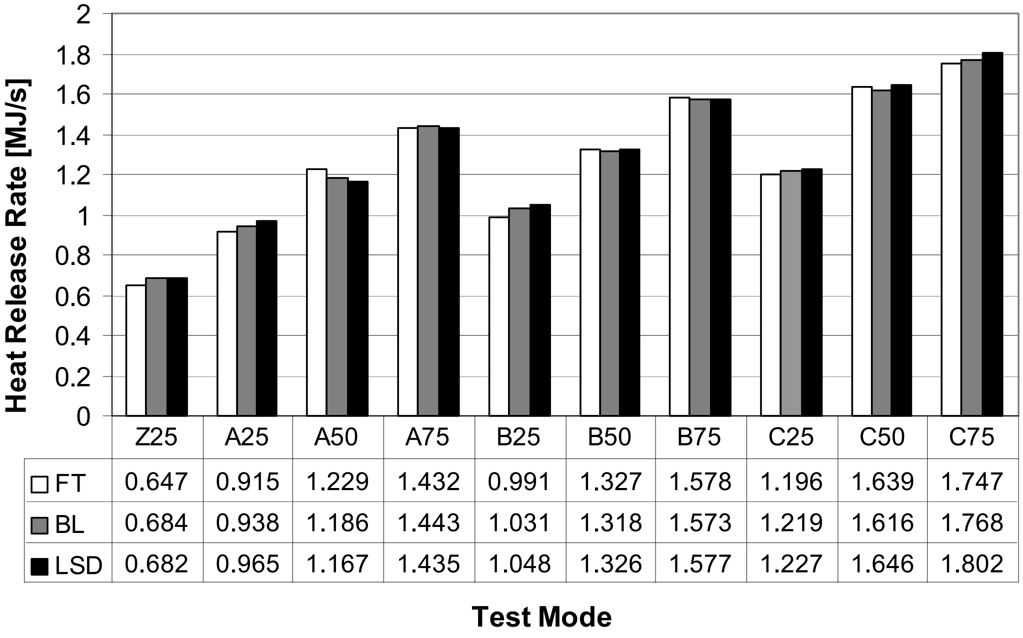


	Z25	A25	A50	A75	B25	B50	B75	C25
☐ FT	349.4	359.2	356.4	356.6	359.6	357.8	351.8	368
▨ BL	350.9	360.2	357	357.2	360.2	358.4	354	368.8
■ LSD	352.8	361	357.4	357.4	360.6	358.8	354.6	370.2

Figure 8.28. Location of pilot injection maximum heat release

8.4.6 Main-Injection Maximum Heat Release Rates and Location

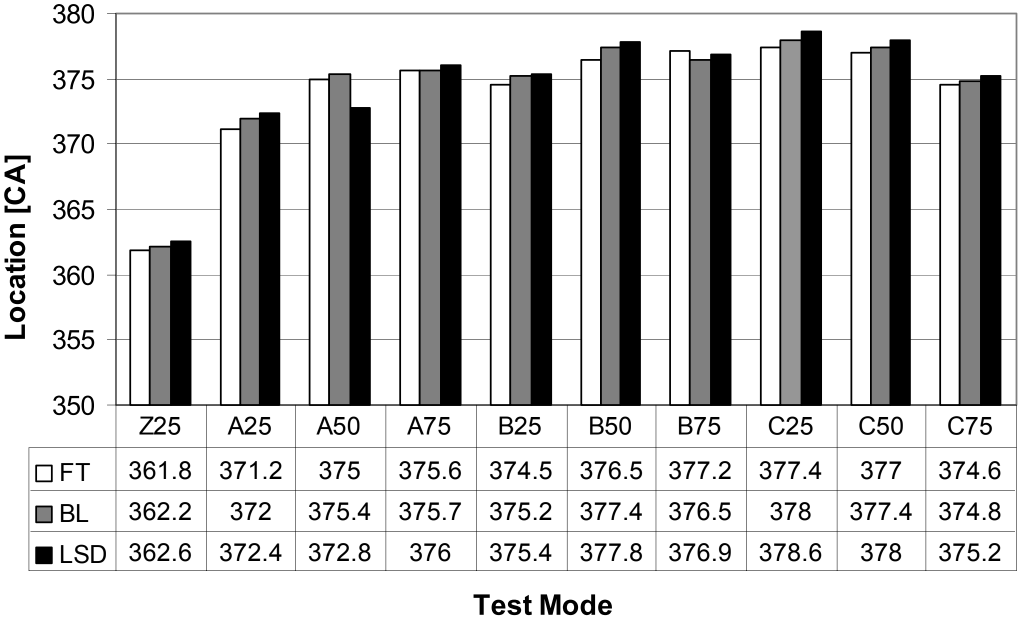
The differences in the maximum heat released for the main injection are quite small, on the order of 1 to 2%. Typically the location of the maximum heat release rate for the main injection event occurred 1 to 2 crank angle degrees earlier for the FT fuel. Once again, the blend exhibited heat release characteristics between that of the FT and low sulfur diesel. Figure 8.29 compares the heat released during the main injection event for each fuel.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	0.647	0.915	1.229	1.432	0.991	1.327	1.578	1.196	1.639	1.747
▨ BL	0.684	0.938	1.186	1.443	1.031	1.318	1.573	1.219	1.616	1.768
■ LSD	0.682	0.965	1.167	1.435	1.048	1.326	1.577	1.227	1.646	1.802

Figure 8.29. Main injection maximum heat release

The fact that the main injection heat release profiles for the various fuels did not differ significantly as reported in previous studies, is primarily attributed to the multiple injection strategy employed by the Cummins ISB. Furthermore, the location of the maximum heat release rates varied less for the higher load conditions, as shown in Figure 8.30.

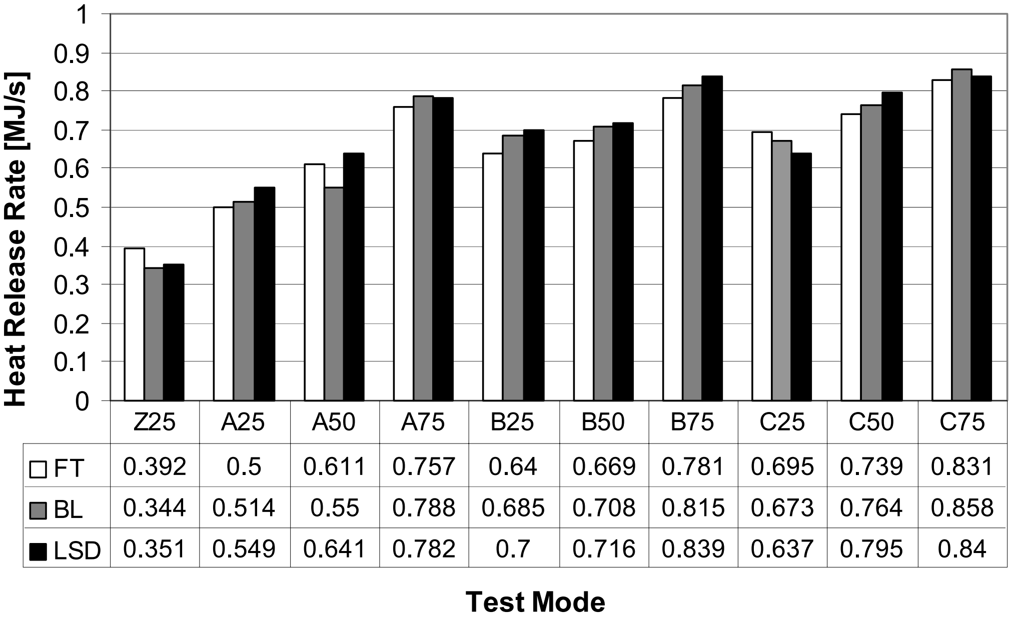


	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	361.8	371.2	375	375.6	374.5	376.5	377.2	377.4	377	374.6
▨ BL	362.2	372	375.4	375.7	375.2	377.4	376.5	378	377.4	374.8
■ LSD	362.6	372.4	372.8	376	375.4	377.8	376.9	378.6	378	375.2

Figure 8.30. Location of main injection maximum heat release

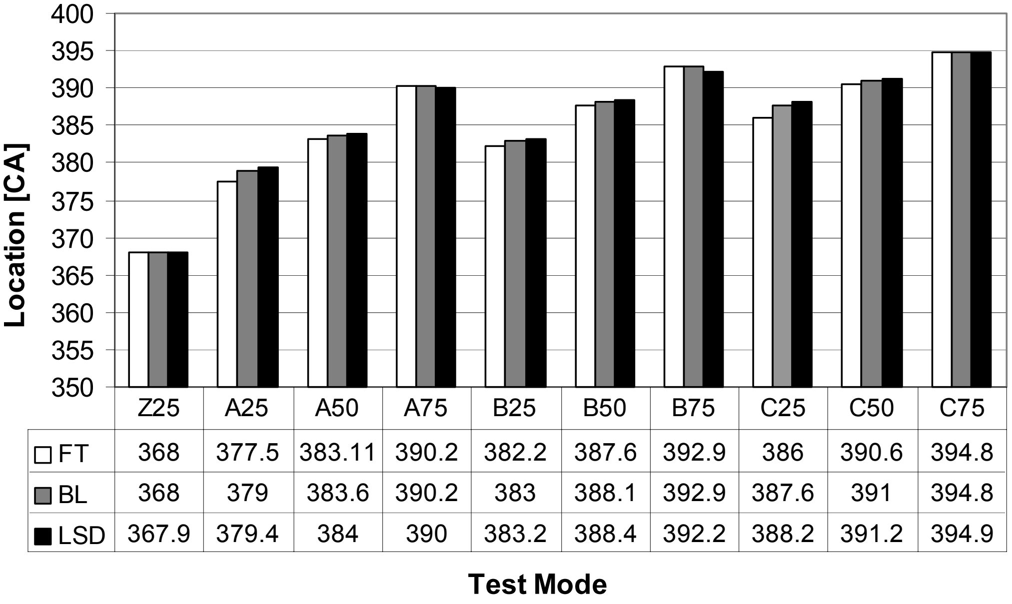
8.4.7 Post-Injection Maximum Heat Release Rates and Location

The post injection maximum heat release rates and corresponding locations are shown in Figure 8.31 and Figure 8.32.



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	0.392	0.5	0.611	0.757	0.64	0.669	0.781	0.695	0.739	0.831
▨ BL	0.344	0.514	0.55	0.788	0.685	0.708	0.815	0.673	0.764	0.858
■ LSD	0.351	0.549	0.641	0.782	0.7	0.716	0.839	0.637	0.795	0.84

Figure 8.31. Post injection maximum heat release rate



	Z25	A25	A50	A75	B25	B50	B75	C25	C50	C75
□ FT	368	377.5	383.11	390.2	382.2	387.6	392.9	386	390.6	394.8
▨ BL	368	379	383.6	390.2	383	388.1	392.9	387.6	391	394.8
■ LSD	367.9	379.4	384	390	383.2	388.4	392.2	388.2	391.2	394.9

Figure 8.32. Location of post injection maximum heat release

The differences in the maximum heat released for the post injection event were slightly greater than those observed in the main injection, with the FT exhibiting a lower average heat release rate for the post injection of approximately 5%. As before, the blend exhibited combustion characteristics between that of the FT and low sulfur diesel.

Unlike the location of the maximum heat release rate for the main injection event, the location of the maximum heat release rate for the post injection event occurred only slightly earlier for the FT fuel. This effect is attributed to the FT fuel's longer tale-end burn duration and subsequently slower tale-end burn rate. In addition, the locations of the post-injection heat release rates were nearly identical for the high load conditions.

8.5 Discussion of Combustion Characteristics

The combustion analysis demonstrated that the significantly higher cetane number of the FT fuel reduced the ignition delay, thus, reducing the amount of fuel vaporized during the pre-mixed phase of combustion. This observation was further supported by the significantly reduced maximum heat release observed in the pilot injection. Furthermore, the lower density and heating value of the FT fuel reduces the amount of fuel injected for a given time interval, and thus, necessitates a slightly longer injection duration in order to achieve the same power output as the baseline fuel. The reduced amount of FT fuel injected during the rich pre-mixed combustion phase may contribute significantly to the reduction in PM formation during this portion of the combustion process. The slightly reduced maximum heat release rates for the main- and post- injections are also indicative of a slightly more uniform combustion in the case of the FT fuel. However, it should be noted that the extreme differences in the heat release profiles for the FT and baseline fuel observed in other studies [7, 22] were not seen in this investigation. The multiple injection strategy is the most likely cause for this discrepancy.

Since the burn duration is a qualitative indicator of the chemical reaction rates during fuel oxidation, the shorter 50% to 90% burn duration for the FT fuel and blend implies a faster burn rate for these fuels as compared to the low-sulfur diesel. This effect is most likely due to the higher cetane number of the FT coupled with the engine's retarded injection timing. As the fuel is injected later in the expansion stroke, the unburned gas temperature in the cylinder decreases. This decrease in cylinder temperature may affect the auto-ignition chemistry of the fuel. Therefore, a high cetane number fuel injected under these conditions, with auto-ignition characteristics that are less sensitive to cylinder temperature, will ignite more readily and maintain a faster rate of combustion than a lower cetane number fuel [28]. The effect of the faster 50% to 90% burn rate coupled with the slightly longer tail-end burn of the FT fuel and blend on PM emissions is difficult to determine from the present study, although it is possible that the longer tail-end burn may contribute to additional soot oxidation in the cylinder.

The effect of the FT fuel on reducing NOx emissions is somewhat lower than other results reported in the literature. This may be due to the influence of the EGR system, multiple injection strategy, and heavily retarded injection timing on reducing the sensitivity of NOx formation in this engine to the fuel properties. Nonetheless, the reduced exhaust and corresponding cylinder temperatures are most likely the main factors contributing to the observed reduction in NOx emissions for the FT fuel.

The explanations presented above apply equally well to the observed emissions and combustion behavior of the blend. Based on the combustion analysis alone, no specific conclusions can be drawn for the more than proportional reduction in PM emissions of the blend. In most cases the blend exhibited combustion behavior closer to that of the baseline diesel, which is to be expected as the blend contained 75% LSD by volume.

8.6 Engine technology

In addition to the combustion characteristics, a number of engine control parameters such as injection timing, EGR fraction, boost pressure, and the time intervals between the pilot-, main-, and post-injection events were monitored throughout the study. No significant differences were observed between any of the engine control parameters and the fuels used. It is, therefore, unlikely that any significant interactions between the fuels and the various engine sub-systems should influence the observed results.

8.7 Comparison to Cummins Data

In order to verify the observed particulate emissions trends, the MIT particulate data was compared with the PM emissions values given for the Cummins 2002 EPA engine certification emissions levels. The results of the PM comparison are presented in Figures 8.33 through 8.35. The PM emissions levels measured at MIT agree very well with the data provided by Cummins for the baseline fuel, thus confirming the repeatability of the results.

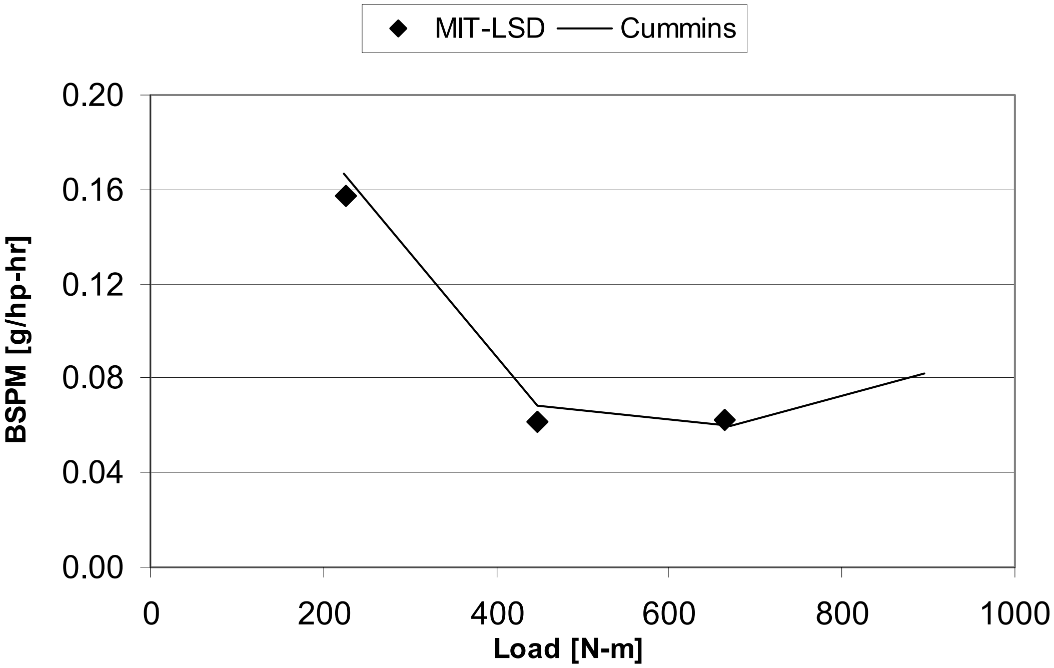


Figure 8.33. Comparison of MIT PM emissions to Cummins PM emissions at an engine speed of 1682 rpm

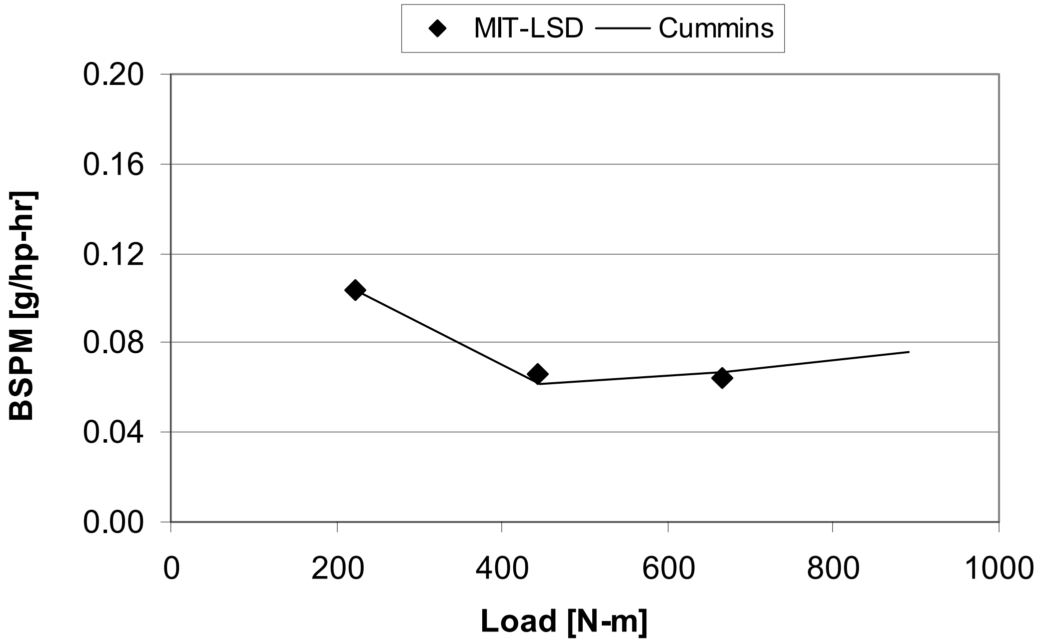


Figure 8.34. Comparison of MIT PM emissions to Cummins PM emissions at an engine speed of 2011 rpm

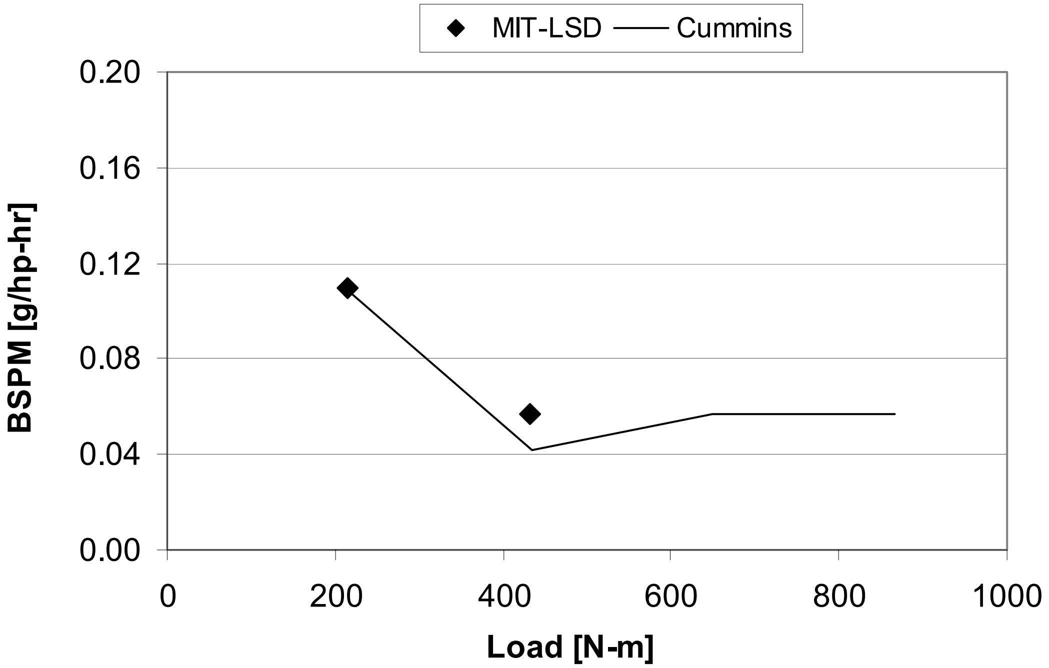


Figure 8.35. Comparison of MIT PM emissions to Cummins PM emissions at an engine speed of 2345 rpm

9.0 Experimental Results and Discussion: Task 2

The major objectives of Task 2 were as follows: to explore opportunities of injection strategy control and exhaust-gas-recirculation (EGR) in pushing the limits of NOx and particulate reduction using Syntroleum Fischer Tropsch fuel, and to modify the engine/control system in order to implement various injection control and EGR strategies. Furthermore the limits of NOx reduction via EGR and injection variables using the specific fuels was investigated, since particulates were substantially lower with the GTL fuel and more easily controlled via exhaust aftertreatment systems. The experimental results are presented in the following sections.

9.1 Emissions Characteristics

Due to the overall-lean operation of diesel engines and the heterogeneous nature of the diesel combustion process, emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC) are typically low, and well below the mandated limits. Therefore, the following discussion focuses primarily on the oxides of nitrogen ($NO_{x)}$ and particular matter (PM) emission behavior in the experiments.

9.1.1 Influence of Fuels and Engine Operating Characteristics on NOx Emissions

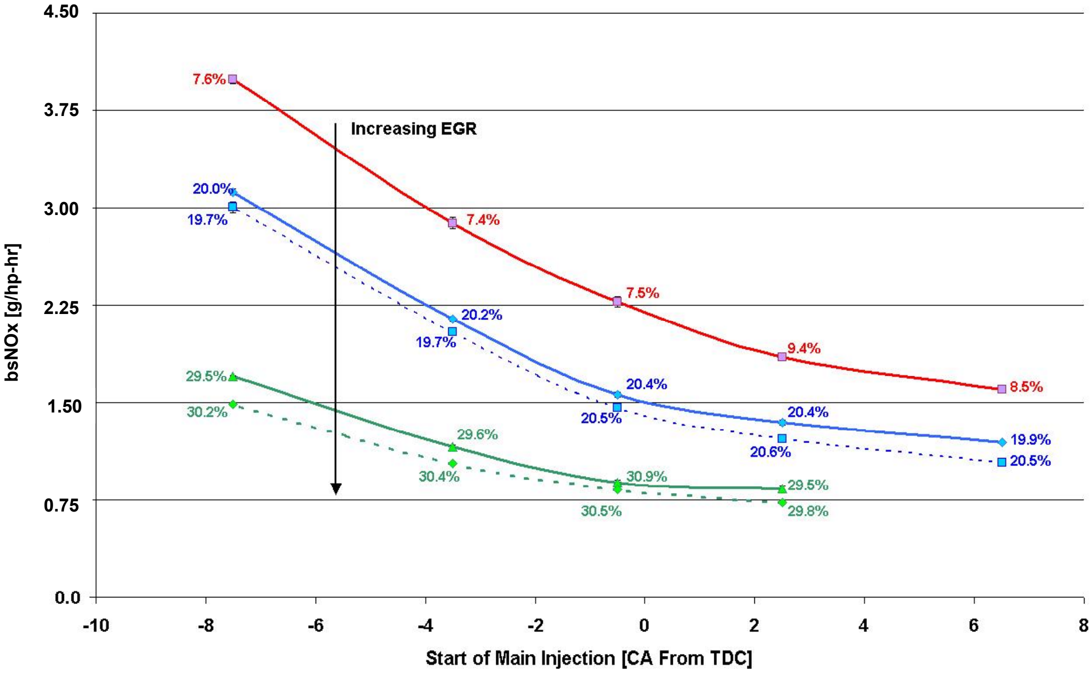


Figure 9.1. Brake-specific NO_x ($bsNO_x$) emissions versus the start of main injection timing for all experimental conditions at 1682 rpm, 1000 kPa BMEP. Solid lines apply to the low sulfur diesel fuel and dashed lines apply to the FT fuel. The individual data labels report the EGR rates for each condition while the error bars show the error for ± 1 S.D. Stock timing points are the middle points.

As shown in Figure 9.1, NO_x output is a strong function of injection timing. This well-known trend is a function of the peak gas temperatures during combustion. Peak cylinder pressure and temperature increase appreciably as injection timing is advanced from the stock timing point while noticeable temperature reductions occur as timing is retarded. Since the predominant NO_x-formation mechanism in diesel engines is thermally driven, NO_x emissions should scale with peak cylinder temperatures. Interestingly, the gas temperatures in the exhaust manifold show the opposite trend with timing, lower temperatures in advanced timing with higher temperatures in retarded timing, beyond TDC. As combustion occurs later in the expansion stroke, less work is extracted per crank angle due to the thermodynamic reduction in efficiency with cooler working fluids, resulting in elevated exhaust gas temperatures.

The results also show that NO_x output is also strongly dependent upon EGR rates. Increasing EGR was effective in decreasing brake specific NO_x for both fuels at every operating condition. At the 50 percent load point, NO_x outputs dropped from 22% – 32% when increasing EGR rates from the reduced- to stock-EGR set points. Increasing EGR from the stock setting, NO_x outputs dropped from 38% – 46% at high loads.

EGR effectively reduces NO_x in two distinct ways. Similarly to SI engines, EGR acts as a diluent with added heat capacity, helping reduce peak gas temperatures. More importantly for diesel engines, especially at high loads, EGR reduces the amount of oxygen available. As the fuel-air equivalence ratio increases towards the stoichiometric value, the mole fraction of oxygen steadily decreases while the mole fractions of both carbon dioxide (CO_2) and water vapor (H_2O) steadily increase in the exhaust-gas composition. Figure 9.2 depicts the influence of the fuel-air equivalence ration on exhaust gas composition for the FT and low sulfur diesel fuel. Furthermore, as the exhaust gas is composed of more polyatomic species, the heat capacity increases (based on the Kinetic Theory of Gases), shown by a related decrease in $\gamma_{exhaust}$ as the fuel-air equivalence ratio becomes richer, as depicted in Figure 9.3.

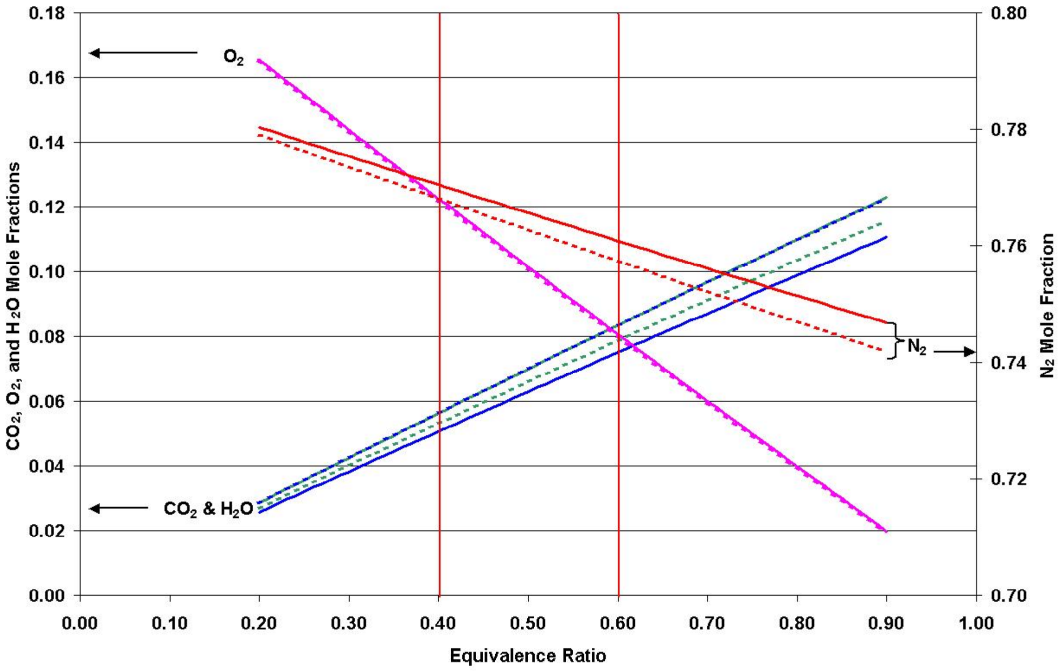


Figure 9.2. Exhaust gas composition versus fuel-air equivalence ratio for No. 2 diesel fuel and FT fuel. Mole fractions are based on No. 2 diesel fuel composition of ($CH_{1.80}$) and FT fuel composition of ($CH_{2.12}$). Solid lines pertain to No. 2 diesel fuel while dotted lines are for FT fuel. For CO_2 and H_2O lines, lower solid line is H_2O mole fraction for No. 2 diesel, while lower dashed line is CO_2 mole fraction for FT

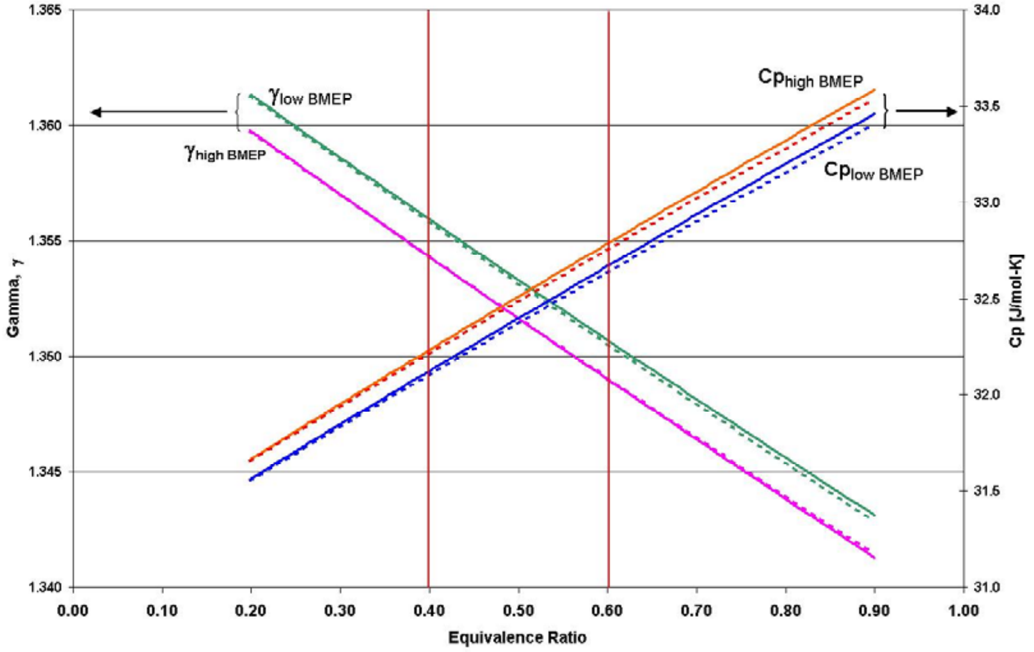


Figure 9.3. Ratio of specific heats of exhaust gas ($\gamma_{exhaust}$) versus fuel-air equivalence ratio of reactants. Mole fractions are based on No. 2 diesel fuel ($CH_{1.80}$). and FT fuel composition of ($CH_{2.12}$). Solid lines pertain to No. 2 diesel fuel while dotted lines are for FT fuel.

In order to verify the NOx emissions trends observed in the first reporting period, the timing sweep was repeated with the Fischer-Tropsch and ultra-low sulfur diesel during the second reporting period. The NOx trends for these two fuels are presented in Figure 9.4. Overall, the FT fuel showed around a 19% improvement in NO_x output for the low speed and load condition, and is in good agreement with the trends observed in the first reporting period.

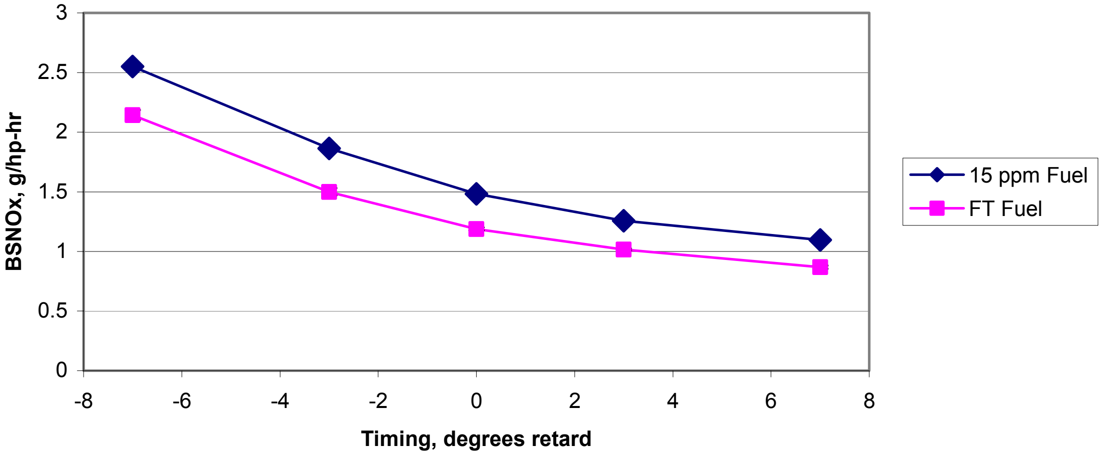


Figure 9.4. Brake-specific NO_x ($bsNO_x$) emissions versus the start of main injection timing for all experimental conditions at 1682 rpm and 480 kPa BMEP with the FT and ULSD fuels. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

Figure 9.5 shows the peak cylinder temperatures calculated from a first-law heat release analysis of the cylinder pressure data from the stock, 3 degrees advanced, and 3 degrees retarded timing points.

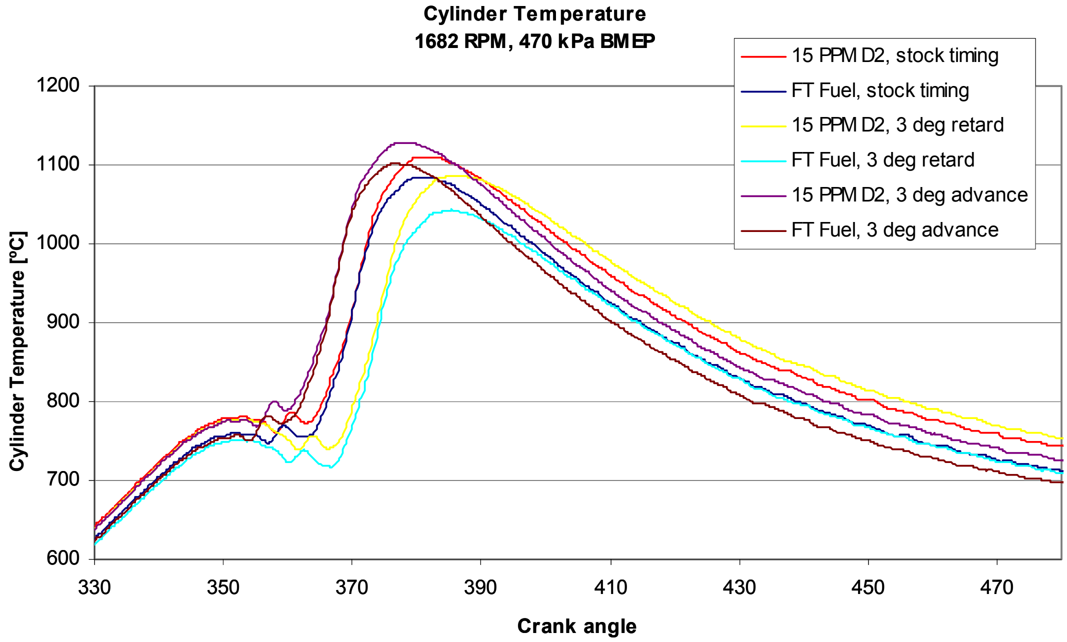


Figure 9.5. Cylinder temperature vs. crank angle for the Fischer-Tropsch and ULSD fuels at 1682 rpm and 470 kPa BMEP at three timings.

FT fuel lowers peak cylinder temperature in all cases. Given the strong dependence of NOx formation on cylinder temperature, the results shown in Figure 9.5 are consistent with the heat release analysis and the observed NOx trends for the timing sweeps.

9.1.2 NO_x Emission Trends with Fuel Properties

Compared to the baseline fuels, FT diesel consistently reduces NO_x emissions at all timing points and engine operating conditions. Comparing NOx values for both fuels at the increased EGR rates shows that from the stock injection timing to the most-retarded timing condition, the NO_x values are almost constant, while both fuels show NO_x increases as timing in advanced, less so for the FT fuel.

An explanation of this behavior is suggested by Lee et. al [16]. It was reported that the H/C ratio of a fuel could impact NO_x emissions by influencing another aspect of the kinetic pathway through reductions of the concentration of species required by the rate-limiting step in the extended Zeldovich mechanism. As shown in Figure 9.2, the mole fraction of water in the exhaust gas of FT fuel is slightly higher than No. 2 diesel fuel due to its higher H/C ratio. It was proposed that since water has a lower tendency to dissociate at high temperatures compared to carbon dioxide, fuels with higher H/C ratios will have lower concentrations of $\dot{O}$ radicals, reducing the kinetic production of NO_x as it relies on radical-oxygen concentration. Furthermore, Figure 9.2 shows that the concentration of nitrogen is lower for the high-H/C ratio FT fuel. Again, a reduction in nitrogen concentration should reduce the production rate of NO_x. The above arguments should also apply to the low-load tests, however the difference in H_2O and N_2 mole fractions between FT fuel and No. 2 diesel fuel decreases as the overall fuel-air equivalence ratio decreases, while the mole fraction of oxygen rises substantially as conditions become leaner. As such, the importance of H_2O dissociation decreases as the radical-oxygen contribution from molecular oxygen takes precedence.

9.1.3 Influence of Fuels and Engine Operating Characteristics on PM Emissions

Figure 9.6 shows the low-load brake-specific particulate matter (bsPM) behavior from the modern 2002 Cummins ISB engine, which is quite different from that of earlier models.

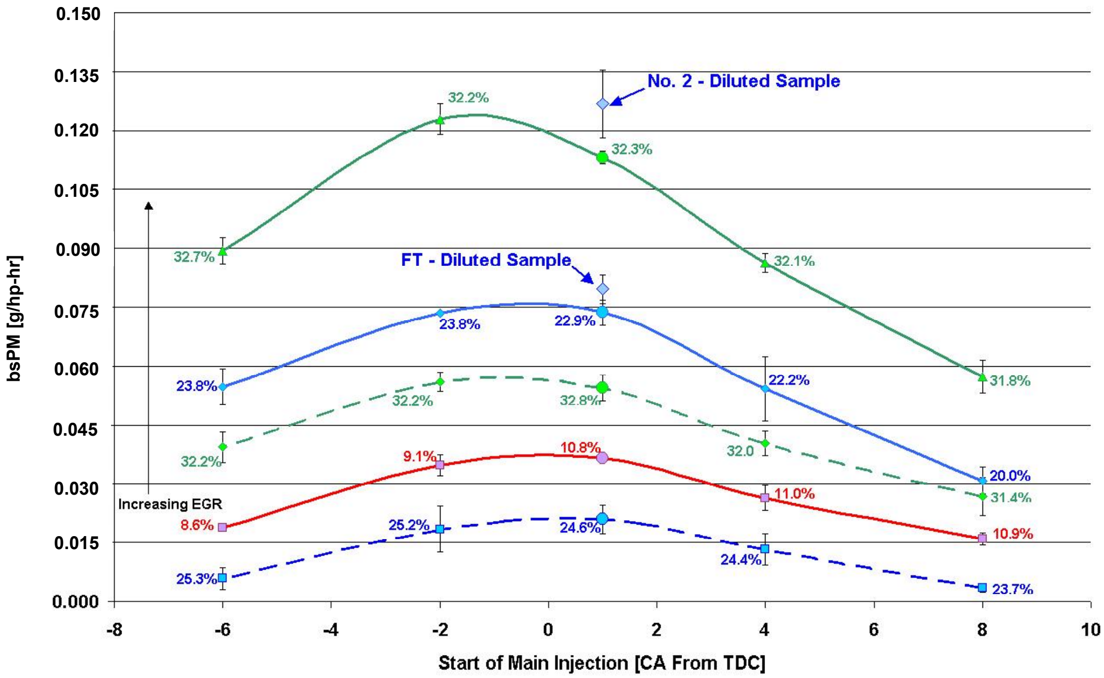


Figure 9.6. Brake-specific particulate matter (bsPM) emissions versus the start of main injection timing for all experimental conditions at 1682 rpm and 470 kPa BMEP. Solid lines apply to the low sulfur diesel fuel and dashed lines apply to FT fuel. The individual data labels report the EGR rates for each condition. Enlarged data points represent stock timing condition.

In all cases, the particulate matter emissions from FT fuel are greatly reduced from that of low sulfur diesel. Traditionally, particulate matter levels reach a minimum as timing is optimized for a specific load, speed, and EGR rate. However, the low-load trends show that the PM output of the test engine actually had locally-maximized PM outputs at the factory injection timing settings and at timings close to TDC (Modes L4 and FTL4) while PM levels drop as injection timing is moved away from TDC.

The particulate matter that exits the engine is based on two competing processes, the extent of particulate formation and oxidation. Many models for soot formation and oxidation exist [43], ranging in scope from empirical, semi-empirical, and detailed-chemistry formulations. Empirical models are relatively crude, as they do not separate formation and oxidation in their prediction of soot while detailed-chemistry models can become overly complex. A commonly used semi-empirical model in diesel engines considers the overall soot mass formation rate, $\frac{dM_s}{dt}$, as a function of the formation rate, $\frac{dM_{sf}}{dt}$, and oxidation rate, $\frac{dM_{so}}{dt}$, considered separately from one another:

Equation 9.1 $$\frac{dM_s}{dt} = \frac{dM_{sf}}{dt} - \frac{dM_{so}}{dt}$$

Equation 9.2 $$\frac{dM_{sf}}{dt} = A_f M_{fv} p^{0.5} \exp\left(\frac{-E_f}{\tilde{R}T}\right)$$

Equation 9.3 $$\frac{dM_{so}}{dt} = A_o M_s x_O p^{1.8} \exp\left(\frac{-E_o}{\tilde{R}T}\right)$$

In Equation 9.2, A_f is the pre-exponential factor for soot formation, M_{fv} is the mass of fuel vapor, and E_f is the activation energy for soot formation. In Equation 9.3, A_o is the pre-exponential factor for oxidation, M_s is the mass of soot, and x_O is the mole fraction of molecular oxygen. Common to both rate equations are the pressure and temperature of the cylinder, p and T, along with the universal gas constant. The formation and oxidation rate equations proposed by Hiroyasu are both Arrhenius-type rate equations with activation energies of $E_f = 8x10^4$ kJ/mol for formation and $E_o = 12x10^4$ for oxidation. The magnitudes of each rate constant make sense, since formation occurs at lower temperatures than oxidation, thus its activation energy should be lower.

Based on the fact that higher peak cylinder pressures and temperatures lead to increasing NO_x as injection timing is advanced, the overall PM output is most likely a difference of two large numbers as formation and oxidation rates are likely elevated. Since PM emissions drop as the cylinder gets hotter, the oxidation rate is most likely dominating as injection timing advances, leading to the drop in PM shown in the data. Additionally, the fact that the combustion duration grows with injection timing advance increases the time for PM oxidation and helps to lower the overall engine-out PM level.

As combustion is phased after TDC, the overall cylinder conditions become cooler as the piston expands the cylinder contents. With the drop in temperature during fuel injection after TDC, the rate of formation of soot is most likely decreasing. Furthermore, the amount of air entrainment before the standing premixed flame seems to play a role in the overall soot formation process. Flynn et al showed [44] that as more oxygen is mixed with the fuel-rich vapor feeding the premixed flame, less carbon went into soot precursor formation and more went into forming carbon monoxide. Air entrainment increases as the unburned gases in the cylinder cool. Therefore, as timing is retarded away from TDC, the PM levels should drop, as the observed with the test data, since less soot is initially formed.

The high load particulate matter results are shown in Figure 9.7, which also shows the reduction of particulate matter switching to FT fuel from low sulfur diesel.

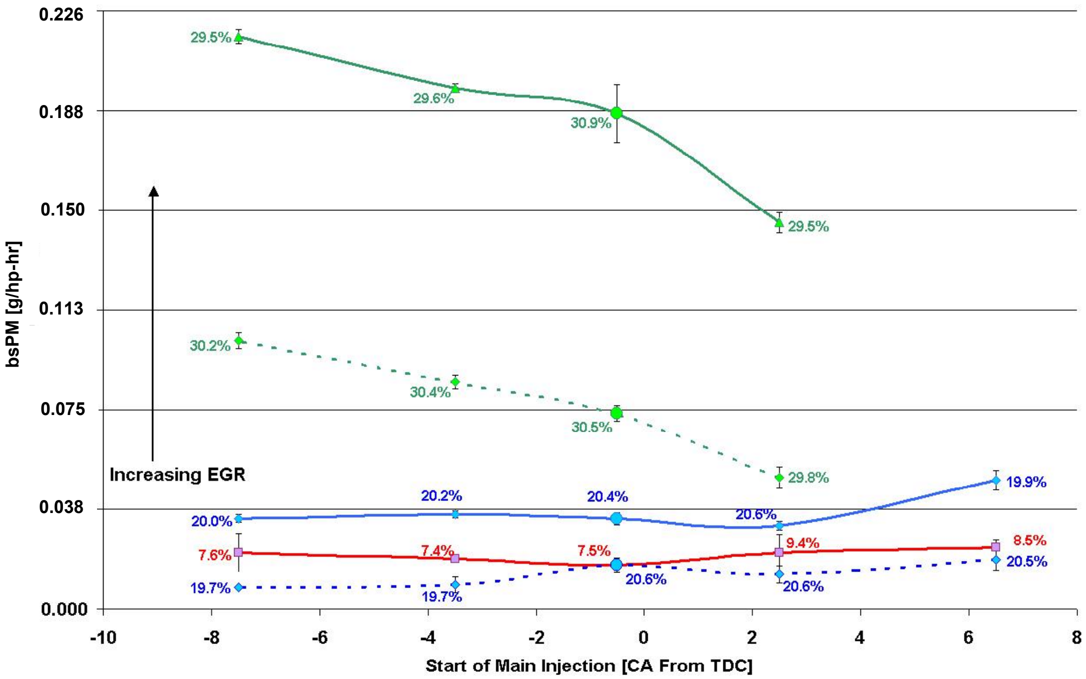


Figure 9.7. Brake-specific particulate matter (bsPM) emissions versus the start of main injection timing for all experimental conditions at 1682 rpm and 1000 kPa BMEP. Solid lines apply to low sulfur diesel fuel and dashed lines apply to FT fuel. The individual data labels report the EGR rates for each condition. Enlarged data points represent the stock timing condition.

The peak in-cylinder pressures and temperatures rise as load increases. With stock and reduced EGR rates, the oxidation mechanism seems to be dominant as timing is advanced due to the elevated bulk cylinder temperatures while reductions in soot oxidation as timing is retarded is accompanied by similar reductions in soot formation helping keep the overall PM output low. In the increased-EGR conditions, the rate of soot oxidation seems to be lower than its formation rate. The relatively smaller amount of fuel-air mixing may be contributing to this trend. As timing is retarded and air entrainment increases, the PM output level drops, suggesting the increased mixing reduces the soot formation rate.

In order to verify the particulate trends observed during the first reporting period, additional timing sweeps with an expanded test matrix including an ultra-low sulfur diesel were carried out as well. Dilute exhaust sampling data was taken for a number of timing points and the result is shown in Figure 9.8.

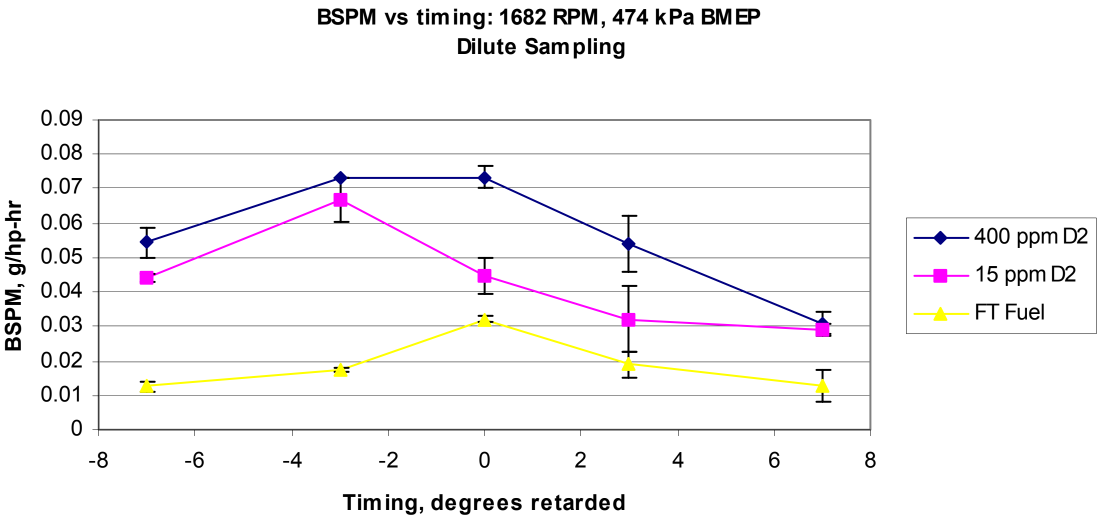


Figure 9.8. Brake-specific particulate matter (bsPM) emissions versus the start of main injection timing at 1682 rpm and 1000 kPa BMEP for a three neat fuels and a blend of 25%FT/75%ULSD.

The PM emissions trends shown in Figure 9.8 are in good agreement with those observed during the first reporting period.

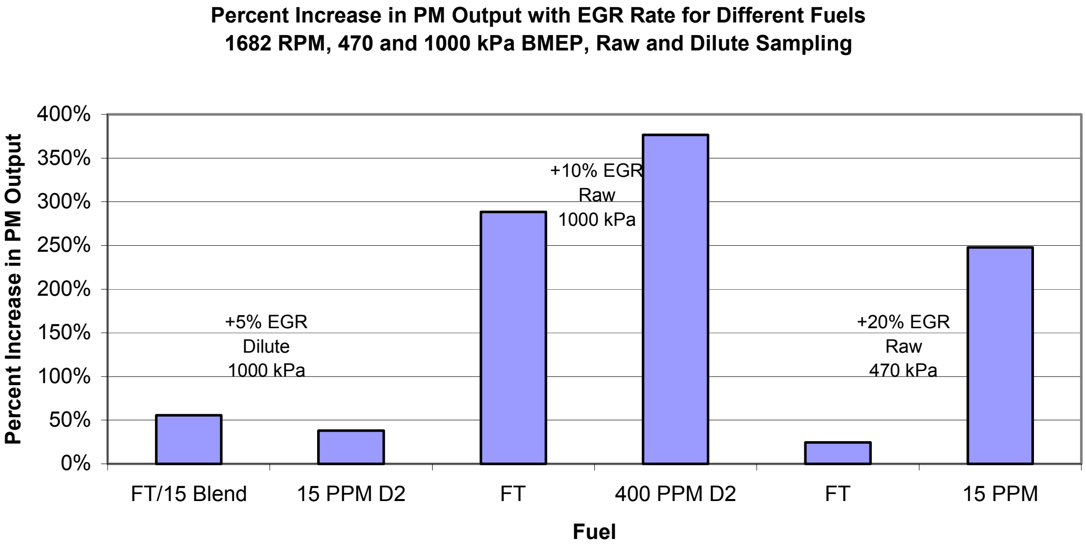


Figure 9.9. Relative increase in PM output with EGR increase for the various neat fuels and blends tested at 1682 rpm and 1000 kPa BMEP.

Figure 9.9 shows the relative increase in PM output with varying EGR rate increase for different fuels. Compared to the 400 PPM, the FT shows a smaller increase in PM output with a 10% (absolute) increase in EGR rate in mid-load tests. Likewise, in a low-load test, the FT fuel showed a smaller increase in PM when EGR rate was increased by 20%. This is indicative of tendency of FT fuel to reduce dependency of emissions on engine operating parameters.

9.1.4 EGR Effects on Particulate Size Distribution

Another trend common to both fuels shown in the aforementioned brake specific particulate matter results is the increase of PM as EGR rates increase. Scans from the SMPS illustrate the effects of EGR on particle size distribution as shown in Figure 9.10.

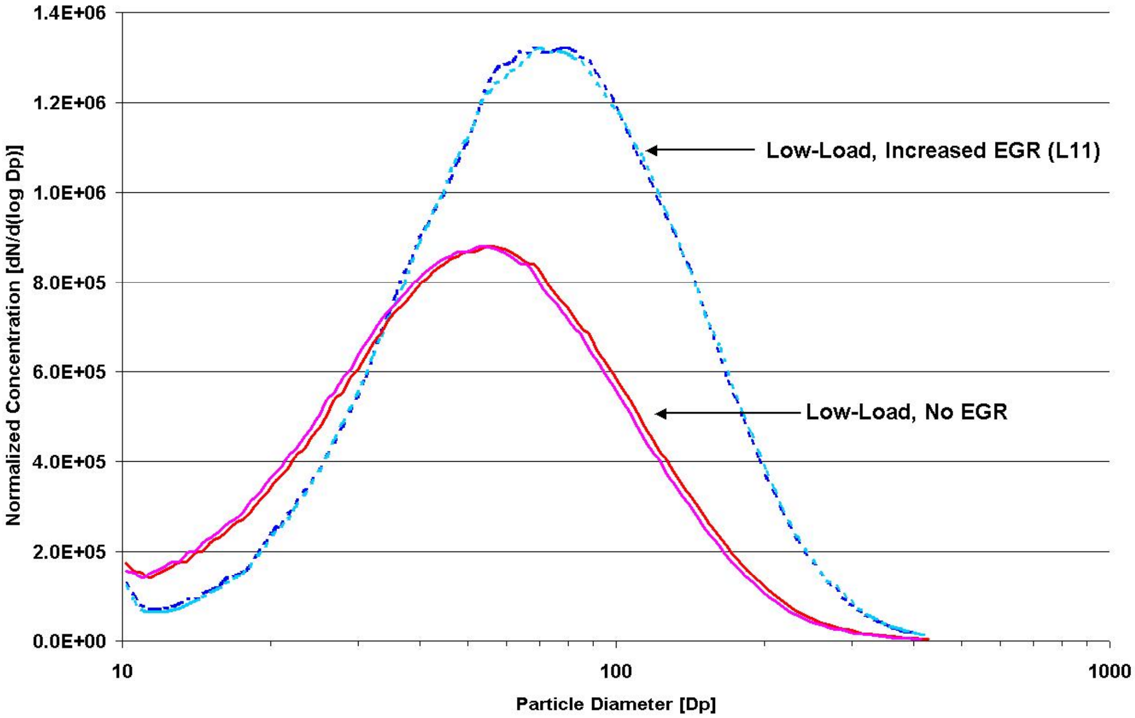


Figure 9.10. SMPS scans at low-load conditions with no EGR and increased-EGR settings (L11).

In general, EGR reduces the overall flame temperature through the increase in heat capacity of the recycled exhaust gases and reduces the oxygen concentration of the fresh air by diluting it with burned-gas products. The combination of the reduced temperature and oxygen concentration lowers the soot oxidation rate. A scanning-mobility particle size (SMPS) scan (see Figure 9.10) corroborates this by showing the size distribution moves towards more and larger particles. Since oxidation is less important, the soot formed initially can grow into larger carbonaceous agglomerates as combustion progresses.

9.1.5 Particulate Matter Emission Trends with Fuel Properties

The expanded test matrix examined the effect of fuel properties and engine operating characteristics on a larger number of neat fuels and blends. The inclusion of FT/D2 fuel blends in this study allowed us to examine the possibility of obtaining the positive effects of using FT without the cost of using pure FT fuel. As discussed earlier FT was blended with the baseline 15 PPM sulfur fuel, as well as the baseline 400 PPM sulfur fuel. This helped demonstrate what portion of the particulate reduction was due to the zero sulfur content of the FT fuel and what might be due to the combustion characteristics of FT fuel.

Figure 9.11 shows the results of low-speed, mid load dilute PM sampling tests with four fuels: neat FT, 15 PPM D2, 400 PPM D2 and the 25%/75% by volume blend of FT and 15 PPM fuels. It can be seen that FT fuel reduces PM output for all timing points and that the blended fuel can produce a varying amount of reduction, depending on timing.

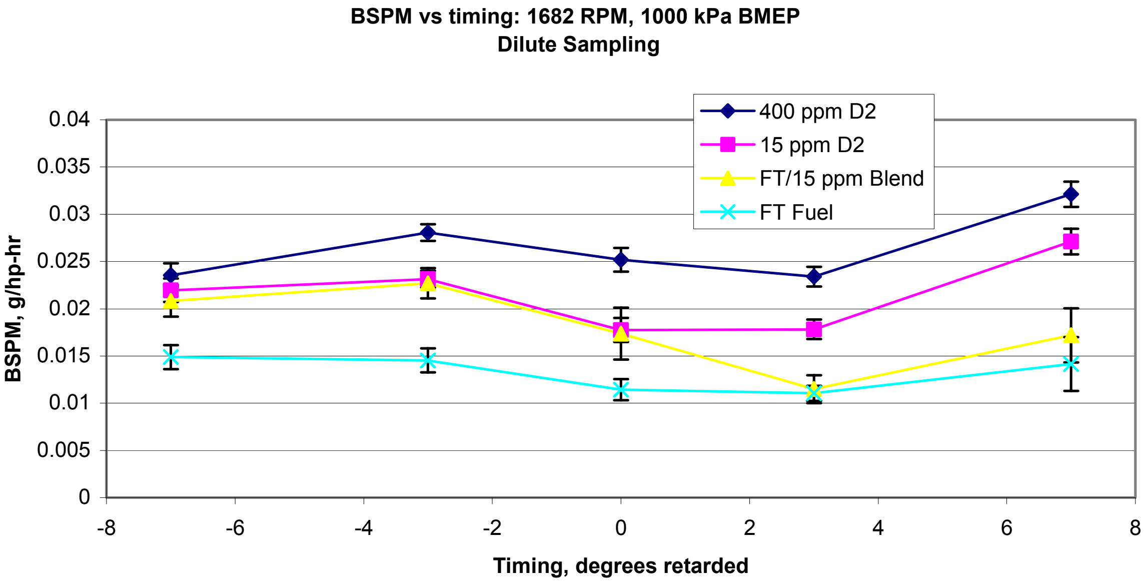


Figure 9.11. BSPM output for four fuels over five injection timings at 1682 rpm and 1000 kPa BMEP

The sulfur content was obviously a potential source of the reduction in the total particulate emissions measured among the fuels of varying sulfur levels. According to Kittelson et al [45], typical diesel exhaust (without any after-treatment devices) has sulfuric acid concentrations ranging from 5 – 20 PPM when using fuel with a sulfur content of 0.04%, or 400 PPM. Estimations were made as to the sulfate contribution to PM for this fuel. Using this sulfate-exhaust concentration, the exhaust of the test engine should have sulfate levels between 0.002 – 0.009 g/hp-hr at the stock timing, stock EGR, low load condition. For stock timing, Figure 9.11 shows a difference in PM output of about 0.005 g/hp-hr between the 400 PPM and 15 PPM fuel. As such, if the difference in fuel sulfur content were the principal contributor to reduced PM output with FT fuel, there should be little difference between particulate output with FT and 15 PPM fuel. However, it can be seen that FT fuel reduces PM levels even further than 15 PPM fuel. Thus, the reduction must be due to more than just reduced fuel sulfur.

Results from raw particulate sampling experiments with fuel blends reinforce this conclusion. As shown in Figure 9.12, the fuel blend that contains 25% FT fuel and 75% 400 PPM fuel reduces PM emissions approximately 24%, compared to 49% for neat FT fuel. Additionally, Figure 9.13 shows results for the blend of FT and 15 PPM fuel. The relative reduction is even greater in this case, again affirming that fuel sulfur reduction only contributes partially to the overall PM reduction. As shown, the FT/D2 blends produce 69% and 50% of the particulate reductions of neat FT versus 15 PPM and 400 PPM fuel, respectively.

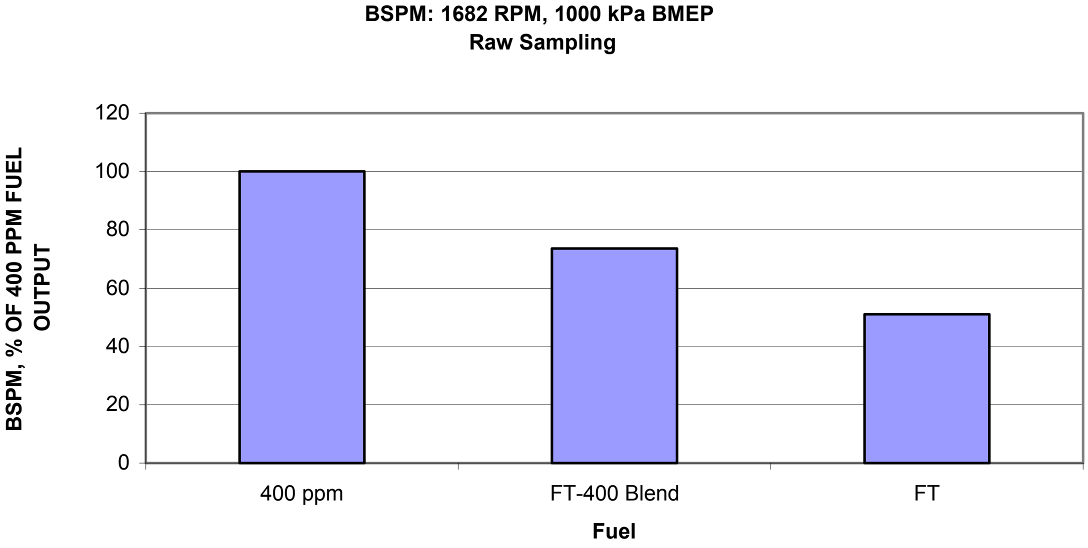


Figure 9.12. Relative reduction in PM emissions for 400 PPM, FT fuel, and their blend at 1682 rpm and 1000 kPa BMEP

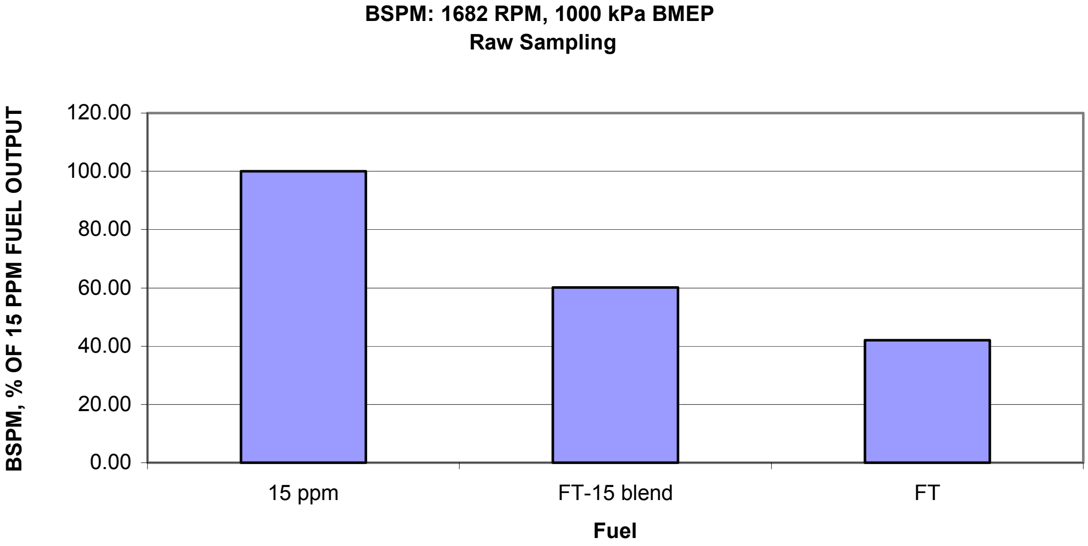


Figure 9.13. Relative reduction in PM emissions for 15 PPM, FT fuel, and their blend at 1682 rpm and 1000 kPa BMEP

Figure 9.13 shows a comparison of PM results from raw sampling of 15 PPM fuel, FT fuel and the blend of the two. The relative reduction in PM with neat FT and the 15 PPM blend is greater than in the case of the 400 PPM fuel and blend. It should be noted that these particular experiments were conducted with raw exhaust sampling to reduce the effect of daily temperature and humidity variation. Based on the raw sampling method, the PM collected in the experiments is most likely carbonaceous agglomerates. Therefore, the PM reductions must be related to the soot particles themselves, and not to the species that usually contribute to surface growth such as volatile species and sulfates. The reason for the reduction in soot particles due to fuel properties is most likely the chemical structure of the fuels themselves. This may explain why there is little difference between the PM collected from the 400 and 15 PPM fuel, compared to the dilute sampling.

The FT fuel shows PM reductions in all operating conditions, consistent with many other results from the literature. The reductions ranged from about 53% – 56% at low loads and about 72% – 89% at high loads. Based on the raw sampling method, the PM collected during the first reporting period was most likely carbonaceous agglomerates. Therefore, the PM reductions must be related to the soot particles themselves, and not to the species that usually contribute to surface growth such as volatile species and sulfates. The reason for the reduction in soot particles due to fuel properties is most likely the chemical structure of the fuels themselves.

Frenklach and Wang [46] and Richter et al. [47] suggest that the initial inception of the smaller polycyclic aromatic hydrocarbons (PAHs) that eventually combine to form soot is dependent upon the availability of aromatic molecules after the initial breakdown of the fuel molecules. If aromatic molecules are present, the hydrogen-abstraction carbon-addition (HACA) mechanism can proceed directly on a simple aromatic to form the second aromatic rings. If, however, no aromatic molecules are present, acetylene must react to form the first ring, such that the above HACA mechanism can act upon this first ring to grow larger and larger particles. Therefore, based on the fact that the FT fuel from the Syntroleum Corporation has less than 0.001% by weight aromatics (see fuel specifications), more time is spent forming the first rings than growing larger PAHs, leading to a reduction in PM when using FT fuel.

9.1.6 PM-NOx Tradeoffs

Typically, NO_x reduction strategies increase PM output and vice versa. This is known as a "NO_x – PM tradeoff" and makes it difficult to meet ever-more stringent emissions requirements for both pollutants. Considering that, it is useful to plot NO_x output against PM output to examine the potential of a certain emissions control scheme in real-world use. Furthermore, this serves to put the presented data into perspective. Figure 9.14 shows the NO_x-PM tradeoff for FT fuel and 15 PPM fuel for the low-speed, mid-load condition. The typical tradeoff behavior can essentially be seen in the 15 PPM fuel curve, though in this case, it appears that advancing timing beyond the stock point increases both PM and NO_x output. Additionally, the stock timing point is nearly optimal.

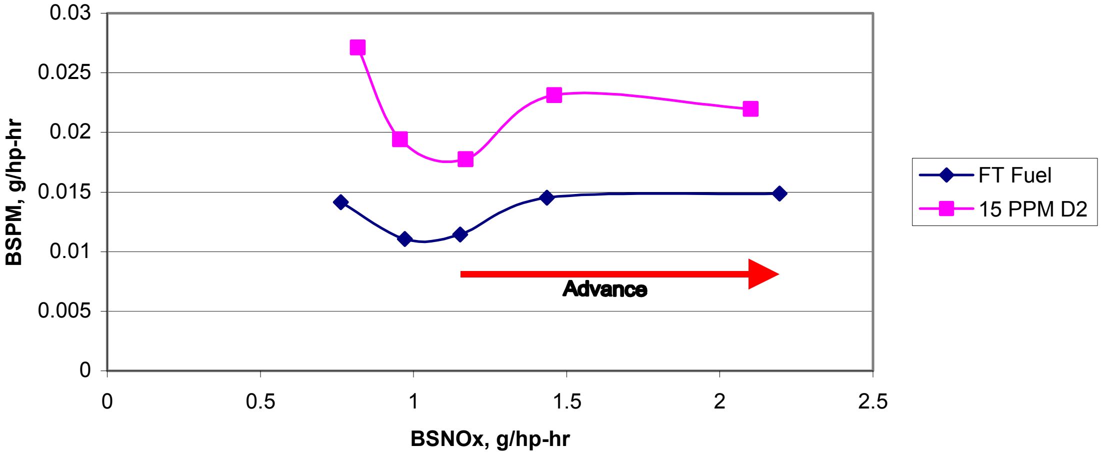


Figure 9.14. BSPM – $BSNO_x$ tradeoff at 1682 rpm and 1000 kPa BMEP

The FT fuel curve shows much less of the typical tradeoff when injection timing is retarded. From Figure 9.14, it is clear that FT fuel allows timing to be further retarded for NO_x control without significant impact on PM output.

9.2 Influence of Engine Operating Characteristics on Combustion

Recently, the combination of numerous laser-imaging tests [44, 48-54] that tracked various aspects of the reacting fuel jet such as fuel distribution and chemical species such as hydroxyl (OH) radicals and nitrous oxide (NO) spatially and temporally have led to a more complete understanding of the development of the diesel combustion process. The major difference between the old diesel combustion model and the new phenomenological model is that all of the fuel goes through two oxidation stages, first partially oxidizing in a fuel-rich premixed flame and then completing oxidation in a stoichiometric, or very-near stoichiometric diffusion flame.

These new revelations of diesel combustion describe the major physical characteristics and processes of combustion such as the spatial and temporal development of the fuel-air plume, equivalence ratios of the standing premixed flame and surrounding diffusion flame, and spatial regions where emissions are most likely forming. Many other details about the combustion event are also important when trying to gain a fundamental understanding of the effects of fuel properties on engine performance and emissions. Interpretation of our current results in light of the new understanding of combustion was performed. Additional analyses with the heat-release-rate curves give such details as how soon after injection the initial premixed burn fraction occurs, crank-angle locations of when certain percentages of the total energy is released, or when the end of combustion occurs. These and other parameters are helpful in determining why fuel properties affect an engine's overall operating characteristics.

9.2.1 Ignition Delay

The ignition delay in diesel combustion is defined as the time between the start of injection and the start of combustion. One of the main factors governing the ignition delay in diesel combustion is the cetane number (CN) of a fuel. Although the magnitude of ignition delay is usually only described chemically through a fuel's (CN), physical processes and conditions inside the combustion chamber are equally important in determining the ignition delay.

Experiments done in constant-volume bombs, steady-flow reactors, and in rapid-compression machines have been used to study the autoignition characteristics of fuel-air mixtures [34]. The ignition delay data from experiments carried out in these different combustion configurations can all be described by the following equation [34]:

Equation 9.4
$$\tau_{id}(CA) = (0.36 + 0.22\bar{S}_p)\exp\left[E_A\left(\frac{1}{\tilde{R}T} - \frac{1}{17{,}190}\right) + \left(\frac{21.2}{p - 12.4}\right)^{0.63}\right]$$

where τ_{id} is the ignition delay, E_A is the apparent activation energy for a fuel to autoignite, $\widetilde{R}$ is the universal gas constant, T is the cylinder temperature, $\overline{S}_p$ [m/s] is the mean piston speed, and T [Kelvin] and p [bars] are the charge temperature and pressure during the ignition delay (taken as TDC conditions). In Equation 9.4, the importance of a fuel's cetane number is correlated by [34]:

Equation 9.5
$$E_A = \frac{618{,}840}{CN + 25}$$

Thus, as expected, as a fuel's CN rating increases, the required activation energy required for autoignition drops, reducing the ignition delay for a given temperature and pressure. Furthermore, the exponential dependence of ignition delay on cylinder temperature is also apparent in Equation 9.4.

Modern fuel-injection technology gives engine designers precise control of fuel delivery, allowing for injection rate shaping and multiple injections per cycle. The test engine used to run experiments is equipped with a Bosch common-rail system, allowing Cummins engineers to use a multiple-injection fueling strategy. According to Cummins engineers, pilot injection is used to reduce the typical diesel "knocking" sound for societal benefits. Pilot injection accomplishes this by reducing the amount of fuel that autoignites in the initial premixed burn fraction, decreasing the sudden pressure rise that is associated with the diesel-engine sound. The small amount of fuel (1 mg/stroke in all experiments) injected a few degrees before the main injection event occurs starts the autoignition chemistry, helping to bring the prevailing cylinder conditions into a more favorable state once the main fuel is injected, reducing the overall ignition delay of the main fueling quantity.

In the burn rate analysis program used to process the cylinder pressure traces, the start of combustion (SOC) was defined as the point after the main start of injection when the heat release went through an inflection point (some conditions had two inflection points; the first was used in these cases), going from a decreasing rate in heat release to an increasing rate of heat release. The heat release drops after the start of the main injection due to the evaporative cooling effect of vaporizing fuel. Due to time constraints, the SOC was manually chosen by visually inspecting the heat-release rate curves. The behavior in the high-load, most advanced cases (H5, FTH5, H15, and FTH15) is suspect, since the SOC was difficult to pinpoint manually. Thus, the following discussions ignore these points when comparing trends.

9.2.1.1 Effect of Injection Timing and EGR on Ignition Delay

In order to reduce overall NO_x emissions, modern diesel engines use heavily retarded timing compared to older engines. Diesel engines from the 1970s and 1980s commonly had injection timings between 20° – 30° bTDC, whereas nowadays, fuel injection occurs around TDC. In the low-load experiments (~480 kPa BMEP), the stock injection timing is 1° aTDC. Since the piston is largely still near TDC, even with advanced and retarded timing, the cylinder temperatures and pressures vary little with injection timing. As compression temperatures and pressures around TDC are much higher versus conditions at 20° – 30° before TDC, the ignition delays in engines with near-TDC timing should be shorter relative to older engines, and should not vary much with injection timing.

Examining Figure 9.15, we see that the average ignition delay under the stock-EGR operating conditions with No.2 diesel fuel is $\tau_d = 3.4° \pm 0.4°$. Repeating the same EGR rate tests with FT fuel resulted in an average ignition delay of $\tau_d = 2.3° \pm 0.3°$. Based on Equation 9.4, which was correlated using TDC conditions, the ignition delay should not change much with timing, although the CN effect should make the ignition delay shorter with FT fuel. The small spread in ignition delay is attributed to the fact that the temperatures and pressures at the start of injection varied little. Using the individual temperatures and pressures at the start of injection, Equation 9.4 predicts differences of about 1° – 2° between low sulfur diesel and FT diesel, which is seen in the data. Thus, since the cetane index of the FT fuel is much larger than the equivalent cetane index of the low sulfur diesel fuel, the ignition delay reduction is expected.

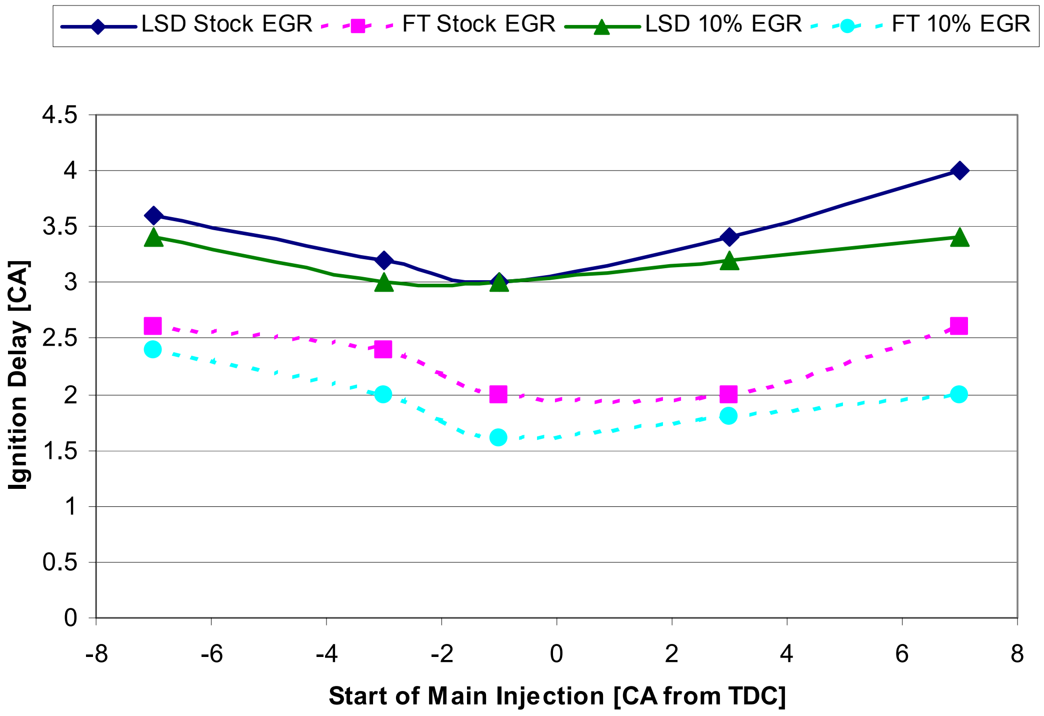


Figure 9.15. Ignition delay comparison between low sulfur diesel fuel and Fischer-Tropsch fuel during timing-sweep tests with <u>stock and elevated EGR</u> rates at 1682 rpm and 480 kPa BMEP. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

Likewise, in the increased-EGR operating conditions shown in Figure 9.15, the FT fuel had ignition delays ($\tau_d = 2.0° \pm 0.3°$) that were about 1.0° shorter than the equivalent operating conditions with the LSD fuel ($\tau_d = 3.2° \pm 0.2°$). Again, the higher relative CN (as CNI $\cong$ CN) rating of the FT fuel reduces the overall ignition delay. The low standard deviation among the recorded spread of ignition delays again shows that the ignition delay did not change much with injection timing. The slight reduction in ignition delay compared to the stock EGR conditions is attributed to the fact that the intake charge temperature is increased due to the addition of hot-products through the recycled exhaust. Intake manifold temperatures jump from $T_{IMT} = \sim 50°C$ at the stock EGR conditions to $T_{IMT} = \sim 70°C$, resulting in temperatures at SOI that range from about $T_{SOI\text{-}Increased\ EGR} = 750 – 825$ K, about 20 – 70 K higher than the stock EGR tests, depending on the injection timing. Pressures around SOI at this EGR rate range from $P_{\text{SOI-Increased EGR}} = 6.0 - 6.8$ MPa, slightly higher than the SOI-pressures at the stock EGR rate due to the increase in cylinder temperatures.

9.2.2 Combustion Duration

After the ignition delay period, auto-ignition establishes the standing premixed flame. Combustion proceeds until either the fuel is completely burned or the flame is quenched. The combustion duration gives a qualitative indication of the chemical reaction rates during the two-stage oxidation of diesel fuel; long durations imply low chemical reaction rates while short durations imply high chemical reaction rates. The combustion duration referred to in the following sections is derived from the heat-release analyses of cylinder pressure traces. Combustion duration was defined as the time between the start of combustion (SOC) and the end of combustion (EOC), the EOC defined as the point of 90% of the integrated heat release. This definition of combustion duration resulted in combustion durations between about 40° – 50° at low loads and 50° – 70° at high loads (more fuel burned at high loads requires more time for combustion). Defining the EOC at locations greater than the 90% integrated heat release point resulted in abnormally long combustion durations, some points being greater than 100°. Heywood [34] suggests that fuel conversion efficiencies are highest when the combustion duration is between 40° – 50°, suggesting that the EOC definition used in the heat-release analysis program is an appropriate, although arbitrary, definition of when combustion ends.

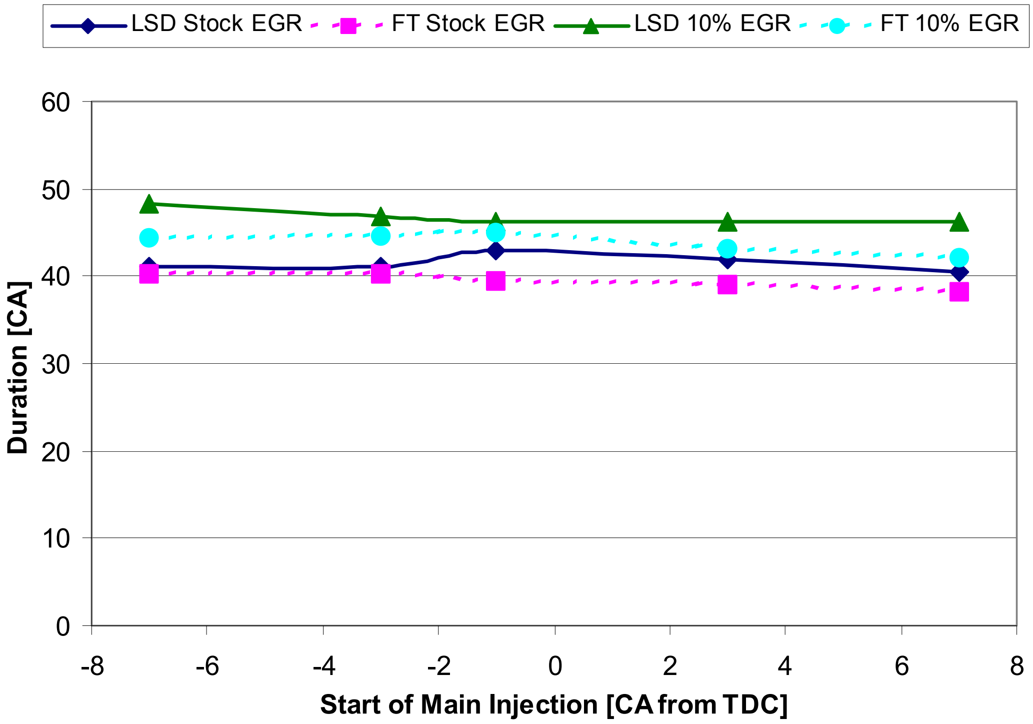


Figure 9.16. Combustion duration using No.2 diesel fuel and Fischer-Tropsch fuel during timing sweep test with stock and elevated EGR rates at 1682 rpm and 480 kPa BMEP. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

Combustion duration results are shown in Figure 9.16, for various timings and EGR rates for the FT fuel and the low sulfur diesel. The major observations are summarized as follows:

(a) Combustion durations for the FT fuel are general shorter than that for No.2 diesel, despite the slightly longer injection durations for the FT fuel (to account for density difference), at comparable conditions.
(b) Combustion durations are relatively insensitive to injection timings for both the low sulfur diesel and FT fuel and at each EGR condition.
(c) Combustion duration increases as EGR rate is increased. Figure 9.16 shows that at a constant BMEP and timing, the combustion duration increases as the EGR rate increases. The combustion duration increased from about 3° – 7° at low loads, depending upon timing, while changing from about 7° – 10° at high loads depending upon timing. This is expected since EGR acts as a diluent.

To get a better understanding of combustion development, the combustion duration was divided into three intervals to describe the beginning, middle, and end of combustion. In the heat release program, in addition to the 90% integrated heat release location that defined EOC, the 10% and 50% integrated heat release locations were calculated. From these points, the durations between SOC to the 10% integrated heat release point, 10% to 50% heat release points, and 50% to 90% heat release points were determined, giving further insight into the combustion duration trends.

9.2.2.1 SOC-to-10% Heat Release Duration

In order to reduce both particulate matter and NO_x output, the test engine is equipped with a common rail fuel injection system, injects fuel around TDC, and uses multiple-injection fueling strategies. As a result of these emission-reducing technologies, the test engine has shorter ignition delays compared to older engines (on a time basis, 0.2 to 0.3 ms for the test engine vs. 0.4 to 1.5 ms for high-compression ratio and turbocharged engines [28]) along with combustion that occurs predominantly in the expansion stroke. This late phasing of combustion leads to trends not seen in older engines.

As show in Figure 9.17, at stock EGR rates, the duration between the start of combustion to the point of 10% heat released increases as timing is retarded from the most-advanced injection timing point. Comparing the LSD fuel and FT diesel, the SOC-to-10% heat release duration is longer for every operating condition with FT diesel. This trend is a function of a fuel's associated ignition delay and the phasing of combustion with respect to TDC. Similar trends with respect to timing (the baseline diesel shows an insensitivity to timing until the most-retarded injection condition) and fuel type are seen with the increased-EGR operating points as well.

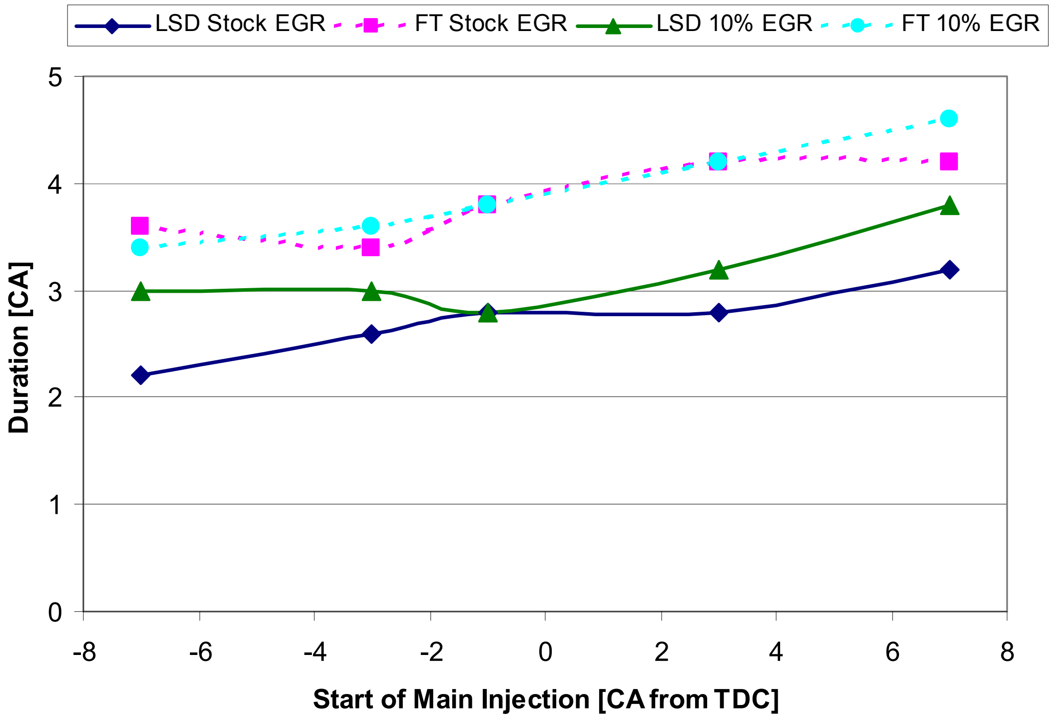


Figure 9.17. SOC-to-10% durations using No.2 diesel fuel and Fischer-Tropsch fuel during timing sweep test with stock EGR rates in low-load tests with stock and elevated EGR rates at 1682 rpm and 480 kPa BMEP. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

The SOC-to-10% heat-release duration should have an inverse relationship with ignition delay; shorter ignition delays lead to longer SOC-to-10% heat release durations. This is shown by the magnitude of the SOC-to-10% heat release durations with FT fuel. With similar trends based on phasing, FT fuel shows prolonged SOC-to-10% heat release durations compared to the baseline diesel fuel at the same operating condition. This occurs due to FT fuel's higher CNI rating versus the low sulfur diesel fuel, which implies less air entrainment and lower initial reaction rates when using FT fuel.

9.2.2.2 10% to 50% Heat Release Duration

Compared to heat release rate curves common to older technology engines, the heat release rates of the modern engine used in this study are drastically different. The longer ignition delays in older engines result in a large initial peak, meaning a considerable amount of fuel underwent auto-ignition in the initial premixed burn. These curves suggest that the majority of the initial heat release is controlled by the auto-ignition event in older engines. Heat release profiles from the model year 2002 (MY02) engine at MIT show that at the initial peak common in older engines is virtually non-existent, the only evidence that auto-ignition occurs is the change in slope as the curve rises to a single peak. Therefore, the diffusion flame dominates the initial heat release in a modern diesel engine.

Since the diffusion flame in a diesel engine burns stoichiometrically, or very close to stoichiometric, its adiabatic flame temperature is very high, ranging from 2300 K – 2700 K [44] depending upon initial conditions. However, the adiabatic flame temperature of a rich premixed flame can be quite low, and researchers suggest that the rich fuel-air mixture in a diesel fuel jet can range from 825K – 1600 K [44]. Therefore, once the diffusion flame establishes, the rate of heat release will completely dominate over that of the premixed flame.

Since the flame lift-off point delineates where the Damköhler number is of order magnitude one, the initial rate of reaction in the diffusion flame will be controlled by the amount of fuel-air mixing, dictated by the pressure difference across the nozzle during injection. Since the injection pressure in modern diesel engines is substantially higher than the peak pressures seen during combustion, the initial rate of heat release following the establishment of the diffusion flame will be mostly dependent upon the injection pressure. Therefore, the near-constant 10%-50% heat release durations shown in Figure 9.18 with both the LSD (8.8° ± 0.4°) and FT fuel (8.4° ± 0.2°) are expected.

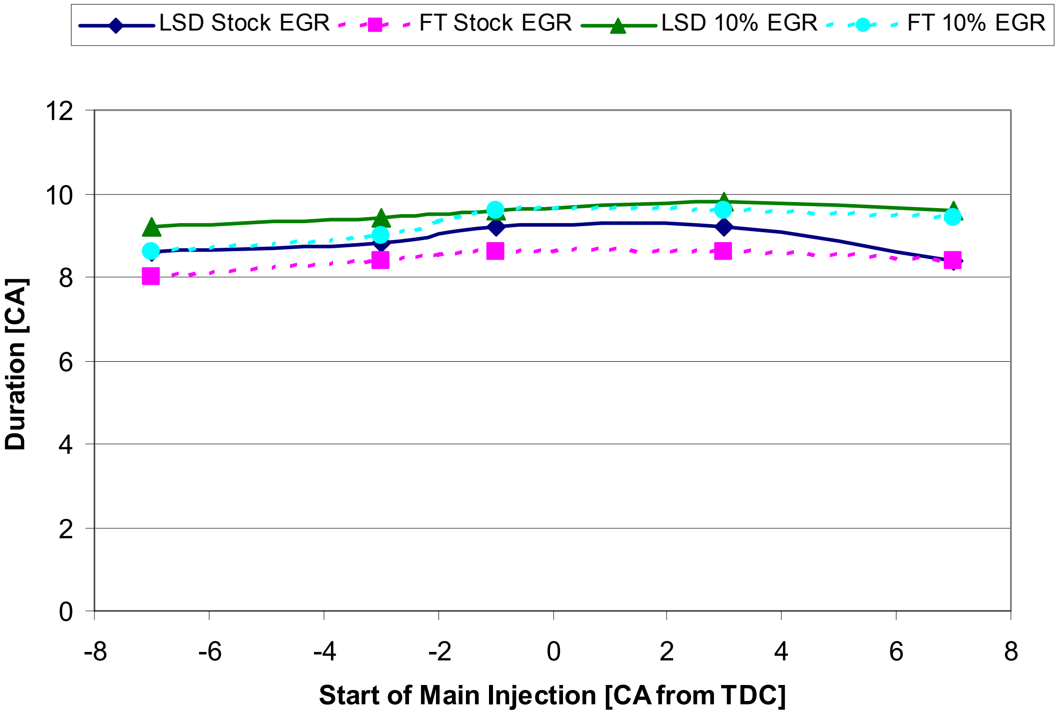


Figure 9.18. 10%-to-50% durations using No.2 diesel fuel and Fischer-Tropsch fuel during timing sweep test with stock EGR rates in low-load tests with <u>stock and elevated EGR</u> rates at 1682 rpm and 480 kPa BMEP. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

9.2.2.3 50%-to-90% Heat Release Duration

Figure 9.19 shows that the 50%-to-90% heat release duration decreases as injection timing is retarded beyond TDC.

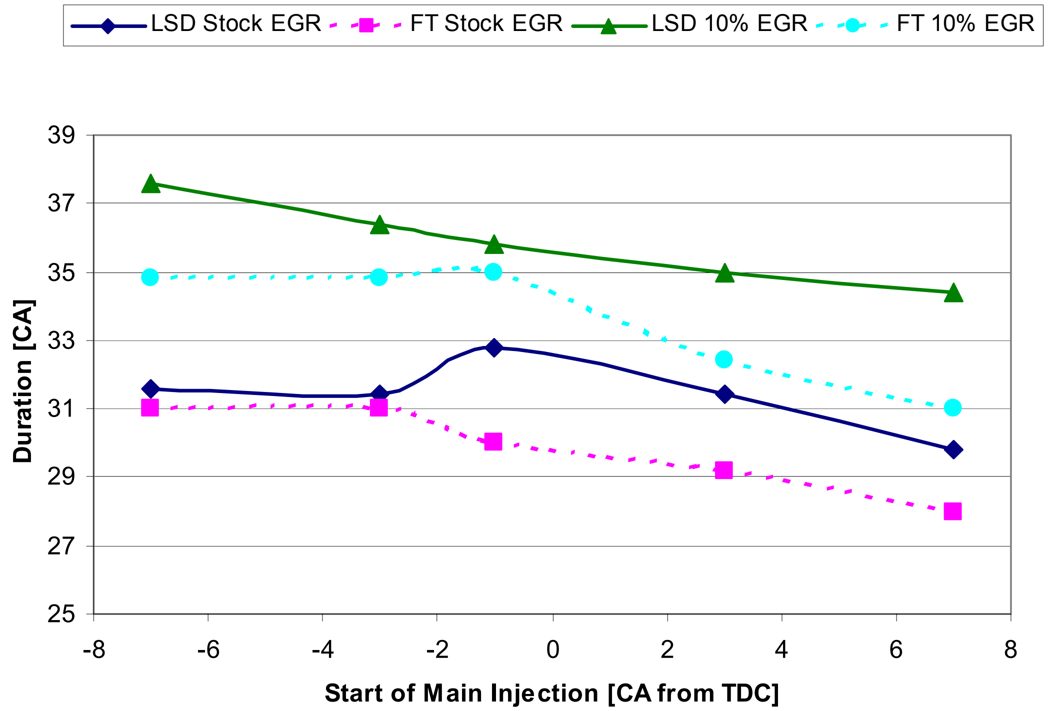


Figure 9.19. 50%-to-90% durations using No.2 diesel fuel and Fischer-Tropsch fuel during timing sweep test with stock EGR rates in low-load tests with stock and elevated EGR rates at 1682 rpm and 480 kPa BMEP. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

Combustion rates must therefore be increasing since the amount of fuel injected into the cylinder to keep the BMEP constant increases as combustion is phased later in the expansion stroke. To increase the chemical reaction rates in diffusion flames, the diffusion-flame-rate characteristics must be improved (laminar burning velocity and/or thermal diffusivity) through changes in ambient conditions, reactant mixture state (equivalence ratio, temperature and pressure), and/or the extent of bulk motion mixing the fuel and oxidizer. For combustion phased towards the expansion stroke, the prevailing cylinder conditions diminish the burning velocity (the effect of the drop in temperature supersedes the effect of the drop in pressure). Thus, either the mixing of fuel and oxidizer is improving or the unburned mixture is reaching a more reactive state as the piston moves away from TDC. These changes in combustion (50-90% burn) rates way into the expansion stroke have important ramification in the observed emission behavior.

9.2.2.4 Combustion Duration Behavior and Fuel Properties

The results in the previous sections show that, at low load, the overall combustion duration is shorter for the FT fuel compared to the low sulfur diesel. First, the SOC-to-10% burn duration takes longer with FT fuel. Next, the 10%-to-50% burn duration was essentially constant for a given fuel and differences between fuels were slight due to physical mixing dominating the combustion rate in the initial inception of the diffusion flame. Therefore, the decrease in overall burn duration due to fuel properties must be related to behavior at the end of combustion (50-90%), which favor a faster burn for FT fuel late in the expansion stroke.

The conceptual model is as follows: In general, as combustion is phased later in the expansion stroke, the temperature of the ambient unburned gas decreases. As fuel is still being injected into the cylinder up until around the point of 50% heat release in both low- and high-load tests, the drop in cylinder temperature affects the auto-ignition chemistry of fuel at the end of injection. As CN increases, the sensitivity on ambient temperature before auto-ignition occurs is lessened. Therefore, especially with combustion phased in the expansion stroke, late-injected fuel of high CN, such as the FT fuel, competing against the motion of the piston that is extracting work and cooling the gases, can still auto-ignite relatively quickly to maintain a reasonable rate of combustion. This is clearly evident in Figure 9.19, which shows that the 3°- and 7°-retard conditions show the largest differences in 50%-to-90% heat release durations, versus timing near TDC.

Comparing the two fuels at high loads, except for the advanced-timing, high-EGR point, the combustion durations were essentially the same, or varied only slightly. The insensitivity of the burn duration to fuel type at a specific condition at high loads is attributed to the increase of the overall cylinder temperature and injection pressure that promote mixing and reduce the time before auto-ignition.

9.3 General Heat Release Trends Between Low Sulfur Diesel and FT Fuel

In order to meet current EPA emission requirements, the test engine uses a high-pressure common-rail fuel injection system, retarded fuel-injection strategies, a cooled EGR system, and a VGT turbocharger. The implementation of the first two aforementioned emission-reducing methods results in heat release characteristics in modern engines that differ substantially from older engines. The lack of an initial, premixed burn peak in newer engines is a function of the small ignition delays and increased injection pressures that reduce the size of the initial fuel-rich mixture that autoignites. Thus, as the majority of the fuel is burned in a diffusion flame, usually one peak persists, although premixed burn peaks are sometimes present depending the degree of injection retard.

At low loads and stock EGR rates, FT fuel exhibited a slightly higher maximum heat release rate, versus the LSD fuel as shown in Figure 9.20. The location of maximum heat release is similar for both fuels, occurring slightly before the point of 50% heat release. The heat release data is consistent with a conceptual model that the FT's higher CN allows for a more rapid autoignition of late-injected fuel at the tail end of combustion, where the unburned gases are cooling from the downward motion of the piston.

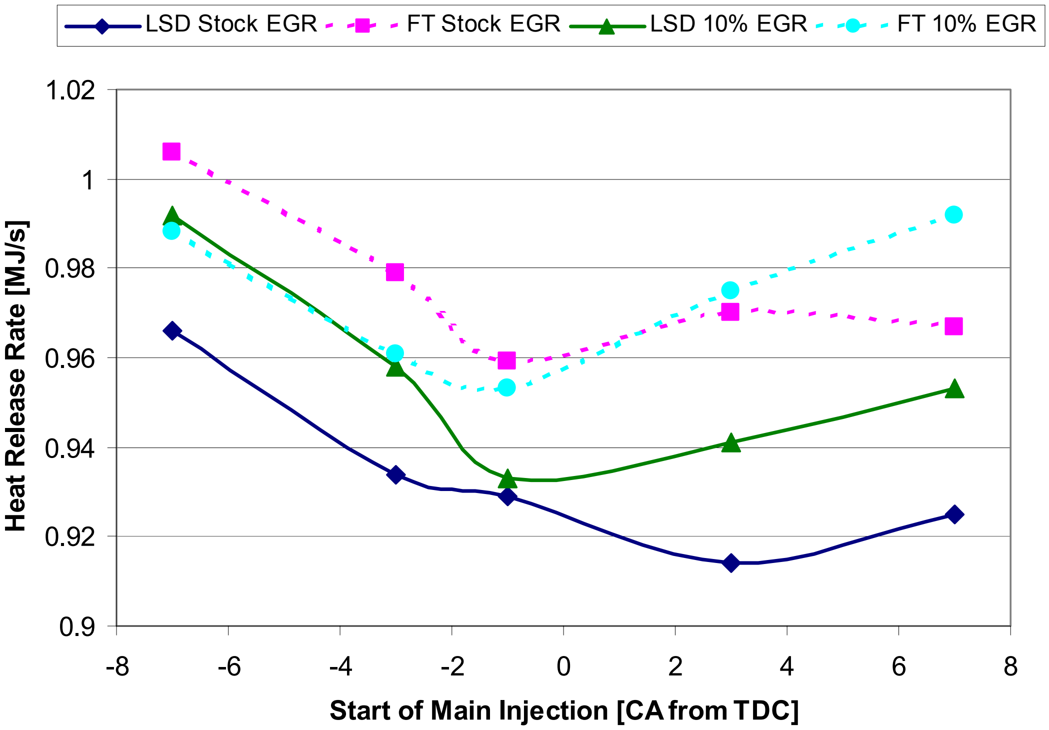


Figure 9.20. Maximum heat release rates for No.2 diesel fuel and Fischer-Tropsch fuel during timing sweep test with stock EGR rates in low-load tests with stock and elevated EGR rates at 1682 rpm and 480 kPa BMEP. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

At low loads with increased EGR rates, the difference in maximum heat release rates is suppressed for more advanced timings. The overall-higher gas temperatures reduce the effect of FT fuel's CNI advantage, closing the gap between the maximum heat release rates. On the other hand, at advanced timings, the FT fuel's CNI advantage affects more strongly the start of combustion. The retarded injection timings show increasingly larger differences between the two fuels in burn rates, again based on the fact the higher CNI rating of FT diesel fuel allows for faster oxidation even as the cylinder contents have cooled due to the late SOC. The slight reduction in the maximum rate of heat release in some timing conditions as EGR is increased is due to the rise in the burned gas fraction that is know to decrease the laminar burning velocity [34]. Since the composition of EGR at low loads still contains a considerable amount of excess air, the oxygen concentration does not drop by much when EGR is increased, only slightly affecting the rate of reactions in the diffusion flame.

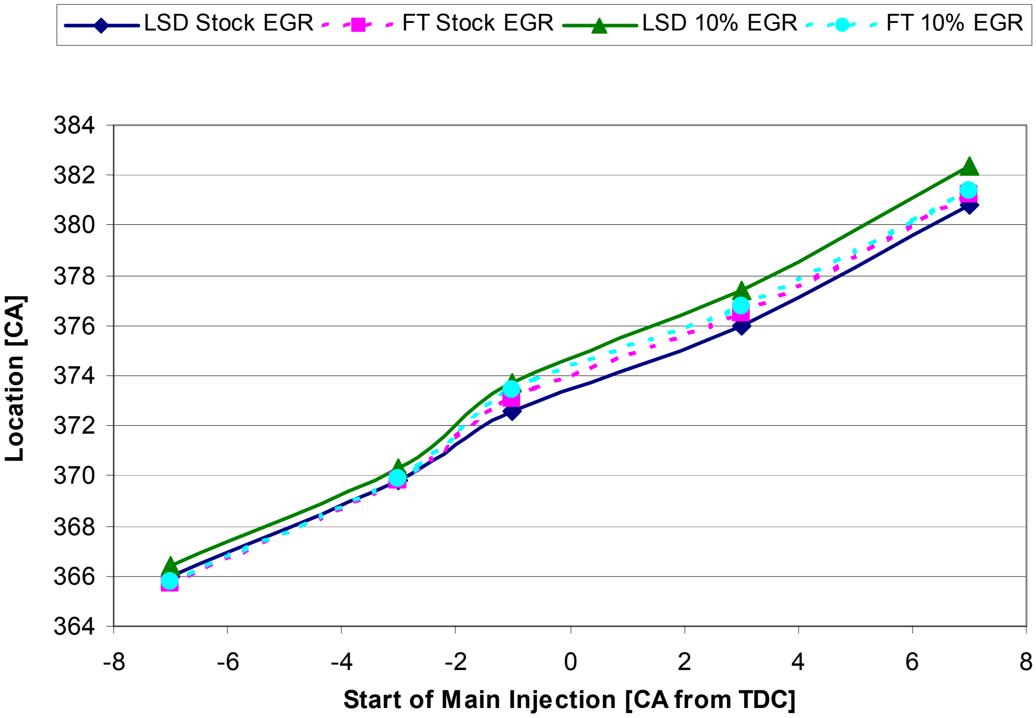


Figure 9.21. Location of maximum heat release for No.2 diesel fuel and Fischer-Tropsch fuel during timing sweep test with stock EGR rates in low-load tests with <u>stock and elevated EGR</u> rates at 1682 rpm and 480 kPa BMEP. Stock timing is in the center with the most advanced timing to the left and the most retarded timing to the right.

In general, the heat release curves for FT diesel show that the heat release rate races to a peak sooner than the low sulfur diesel, due to the reduced ignition delay times with FT fuel at low loads. Also, although the maximum heat release rates for FT fuel are different from the LSD at the low load conditions discussed above, the general shape and characteristics of the heat release curves for each operating condition are essentially the same. These suggest that the oxidation pathways for each fuel are not drastically different [9]. Of note, however, are the most-retarded injection timings at stock and increased EGR rates (Modes L3, FTL3, L13, and FTL13). As combustion in these conditions is phased furthest away from TDC, fuel is injected into increasingly cooler conditions, making autoignition chemistry more important. The low sulfur diesel heat release rate approaches the behavior of the classical heat release shape, at the most retarded timing conditions, as two peaks are clearly evident, supporting the fact that the initial and standing premixed flame are increasingly important due to the low CN number rating of the fuel. Under the same engine conditions with FT fuel, the peak due to the premixed flame is heavily reduced in magnitude, again a function of FT fuel's higher CNI rating.

10.0 Experimental Results and Discussion: Task 3

The major objectives of Task 3 were as follows: to evaluate exhaust aftertreatment systems performance and design tradeoffs available using gas-to-liquid fuels and further optimize the fuel/engine/emission-control system. This chapter presents the results of the investigation into FT fuels and their effects on diesel particulate traps.

10.1 Baseline Emissions

The specific emissions rates for the regulated emissions of interest are shown in Table 10.1. The emissions values presented below were measured prior to installation of the trap and agree very well with previous measurements taken from the same engine using both the FT and low sulfur diesel.

		400 ppm	FT	Percent Difference
PM	[g/hp-hr]	0.157	0.070	-55.43%
NOx	[g/hp-hr]	2.007	1.509	-24.82%
NO	[g/hp-hr]	1.816	1.364	-24.90%
NO2	[g/hp-hr]	0.192	0.146	-24.03%
Nox/PM	[g/hp-hr]	12.752	21.512	68.69%
NO2/Nox	[g/hp-hr]	0.095	0.096	1.05%

Table 10.1. Specific emissions comparison at 1682 rpm and 470 kPa BMEP

The percent difference in the table above is calculated by subtracting the emissions values of the FT fuel from the 400 PPM fuel values. Negative values indicate a decrease in emissions with the FT fuel and positive values indicate an increase. As demonstrated in previous reporting periods, S-2 FT diesel reduces particulate emissions by approximately 50% on average as compared to the 400 PPM sulfur diesel fuel. Although the nearly 25% reduction in NOx emissions with the FT fuel is near the high end of the range, on average S-2 diesel reduced NOx emissions by approximately 12.5% over all of the operating conditions under investigation in [55] and the 1682 rpm, 25% load point yielded a similar reduction in NOx emissions in the previous study as well. Despite the overall reduction in NOx emissions, the ratio of NO_2/NOx remained nearly constant for both of the fuels at approximately 0.095. Of interest is the nearly 50% increase in the NOx/PM ratio with the FT fuel, due to the significant reduction in particulate emissions of the FT [55].

In order to determine more precisely the composition of the particulates entering the trap, a number of particulate samples were sent to an emissions/chemistry laboratory for analysis. The results of the analysis were presented in Section 8.2.5.

In both cases the particulate emissions were sampled before the trap directly from the raw exhaust stream. Furthermore, the particulate samples were collected from the raw exhaust stream using heated sample lines to prevent any water from condensing out of the exhaust stream, as well as to maintain the particulate composition. This was done in order to identify the exact particulate composition entering the trap, rather than diluting and cooling the particulates by using the mini-dilution tunnel. As a result, the soluble organic fraction and sulfates are quite small for both cases, as the hot raw exhaust conditions between the turbo outlet and trap inlet are not conducive to the condensation of various gaseous species onto the PM.

10.2 Trap Performance

The pressure drop trends for each trap loaded with the two different fuels are depicted in Fig. 10.1 and Fig. 10.2. Trap 1 averaged a 13.4% lower pressure drop with the FT fuel as compared to the LSD with the reduction in pressure drop ranging from 8.3% to 26.6%. On the other hand, trap 2 averaged a 30.2% lower pressure drop with the FT fuel, with the reduction in pressure drop ranging from 23% to 39% on average.

Both the trap loading profiles for the FT fuel and low sulfur diesel exhibit a steeper, more rapid, increase in the pressure drop over the trap during the first 1 to 4 hours of trap loading. Following the initial trap loading phase, the pressure drop across the trap increased at a slower rate, however the difference between the pressure drop profiles for each fuel increased significantly over time.

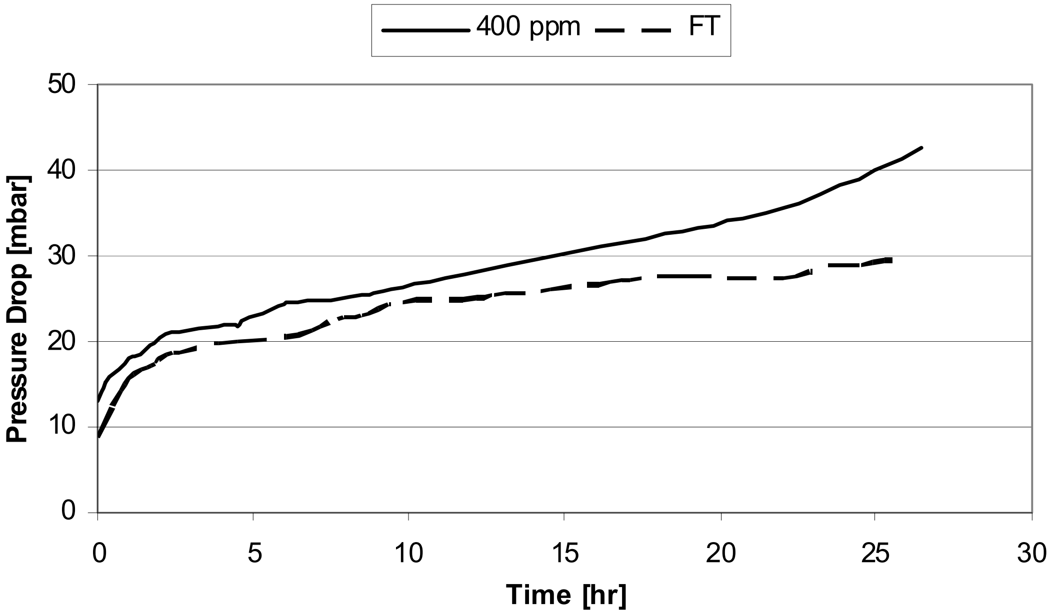


Figure 10.1. Pressure drop trends for trap 1

Following the 25 hour trap loading period, the exhaust backpressure in front of the traps loaded with LSD reached 86 mbar, and the exhaust backpressure in front of the traps loaded with the FT fuel reached 67.5 mbar. The maximum allowable backpressure for EPA certification on the 2002 Cummins ISB 300 is 103.4 mbar (3 in-Hg). The increased backpressure led to a slight but noticeable change in some of the engine control settings, as the ECU attempted to compensate for the increased backpressure.

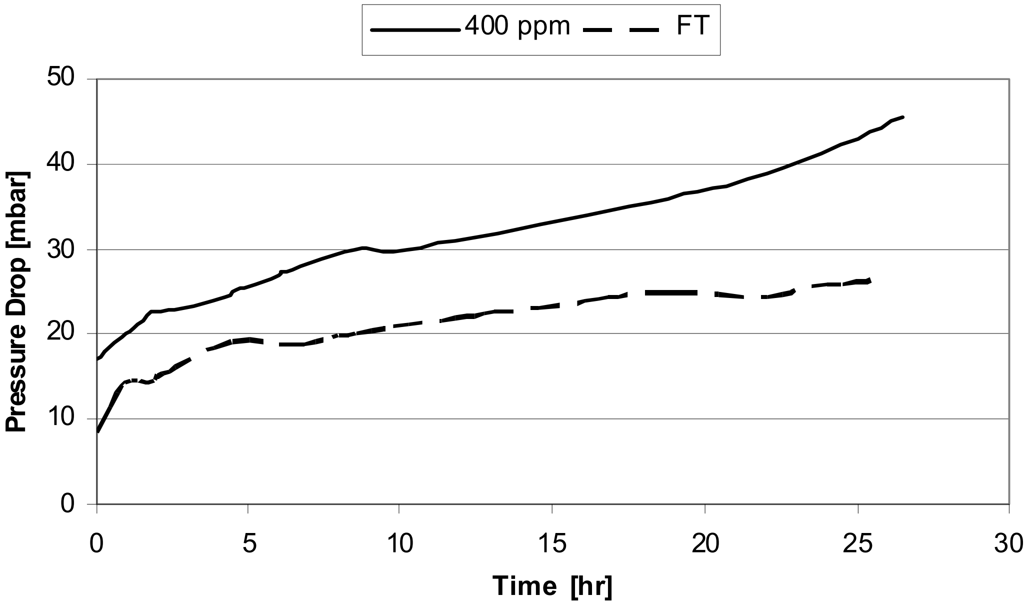


Figure 10.2. Pressure drop trends for trap 2

The pressure drop trends for trap 2, located farthest from the engine, follow the same general trends as those observed in trap 1. However, due to the significantly lower clean pressure drop over the trap in the FT fuel case, the difference in pressure drop between the two traps is greater. Despite the increased difference between the two pressure drop curves for trap 2, the rate of increase in pressure drop for both fuels is very similar to those observed in trap 1. In both cases the traps loaded with the FT fuel reached a maximum pressure drop of 29 mbar and 26 mbar for traps 1 and 2 respectively, an increase over the clean pressure drop by a factor of 2.4. Furthermore, the traps loaded with the LSD reached a maximum pressure drop after 25 hours of 42 mbar and 45 mbar for traps 1 and 2 respectively. This yielded an increase over the clean pressure drop of trap 1 by a factor of 2.8 and an increase over the clean pressure drop of trap 2 by factor of 2.7.

In order to account for variations in clean trap pressure drop, as well as temperature and flow variations in the exhaust system, a dimensionless loading parameter was developed, the results of which are presented in a subsequent section.

In addition to trap pressure characteristics, the temperature of the inlet and outlet exhaust gas streams and temperatures inside the trap were also monitored during the course of this investigation. A detailed list of all the temperatures monitored both inside and outside the trap is presented in Table 10.2.

Location		400 ppm		FT		FT-400 ppm
		Raw Temp	Difference from Inlet	Raw Temp	Difference from Inlet	Percent Difference
Trap 1		[°C]	[°C]	[°C]	[°C]	[%]
	Inlet	275.6	0.0	274.0	0.0	-0.6
	Front Middle 2"	282.1	6.5	275.6	1.6	-2.3
	Front Middle 10"	283.5	7.9	276.5	2.5	-2.5
	Front Bottom 10"	268.0	-7.6	250.6	-23.5	-6.5
	Front Bottom 2"	271.7	-3.9	263.8	-10.2	-2.9
	Back Middle 10"	282.9	7.3	275.8	1.8	-2.5
	Back Middle 6"	284.6	9.0	276.3	2.3	-2.9
	Back Middle 2"	284.3	8.8	276.7	2.6	-2.7
	Outlet	280.9	5.4	273.6	-0.5	-2.6
Trap 2						
	Inlet	285.4	0.0	284.8	0.0	-0.2
	Front Middle 2"	284.1	-1.3	278.4	-6.4	-2.0
	Front Middle 10"	285.6	0.2	279.2	-5.6	-2.2
	Front Bottom 10"	276.4	-9.0	258.3	-26.5	-6.5
	Front Bottom 2"	280.5	-4.8	273.5	-11.2	-2.5
	Back Middle 10"	285.7	0.3	277.9	-6.9	-2.7
	Back Middle 6"	287.5	2.1	279.3	-5.5	-2.8
	Back Middle 2"	286.5	1.2	278.3	-6.5	-2.9
	Outlet	277.2	-8.2	276.4	-8.4	-0.3

Table 10.2. Trap temperatures and corresponding locations

The traps loaded with FT fuel exhibited a 2.5% reduction in inlet and internal trap temperature as compared to the traps loaded with the LSD, and the reduction in internal trap temperatures ranged from a minimum of 0.2% to a maximum of 6.5%.

In the case of the low sulfur diesel, trap temperatures measured inside trap 1 exhibited a slight increase inside the trap, with a maximum increase of approximately 9.0 °C above the trap inlet temperature measured inside the middle of the trap and an increase of 5.5 °C over the inlet temperature measured at the trap outlet. The temperature differences measured for trap 2 with the LSD were not nearly as significant. Furthermore, neither trap 1 nor trap 2 exhibited any significant increase in trap temperature when loaded with the FT fuel. As could be expected, temperatures measured inside the middle of the traps were warmest, with temperatures either at or slightly above the inlet gas temperature; however temperatures measured near the outside edge and back of the trap were up to 26.5 °C cooler for the FT case.

Trap inlet temperatures remained fairly constant over the entire test duration, and were measured at 275 °C for trap 1 and 285 °C for trap 2 when loaded with LSD. Trap inlet temperatures for the traps loaded with FT fuel averaged 1 to 2 °C cooler. The nearly 10 °C temperature difference between the two traps is most likely due to a slight variation in exhaust flow between the two branches of the exhaust system.

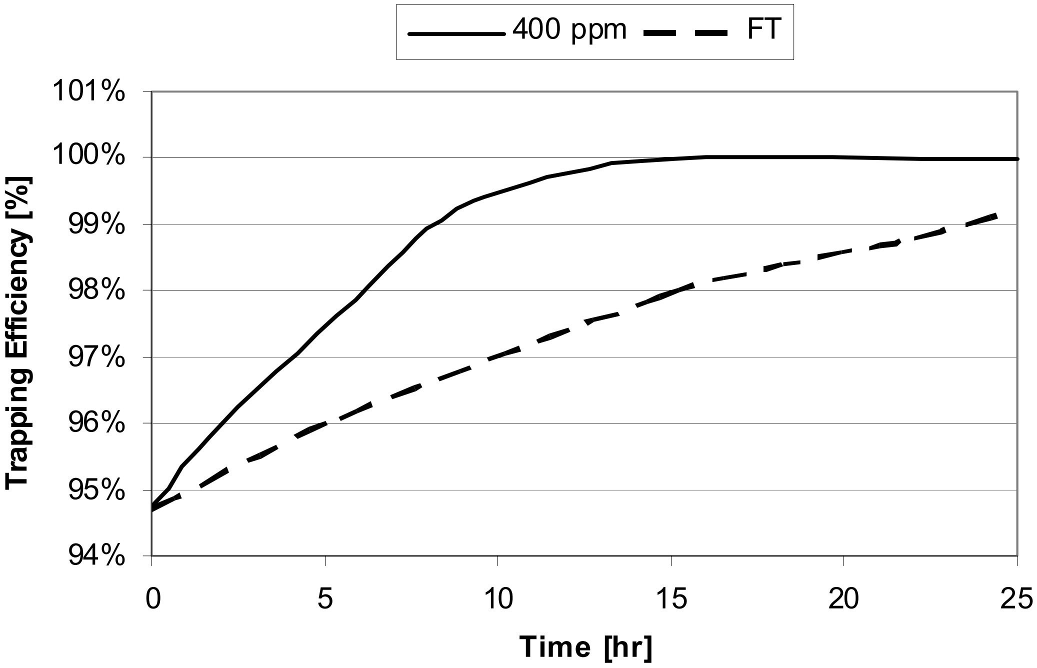


Figure 10.3. Trapping efficiency comparison

Figure 10.3 presents the trapping efficiencies measured over the duration of the test. The trapping efficiency was determined by comparing the amount of particulates collected downstream of the trap with those collected upstream of the trap. The pre- and post-trap PM emissions were sampled simultaneously to eliminate any variability in PM emissions due to engine operating conditions or changes in exhaust pressure and flow. The trapping efficiency is defined as follows:

Equation 10.1

$$\text{Trapping Efficiency} = \frac{[\text{PM no trap}] - [\text{PM with trap}]}{[\text{PM no trap}]}$$

where all PM emissions are normalized with brake specific units to facilitate direct comparison [56].

The increase in trapping efficiency as the traps were loaded is to be expected, as increased soot loading enhances the ability of cellular ceramic Cordierite substrates to trap and retain soot. Furthermore, the rate of increase in trapping efficiency is significantly lower for the traps loaded with the FT fuel, although the trapping efficiency of the traps loaded with FT fuel did approach the same trapping efficiency of the LSD loaded traps near the end of the test period. In both cases the final trapping efficiencies were in excess of 99.0%.

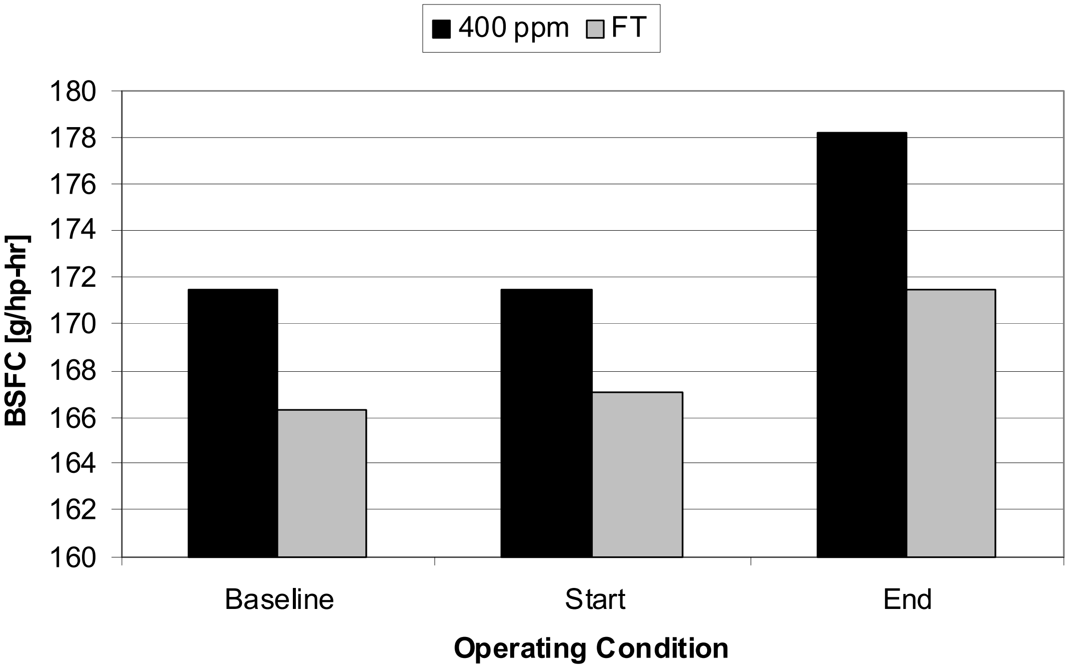


Figure 10.4. Fuel consumption comparison

Figure 10.4 presents the measured fuel consumption rates (normalized to the heating value of the No. 2 diesel) for three different cases: the baseline case with no trap installed, the fuel consumption at the beginning of the trap loading tests, and the fuel consumption at the end of the tests. The fuel consumption for the FT case is lower for the baseline case and both trap loading conditions. This is due to the slightly higher heating value of the FT fuel (on a mass basis). However, due to the FT fuel's significantly lower density, it heating value on a volumetric basis is lower than that of the low sulfur diesel fuel, resulting in less energy injected into the cylinder for the same volume of fuel consumed. Thus, fuel consumption on a volumetric basis is higher with the FT fuel. Despite this fact, the large reduction in Pm emissions and corresponding lower increase in trap pressure drop with the FT fuel results in a lower rate of increase in fuel consumption for the FT fuel as compared to the LSD over the duration of the tests.

10.3 Trap Emissions

Aside from particulates, gaseous emissions of NOx, NO, CO_2, CO, O_2, HC, and SO_2 were also measured before and after the traps. In all cases the general trends observed during the baseline tests were also observed with the trap installed, although some emissions did vary across the trap as well. The NOx and NO_2 emissions trends are presented in Figures 10.5 and 10.6.

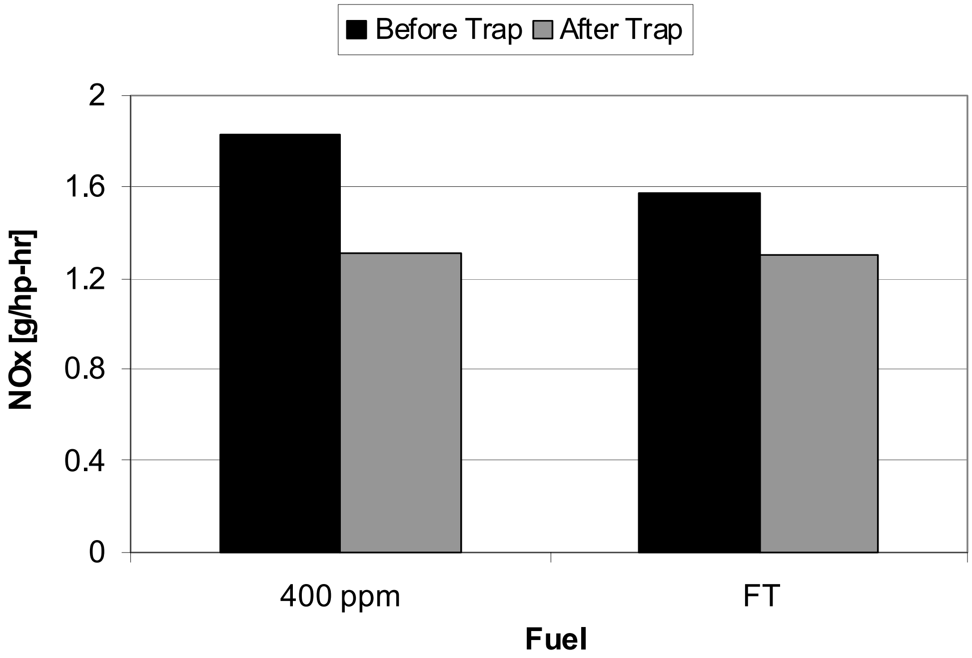


Figure 10.5. Comparison of specific NOx emissions before and after the trap

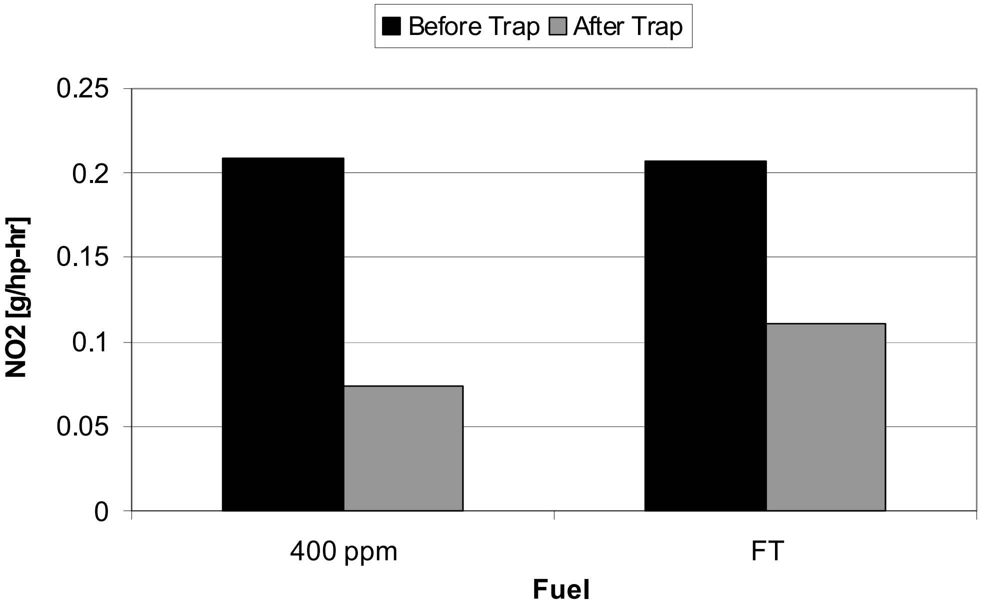


Figure 10.6. Comparison of specific NO_2 emissions before and after the trap

The NO_2 emissions were computed from the difference between the measured NOx and NO emissions. In all of the cases, both NOx and NO_2 levels were observed to decrease across the trap. As slow soot oxidation via NO_2 can occur at temperatures above 200 °C, the drop in NO_2 levels across the trap is most likely due to this effect. Although both fuels exhibit nearly the same NO_2 levels entering the traps, the NO_2 levels were observed to decrease by approximately 75% over the traps loaded with the LSD, compared to a drop in NO_2 levels of only 50% over the traps loaded with FT fuel.

Consistent with a slow rate of soot oxidation via NO_2, CO_2 and CO emission were also observed to increase slightly over the traps as well. The CO_2 and CO emissions trends are presented in Fig. 10.7 and Fig. 10.8. Once again, the increase in CO_2 and CO emissions across the trap is slightly greater for the traps loaded with LSD than FT fuel.

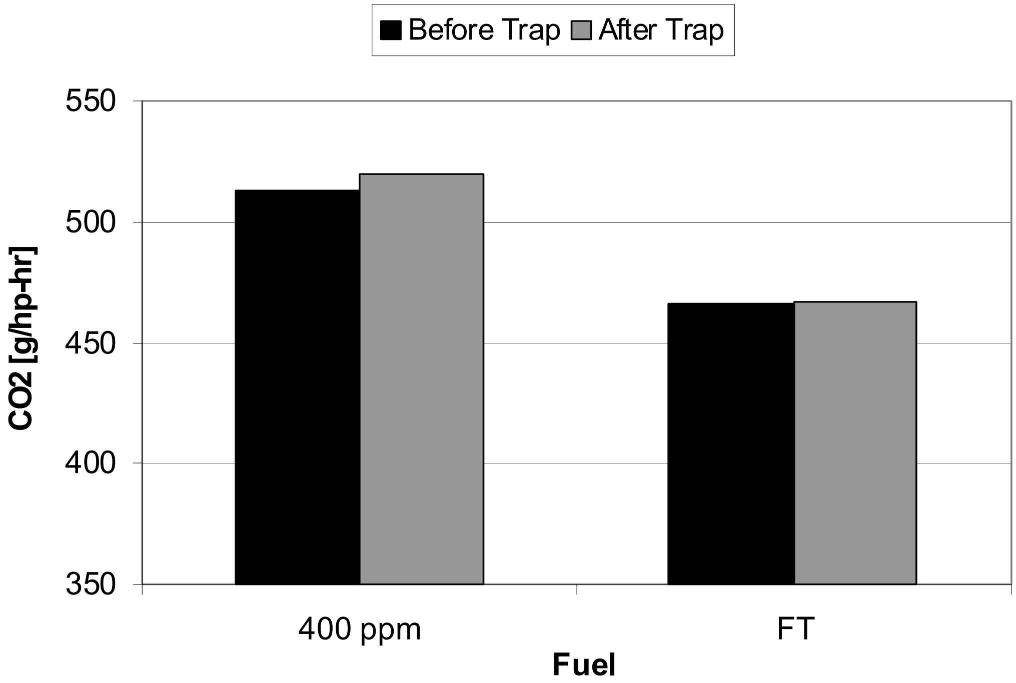


Figure 10.7. Comparison of specific CO_2 emissions before and after the trap

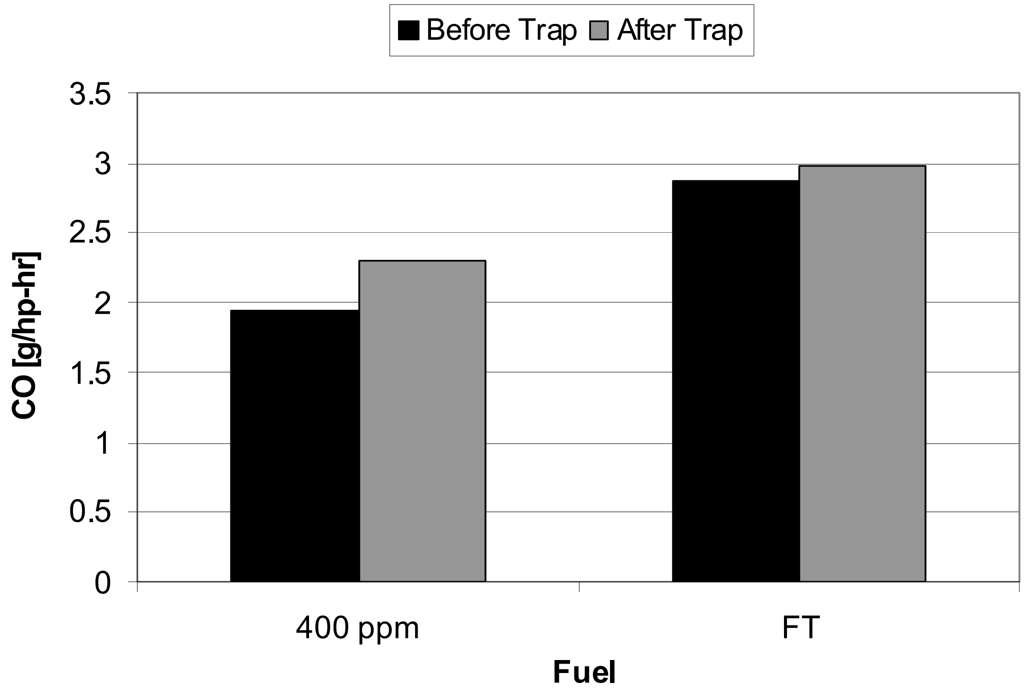


Figure 10.8. Comparison of specific CO emissions before and after the trap

No significant changes in the oxygen level were observed before or after the trap in either case. For both the FT fuel and LSD, the oxygen content in the exhaust remained fairly constant between 12.0% and 13.0%. Due to the low trap loading temperatures, 280 °C, soot oxidation via O_2 is highly unlikely as temperatures in excess of 500°C are required.

Hydrocarbon emissions trends before and after the trap are shown in Figure 10.9. A slight decrease in overall HC emissions across the trap is observed. Due to the extremely low level of HC emissions for both fuels, near the lower limit of the analyzer, further detailed investigation is warranted to explain the drop in HC emissions across the trap. However, it is possible that a small portion of the hydrocarbons may be condensing on the soot within the trap.

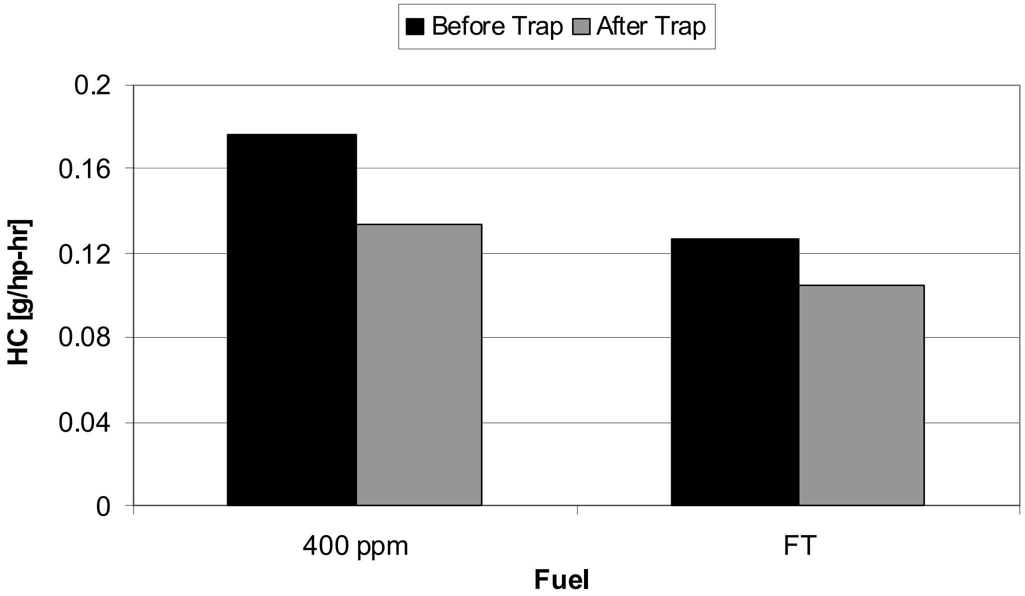


Figure 10.9. Comparison of specific HC emissions before and after the trap

SO_2 emissions in the exhaust stream were measured for both fuels as well. The SO_2 emissions for the LSD are significantly higher than those of the FT fuel, due to the significantly higher sulfur content (400 PPM) of the LSD. Furthermore, the SO_2 levels measured when the traps were loaded with the FT fuel are due entirely to the sulfur present in the lubricating oil, as the FT fuel contains zero sulfur. Figure 10.10 presents the SO_2 emissions trends before and after the trap.

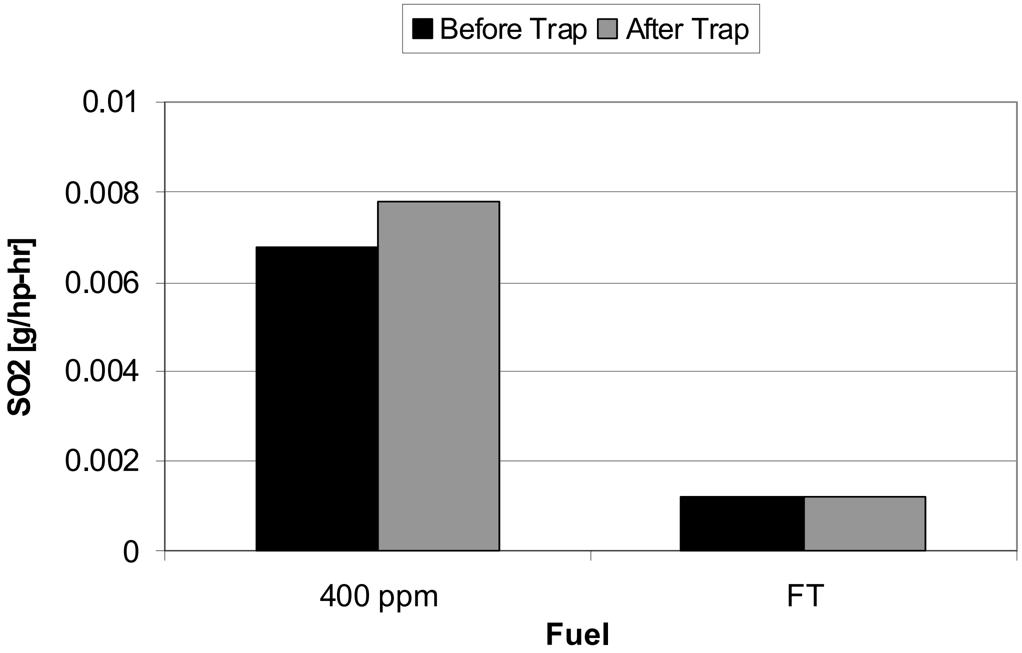


Figure 10.10. Comparison of specific SO_2 emissions before and after the trap

10.4 Estimated Parameters

While all of the DPT loading with both fuels was carried out at the same steady state engine operating condition to minimize any variation between the tests, exhaust flow conditions are affected by changes in backpressure. Furthermore, viscosity and density effects are also influenced by temperature variations. In addition, not all traps exhibited the same clean pressure drop. As pressure drop is a function of exhaust flow, PM accumulation in the trap, and trap geometry a dimensionless parameter was utilized to account for any slight variations in temperature and flow. The dimensionless loading parameter, M, is defined as follows:

Equation 10.2

$$M = \frac{(\Delta P)\ \text{loaded}}{(\Delta P)\ \text{clean}}$$

This parameter, therefore, indicates trap conditions independent of flow and is equal to unity for a clean trap and greater than 1 for a loaded trap. A detailed description of this dimensionless parameter can be found in [56].

In addition to the loading parameter, the amount of particulates accumulated in the trap was estimated as well. The net accumulation rate was determined from a mass balance as follows:

Equation 10.3

$$\dot{m} = \dot{m}_{in} - \dot{m}_{out} - \dot{m}_{oxd}$$

$\dot{m}_{in}$ = PM flow rate into trap

$\dot{m}_{out}$ = PM flow rate out of trap

$\dot{m}_{oxd}$ = PM oxidation rate in trap

Equation 10.3 was then integrated over time to estimate the total amount of particulates accumulated within the trap [56]. The PM flow rate into and out of the trap was measured directly at periodic intervals throughout the course of the investigation. The rate of soot oxidation within the trap was estimated from the rate of NO_2 reduction across the trap, since each NO_2 molecule can only react with one carbon molecule in the soot [57]. As the trap inlet temperature remained fairly constant between 275°C and 285°C, it was assumed that the decrease in NO_2 concentration across the trap and the observed increase in CO concentration after the trap was due to oxidation with the carbon in the soot according to the following chemical reaction:

Equation 10.4 $$C + NO_2 \rightarrow CO + NO.$$

While the amount of NO_2 in the exhaust is small, and the exhaust temperatures still fairly low, slow soot oxidation under these conditions these conditions has been observed in a number of studies [57, 58].

Figure 10.11 presents the estimated particulate accumulation within the trap based on the calculations presented above.

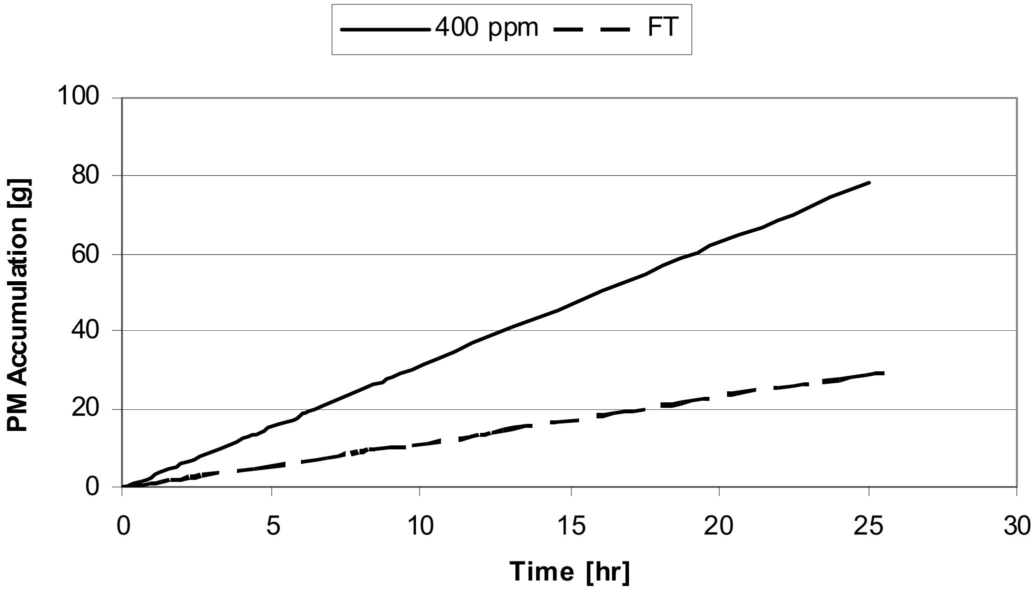


Figure 10.11. Estimated particulate accumulation

Since all of the traps were loaded at one single steady state engine operating condition, the rate of soot accumulation remained fairly constant over the duration of the tests. Furthermore, the estimated FT soot accumulation in the trap was significantly less than the LSD generated soot, due to the lower PM emissions of the FT fuel, and differences in the estimated oxidation rates of the particulates generated from both of the fuels. On average, the estimated oxidation rate for FT particulates was approximately 30% lower than that of the LSD particulates.

In order eliminate the dependence of the pressure drop on the actual physical dimensions of the trap, the dimensionless loading parameter, M, was plotted against the percentage of void volume in the channels and substrate available for particulate deposition.

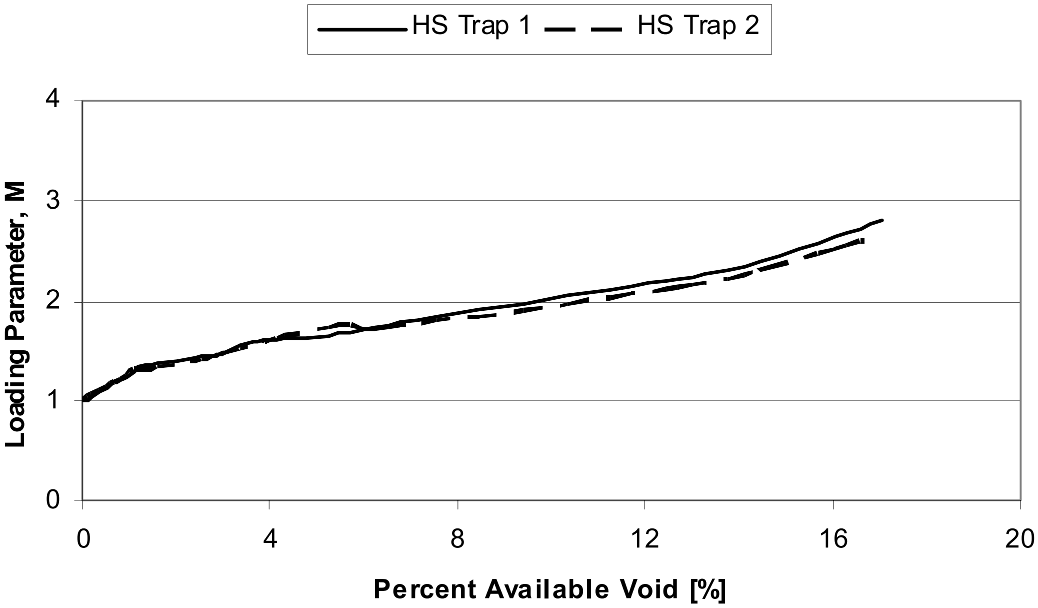


Figure 10.12. Comparison of loading parameter with percent available void for low sulfur diesel

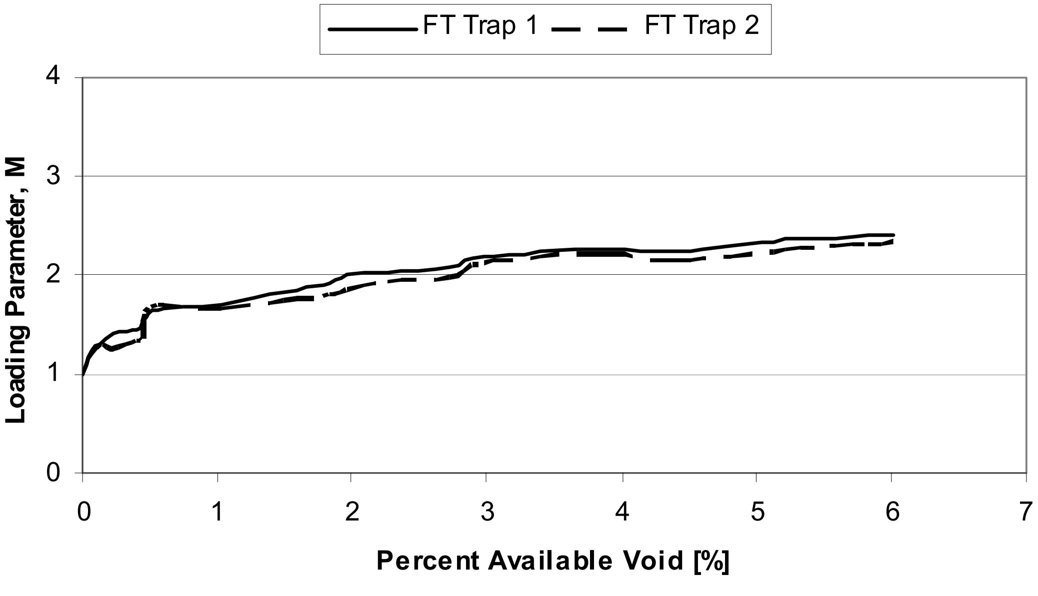


Figure 10.13. Comparison of loading parameter with percent available void for FT diesel

Figure 10.12 and Figure 10.13 depict the loading parameter plotted against the percentage of available void for each fuel. The percentage of available void was calculated given the ceramic substrate's known porosity of 48% and assuming a particulate density of 0.056 g/cm^3 [59]. At the end of the 25 hour loading period, the FT particulates were estimated to occupy only 6% of the available void within the trap while the LSD particulates occupied approximately 16% of the available void. As a result, the loading parameter for the traps loaded with LSD is also significantly higher as compared to the traps loaded with FT fuel.

Based on the differences in the loading parameter for the two cases, a reduction in pressure drop of 14.5% on average was observed for the traps loaded with FT particulates.

10.5 Discussion of Aftertreatment System Effects

The observed differences in diesel particulate trap performance characteristics between the traps loaded with Fischer-Tropsch and low sulfur diesel can be explained by the differences in the fuel properties and emissions trends. The reduced trap pressure drop observed in the traps loaded with FT fuel is primarily due to the significantly lower PM emission levels of the Fischer-Tropsch diesel. However, the reduction in pressure drop observed in the traps loaded with FT particulates, 14% to 15% on average, is not as great as would be expected given the 50% reduction in engine out PM emissions of the FT fuel.

The slower rate of particulate accumulation in the traps loaded with the FT fuel is primarily responsible for the slower rate of increase in trapping efficiency for these traps as well, since the trapping efficiency of cellular ceramic traps increases with trap loading level. Despite this fact, final trapping efficiencies at the end of the 25 hour trap loading period were in excess of 99% for both cases.

The accelerated rate of trap loading in the case of the low sulfur diesel resulted in a greater increase in fuel consumption for the LSD over the duration of the tests, as compared to the FT fuel. The slightly lower heating value (volumetric basis) of the FT diesel resulted in a small increase in the fuel consumption rate for the FT fuel. However, the higher backpressure that resulted from the increased trap loading levels with the LSD may lead to an interesting trade-off at elevated trap loading levels, where the increase in backpressure and fuel consumption for the LSD loaded traps would offset any fuel consumption differences at these conditions. Therefore, the small fuel consumption penalty incurred with the FT fuel due to its slightly lower heating value may be offset by the greater increase in fuel consumption with the LSD at elevated trap loading levels.

Aside from the large difference in the PM emissions of the two fuels, the decline in NO_2 levels across the traps and corresponding increase in CO and CO_2 emissions was much greater for the LSD loaded traps than for the traps loaded with FT diesel. Furthermore, the traps loaded with the low sulfur diesel exhibited slightly higher inlet and internal temperatures, on the order of 2.5% greater, when compared to the FT cases. The difference in NO_2 levels across the traps and trap temperature profiles for each fuel suggest that some slow soot oxidation via NO_2 is taking place. Based on differences in the measured NO_2, CO, and CO_2 concentrations in the exhaust stream before and after the traps, oxidation rates for the soot generated by each fuel were estimated. The oxidation rate for the PM generated by the FT fuel was estimated to be approximately 30% lower than that of the PM generated by the LSD. These differences in oxidation rates also contribute to the observed differences in trapping efficiencies and pressure drop profiles.

The slower oxidation rate of the FT particulates may, therefore, partially explain the smaller than expected difference in the pressure drop profiles between the two fuels. Due to the similar composition of the raw FT and LSD particulates (primarily carbonaceous matter) and the similar exhaust conditions under which both traps were loaded, further investigation into the actual oxidation rates is warranted.

Additionally, other studies have noted the fact that the manner in which the soot is distributed within the trap may contribute significantly to the pressure drop characteristics measured over the DPT [57]. Potential differences in the manner in which the FT particulates are distributed within the trap may provide additional insight into the differences between the pressure drop profiles as well.

Aside from the fuel effects on the DPT performance characteristics, the increase in exhaust backpressure as the traps were loaded resulted in some slight but noticeable changes and interactions with the engine's electronic control system. Since no modifications to the stock ISB 300 factory calibrations were made, the increased backpressure created by the traps increased the flow of exhaust through the engine's EGR system. As a result, the ECU attempted to compensate by varying VGT and EGR valve position, and the time needed for the engine to settle in to steady state operation upon initial start-up increased as well.

11.0 CONCLUSIONS

An investigation into the relationship between fuel properties, combustion characteristics, and exhaust emissions was carried out using a pre-production 2002 Cummins ISB 300 direct injection turbo-diesel engine. Current results confirm the results presented in previous reporting periods that the Fischer-Tropsch (FT) gas-to-liquid diesel fuel from the Syntroleum small footprint plant performs better and with lower emissions than regular diesel fuel in a modern (MY 2002) direct injection diesel engine. Further improvements in performance and emissions can be realized by configuring the engine to take advantage of FT diesel fuel's properties, and the addition of exhaust aftertreatment systems. A small fraction of FT fuel blended with regular No. 2 diesel (low sulfur and ultra-low sulfur diesel) can offer significant PM emission reductions more than shown by its proportion in the blended fuel. Furthermore, the FT diesel significantly extended the trapping period and reduced the regeneration frequency of an un-catalyzed cordierite diesel particulate trap as compared to the baseline low sulfur diesel.

The modern engine technology and related subsystems employed by the Cummins ISB has a profound effect on the manner in which the fuel properties affect engine out emissions. The cetane number (CN) of a fuel is commonly believed to control NO_x output by dictating the amount of fuel that auto-ignites in the initial premixed burn fraction. However, the modern engine tested is designed to have small premixed burn fractions, such as those with high injection pressures to promote good mixing along with late injection in hot cylinder conditions around TDC. Thus, NOx emissions are less sensitive to the value of a fuel's CN. On the other hand, combustion data show that the FT fuel burns faster during the latter part of combustion, in back-to-back comparisons with No. 2 diesel. This helps to oxidize particulates, and when combined with retarded injection timing past TDC provides an optimal combination of both NOx and particulate reduction. Furthermore the multiple injection strategy, employed in the Cummins ISB, also has a significant effect on the in-cylinder combustion process and plays a significant role in reducing NOx and PM emissions.

The additional tests performed since the last report investigated the relationship between fuel properties, emissions, and diesel particulate trap performance characteristics. Uncoated Cordierite ceramic substrates were loaded using Fischer-Tropsch and a conventional 400 PPM sulfur diesel fuel for 25 hours each. Pre- and post-trap emissions, temperature, pressure drop, and trapping efficiency were measured under steady-state engine operation. Furthermore, a detailed analysis of the particulates was carried out to provide further insight into the differences in the trap loading and performance characteristics. The data collected over the duration of this study leads to the following updated conclusions:

<u>Task 1:</u> Fuel Effects on Combustion and Emissions

- For a modern MY '02 heavy-duty diesel engine, FT fuel reduces particulate emissions substantially, mostly in the range of 25-50% for a variety of steady-state conditions tested. Under light load, low speed conditions typical of urban driving, particulate reductions can reach up to 75%.

- A blend of 25% (by volume) FT fuel with 75% 400 PPM sulfur fuel showed that the 25% FT fuel in the blend produced about half of the particulate reduction of using neat FT fuel alone.

- Significant non-sulfur effects are responsible for the large reductions in PM emissions observed for the FT fuel and blends. The results of the PM analysis carried out at the emissions-chemistry laboratory of a major engine manufacturer confirmed these findings, and demonstrated reductions in the range of 40% to 60% in SOL and SOF for the blend when compared to the reductions observed for the neat FT fuel alone.

- For the same modern engine, FT diesel fuel reduces NOx emissions consistently from 6-20% versus No. 2 diesel fuel. The more recent results are consistent with previous results of 6-13% reduction and with overall results reported in the literature. FT fuel's higher cetane number and a shorter ignition delay allow fuel injection to be further retarded for NOx control.

- The reduction in NOx emissions for the FT fuel and blend was directly correlated to the measured reduction in exhaust temperatures and shorter diffusion burn. This data confirms that a temperature sensitive extended Zeldovich type mechanism is primarily responsible for NOx formation in the power cylinder [55].

- While emissions of hydrocarbons were low, and typically within acceptable limits, the significantly higher rate of HC emissions from the ultra-low sulfur diesel fuel is most likely due to the fuel's higher volatility and significantly different distillation curve. These two factors may also be responsible for the relatively higher sulfur to sulfate conversion rate observed for the ULSD [55].

- The increased cetane number of the FT and blend decreased the ignition delay compared to the baseline fuel. The shorter ignition delay and lower density of the FT fuel and blend contributed to a significant reduction in the maximum heat release of the pilot injection, thus reducing initial particulate formation [55].

- FT fuel burns faster during the latter part of combustion, especially when combustion occurs predominantly during the expansion stroke. The faster 50% to 90% burn duration of the FT fuel may lead to additional particulate oxidation [55]. Therefore, late injection timing retard at or after TDC can be employed for large NOx reduction in modern engines.

<u>Task 2:</u> Interaction of Fuel Effects and Influence of Engine Parameters on Emissions

- For a modern MY 02 heavy-duty diesel engine, steady-state results indicate that FT fuel reduces particulate emission substantially (50-75%) over the entire timing and EGR sweep compared to the baseline low sulfur diesel fuel (400 PPM sulfur). Favorable combustion effects for the FT fuel for late injection timings also contributed significant particulate reduction.

- From examining exhaust mole fractions of water, CO, and CO_2, the higher H/C ratio of FT fuel appeared to have a small but perceptible effect on products of combustion that may make it more difficult to produce NOx.

- Conventional diesel fuel normally produces more particulate matter as EGR increases. FT fuel removes the sensitive dependence of PM production on EGR rate, allowing significant NOx reductions through the use of higher EGR rates before PM levels become substantially large.

- Injection timing has no adverse effects on emissions with FT fuel. FT diesel fuel follows the same trends as the petroleum-based No. 2 diesel fuel used in the experiments. As timing is advanced, both fuels show increases in NOx while timing retard results in NOx reductions, showing both fuels have the same NOx production mechanisms. With PM, both fuels show reductions in emissions as timing is changed from the stock timing point.

- Increases in PM output from increased EGR rates can be controlled by aftertreatment systems without concern of system performance deterioration from fuel sulfur, as FT diesel fuel is virtually sulfur free.

- In addition, as established elsewhere but not within the current scope of this work, sulfur-free fuel does not poison catalysts in NOx aftertreatment systems with sulfur originating from the fuel. Sulfur in the lubricant presents a different problem.

Task 3: Fuel Effects on Particulate Aftertreatment Systems

- The diesel particulate traps loaded using FT diesel exhibited a slower rate of increase in pressure drop and a reduction in trap pressure drop of 14.5% on average [60].

- The reduced pressure drop for the traps loaded using FT fuel is primarily due to the significant reduction in PM emissions of the FT diesel [60].

- The slower initial increase in trapping efficiency of the FT fuel is due to the slower rate of PM accumulation in the trap [60].

- The differences in trap temperature profiles, NO_2, CO, and CO_2 emissions all suggest that some slow soot oxidation via NO_2 is occurring [60].

- FT particulates may oxidize at a slower rate in the presence of NO_2 as compared to particulates generated from conventional diesel fuel [60].

- The slower rate of FT particulate oxidation may contribute to the smaller than expected difference between the pressure drop profiles for the two fuels [60].

- FT fuels may present a slight fuel economy advantage at elevated trap loading levels [60].

- Fisher-Tropsch fuels extend the trapping period and reduce regeneration frequency due to their lower PM emission rates [60].

- The use of zero sulfur FT fuels may also allow the use of more aggressive exhaust after-treatment systems [60].

Additional investigation into the after-treatment system/engine calibration and control system interactions and FT particulate oxidation rate may help to further explain the observed DPT performance characteristics. Research in this area is ongoing and current work investigating the effects of FT fuels on catalyzed traps is expected to provide further insight into the potential benefits of FT fuels and their interactions with diesel particulate trap systems.

In summary, FT fuel gives greater freedom to engine designers when trying to optimize the engine/emission-control/fuel system in modern engines, by providing the fuel properties as another flexible set of variables that affect the combustion and emission processes. Furthermore, the zero sulfur nature of the FT fuel allows for the use of additional and more aggressive exhaust aftertreatment devices, previously impossible due to the deleterious effects of fuel sulfur on the catalyst.

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Supporting Economic Analysis for US DOE-Sponsored ICRC Clean Fuels Program

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ABSTRACT

TIAX assisted the ICRC team to assess the impact of the introduction of ultraclean fuels produced by small footprint Gas-to-Liquid (GTL) facilities on fuel costs, air emissions and energy efficiency. The Gas-to-Liquid process converts synthesis gas (carbon monoxide and hydrogen) to liquid fuels through Fischer-Tropsch catalysis that produces a range of liquid hydrocarbons plus water, heat and, optionally, electricity (turbine-driven generator). Here, the term "small footprint" means a facility that produces less than 10,000 barrels per day of liquid fuels. The goal of this study was to determine the feasibility of employing such plants for fueling the local needs of, for example, remote villages or mining operations, using locally available feedstocks.

We identified stranded natural gas and biomass as potentially viable feedstocks for the production of GTL fuels from small footprint plants. Both exist in sufficient quantities but in small enough streams to warrant the construction of small footprint plants. For natural gas, when the plants produce power as well as fuel, we found conditions under which the internal rate of return for plants with a 20 year lifetime ranged as high as 9% to 146%, depending on plant size and the cost of feedstock and the price at which the products could be sold. For biomass, which requires a significantly larger capital investment than does natural gas, we could not identify conditions that led to positive returns, implying that this type of plant would need subsidies to make it viable. Other resources, coal, shale oil and coal bed methane, either were available in reservoirs large enough to support large facilities that are more cost effective when run at scale or they were too far from markets to offer the benefits of local supply.

To estimate the economics of fuel production with small footprint plants we considered scenarios that included wide ranges for future prices for the principal products of GTL, fuel ($24-$55 per barrel) and electricity ($0.03 to $0.11 per kWh). At the low end, which corresponds roughly to consensus projections prior to the end of 2005, a small footprint plant constructed using conventional unit operations appears to be unprofitable in the absence of subsidies that might accompany the production of the ultraclean fuel. However, a hypothetical plant that employs a novel, modular, packaging of the production technologies appears to offer significant economic benefits, particularly at production capacities less than 1000 barrels per day. At the high end, which corresponds roughly to consensus projections that take into account the recent increases in petroleum costs, we estimate profitably, overlapping economics for both a conventional plant and the hypothetical, modular plant.

To compare the emissions and fuel economy for vehicles fueled with Fischer-Tropsch diesel and conventional diesel we constructed well-to-wheels analyses that included the effects of fuel generation, transportation and use. The benefit of GTL fuels with respect to criteria pollutants, NOx, CO and PM, is complicated by the mandated introduction of very clean diesel engines nearly simultaneously with the earliest practical introduction of small footprint plants. Thus, in our analysis the benefits of GTL fuels were applied only to the older fraction of the vehicle fleet and can therefore be expected to diminish as those vehicles are taken out of service. We understood but did not attempt to quantify other, potential advantages of GTL fuels. For example, with sophisticated engine control systems, it is likely that approaches can be found, if they are sought, to take advantage of a fuel with inherently less tendency to produce emissions. In that case, or if the improvements presaged by EPA regulations are not fully realized, additional benefits would accrue from the availability of a very clean fuel.

Even under the conservative assumptions we made, significant savings in NOx and PM—15% and 35%, respectively—were projected for two heavier vehicle classes, buses and utility trucks, if fueled with GTL fuels since in 2015 (the year that we envisage small footprint plants being commercialized) almost 80% of those fleets will consist of vehicles purchased prior to 2010. Because there are so few light duty diesel vehicles in the current fleet, the benefits of using GTL-derived fuels are projected to be very small in this category (<5% decreases in criteria pollutants) since the future fleet will consist primarily of modern, low emission vehicles at the start of the study period. Since the GTL process consumes a much larger portion of the feedstock for just the operation of the plant than does a conventional refinery (60% in our model versus about 20% for a refinery), there is a significantly larger CO_2 burden for using GTL compared to that of using petroleum-derived diesel

fuel. However, biomass-derived GTL fuels can, in principle, exhibit net zero CO_2 emissions, leading to as much as 75% reductions in CO_2 from the projected fleet.

In addition to potential emissions benefits, the production of GTL fuels offers the promise of energy security associated with using non-conventional, domestically based resources. Such considerations are now fostering the development of large scale GTL plants that might supply a significant fraction of the US fuel demand. Moreover, the GTL process produces its carbon dioxide in fairly rich streams that therefore facilitate CO_2 sequestration or carbon recycling schemes. We explicitly considered the value of the energy security afforded by small footprint plants in our calculations that took into account the cost of alternative sources of energy in remote regions. We did not consider the possibility of CO_2 sequestration for the small footprint plants because the confluence of a remote market, an adjacent source of feedstock and an adjacent CO_2 sink seemed improbable.

In a second task of this study we applied these same methods to the feedstocks, conditions and opportunities that pertain in Alaska. Three sizes of plants were investigated: 600 and 6000 barrels per day, corresponding to feedstock availability for small and medium sized plants, and a 19,000 barrel per day facility, such as might be constructed to use coastal reservoirs of natural gas known to exist in the Kenai Peninsula. Because we assumed that the small footprint plants to be constructed in remote areas would be mostly prefabricated and would be operated by a small staff our estimates were only modestly higher for the remote plants for both the capital costs of the plants (2-10%) and the operating costs (1-7%), depending on plant size. The higher price of conventional fuel in Alaska therefore contributed significantly to the economic performance of GTL plants at all size ranges: the economic value, estimated as internal rate of return, could be greater than 100% for natural gas-fueled plants, providing that markets could be found at the higher prices for all of the products (naphtha, GTL fuel and electricity). We note, however, that even the smallest sized plant would supply fleets as large as 10,000 light duty vehicles or 800-900 heavy duty vehicles, which is a larger range than would likely be found in remote communities. Therefore, to realize the full emissions and economic benefits of a small footprint plant will require export of fuel. Our analysis indicated that biomass-fueled plants would be much more expensive to construct than natural gas-fueled plants, implying that, even in Alaska, the products from a small footprint GTL plant would require significant subsidies ($3-5/gal) to compete with conventional fuel and power.

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EXECUTIVE SUMMARY

Distillate fuels and feedstocks—diesel fuel, kerosene and naphtha—can be produced from carbon-based fuels like natural gas, coal and biomass through a process called Fischer-Tropsch Synthesis or Gas-to-Liquids (GTL). The chemical reactions consist of, first, converting the carbon-based fuel to the gases carbon monoxide and hydrogen; second, combining the CO and H_2 to form long chain, liquid hydrocarbon molecules (the Fischer-Tropsch reaction) and, finally, distilling and upgrading the hydrocarbon liquids into the desired products through standard processes borrowed from the petroleum refining industry. Thus, the overall process can start with either gaseous or solid fuels and ends with liquid fuels that are more convenient to distribute and use. The processes can be combined into a dedicated facility that, in principle, can make use of carbon-based resources that are remote or too small to be employed in more conventional ways. The product fuels are necessarily “ultraclean” in the sense that they contain vanishingly small quantities of sulfur-containing or aromatic molecules. Moreover, the structure of the GTL fuel that has the right boiling point and ignition characteristics to be used in diesel engines is inherently less soot-forming than conventional diesel fuel.

For all of these reasons, GTL processes are being actively considered for use in accessing both large sources of stranded gas, e.g., in the Middle East, and for accessing very small, domestic sources of gas that are too small to be economically connected to a pipeline but which might serve the needs of a remote community or industrial site.

As part of this ICRC-led project, TIAX was asked to estimate the economics, emissions and energy requirements associated with using small footprint plants to produce ultraclean fuels from small scale resources. We have completed an assay of the amount of gas in the continental US that might be suitable for processing in this manner and we have refined our estimates of the cost of the facilities and operations required to carry out the conversion. We have also completed a well-to-wheels analysis of the generation and use of the liquid fuels in specific applications. Finally, we have extended the analyses to consider the special case of Alaska, where fuel is less easily distributed and has a higher cost.

In our first task, using available literature, we bounded the potential gas reserves that might be suitable for this process in the Lower 48 States. On the low side, the US DOE GASIS database contains records for about 3000 wells of sufficient size (greater 1 billion but less than 10 billion standard cubic feet of gas in recoverable reserves), that are listed as not currently producing, and that have gas of suitable quality for processing by a small footprint plant (e.g., low sulfur). On the high side, through a logarithmic extrapolation of all the wells in the GASIS database, we estimate that the lower 48 states may contain as many as 150,000 gas wells with reserves between 1 billion and 10 billion standard cubic feet, for a total of the equivalent of 65 billion barrels of oil, if processed by a small footprint plant. This large range of estimates could be narrowed through additional research that details the dependencies on resource size, efficiency and cost of discovery and cost of extraction, considerations that lie beyond the scope of the current study. Moreover, given the recent rise in the price of gas, it is likely that many of the wells in GASIS may have come into play since 1996 when that survey was compiled.

We also considered biomass, coal and petroleum coke as possible feedstocks to a small footprint GTL plant. Biomass is readily available in quantities consistent with supplying a small footprint plant but the type and costs are location dependent. Conversion of biomass requires a gasification step that is less burdensome than the gasification of coal. Evidently, coal and petroleum coke are available in quite large quantities but each was ruled out early on as being unsuitable for a small footprint plant because each requires an oxygen-blown gasifier, and thus an air-separation facility, which does not appear to be economically feasible for such small facilities.

We found limited opportunities to use the other feedstocks (coalbed methane, tight gas, shale gas and coal gas)—either they were available in reservoirs large enough to support large facilities that are more cost effective when run at scale or they were too far from markets to offer the benefits of local supply. The limited supply and higher production costs of using these feedstocks screened them out of detailed analysis.

By extending a techno-economic analysis developed for much larger scale plants, we estimated the conditions that would permit a small footprint GTL plant to realize a profit. The model we have constructed, which permits facile variation in the size and location of the plant, agrees very well with both the overall capital and operating expenses of small footprint plants that have been estimated by much more detailed calculations by Syntroleum and others. In our analyses, we have considered ranges of prices for fuel and electricity that span projections taking into account historical trends as well as the recent (2005), large increases in the price of petroleum. The relevant conditions for profitability, notably, access to cheap feedstock and high prices for distillate product, imply that the lower 48 states offer fewer opportunities if the small footprint plant were constructed using standard, "stick-built" technology borrowed from the refining industry. In that case, our analyses for the construction and operation of the plant over twenty years showed negative net present values and internal rates of return for $1/MMBTU gas and $24/bbl crude except for the largest plant sizes (>6000 bbl/day). The financial metrics become positive for stick-built plants larger than about 500 bbl/day when the price of petroleum (which sets the price for which the GTL products can be sold) rises to $55/bbl. However, a different approach, a hypothetical plant constructed from modular units that contain the principal unit operations of syn-gas generation, steam reforming and Fischer-Tropsch synthesis in one pressure vessel appears to offer a much more profitable route to converting stranded or underutilized gas resources. The estimated economics for this novel design are positive for plants larger than about 100 bbl/day, even in the case of $24/bbl crude.

Finally, by combining published studies we have constructed a well-to-wheels comparison of the emissions and fuel economy for vehicles fueled with Fischer-Tropsch diesel and conventional diesel. The tank-to-wheels fuel economies of the two fuels are similar (differing primarily because of the slightly different specific and volumetric heating values). Evidently, the lower well-to-tank energy efficiency of producing Fischer-Tropsch diesel compared with that of refining petroleum must be balanced against the energy security associated with employing a wholly domestic resource.

In addition to convenience and energy security, GTL fuels can offer environmental benefits with respect to CO_2 and criteria pollutants. Biomass-derived fuels can, in principle, exhibit net zero CO_2 emissions; GTL-fuels based on natural gas have well-to-wheels CO_2 emissions that are necessarily larger than would accompany the direct use of natural gas because the GTL conversion process has an overall energy efficiency of between 40-60%, depending on the use of waste heat for generating electricity or for space heating.

The benefit of GTL fuels with respect to criteria pollutants, NOx, CO and PM, is complicated by the mandated introduction of very clean diesel engines nearly simultaneously with the earliest practical introduction of small footprint plants. The powertrains that will be used to meet upcoming EPA regulations will need substantial emission control even if the engines were fueled with GTL fuels (mandated decreases in NOx and particulates exceeding 90% compared to 10-50% decreases that can be obtained through the use of GTL fuels only). Moreover, there is preliminary evidence that the use of GTL fuels in some modern engines without retuning actually leads to increases in NOx emissions. Thus, in our analysis the benefits of GTL fuels were applied to the older fraction of the vehicle fleet and could therefore diminish as those vehicles are taken out of service. We understood but did not attempt to quantify other, potential advantages of GTL fuels. For example, with sophisticated engine control systems, it is likely that approaches can be found, if they are sought, to take advantage of a fuel with inherently less tendency to produce emissions. In that case, or if the improvements presaged by EPA regulations are not fully realized, additional benefits would accrue from the availability of a very clean fuel.

Even under these conservative assumptions, significant savings in NOx and PM—15% and 35%, respectively—were projected for the two heavier vehicle classes, buses and utility trucks, if fueled with GTL fuels since almost 80% of those fleets in 2015, the assumed starting date for commercial introduction of small footprint plants, will consist of vehicles purchased prior to the introduction of Tier 2 vehicles (2007-2010). Because there are so few light duty diesel vehicles in the current fleet, the benefits of using GTL-derived fuels are projected to be very small in this category (<5% decreases in criteria pollutants) since the future fleet will consist primarily of modern, low emission vehicles. The "cost" of achieving NOx and PM abatement via FTD from small footprint plants is negative: since plants as small as 100 barrels per day can be operated profitably, the NOx and PM generate a real credit if the plant uses cheap, stranded natural gas. If the plant is, instead, fueled with biomass, then we estimate that the costs of NOx and PM abatements are in line with those that can be achieved through exhaust gas treatment and fleet modifications.

Since the GTL process consumes a much larger portion of the feedstock for just the operation of the plant than does a conventional refinery (60% in our model versus about 20% for a refinery[1]), there is a significantly larger energy penalty and CO_2 burden for using GTL compared to that of using petroleum-derived diesel fuel. However, biomass-derived GTL fuels can, in principle, exhibit net zero CO_2 emissions, leading to as much as 75% reductions in CO_2 from the projected fleet.

In addition to potential emissions benefits, the production of GTL fuels offers the promise of energy security associated with using non-conventional, domestically based resource. Such considerations are now fostering the development of large scale GTL plants that might supply a significant fraction of the US fuel demand. Moreover, the GTL process produces its carbon dioxide in fairly rich streams that therefore facilitate CO_2 sequestration or carbon recycling schemes. We explicitly considered the value of the energy security afforded by small footprint plants in our calculations that took into account the cost of alternative sources of energy in remote regions. We did not consider the possibility of CO_2 sequestration for the small footprint plants because the confluence of a remote market, an adjacent source of feedstock and an adjacent CO_2 sink seemed improbable.

In a second part of this study we applied these same methods to the feedstocks, conditions and opportunities that pertain in Alaska. Three sizes of plants were investigated: 600 and 6000 barrels per day, corresponding to feedstock availability for small and medium sized plants, and a 19,000 barrel per day facility, such as might be constructed to use coastal reservoirs of natural gas known to exist in the Kenai Peninsula. Because we assumed that the small footprint plants to be constructed in remote areas would be mostly prefabricated and would be operated by a small staff our estimates were only modestly higher for both the capital costs of the plants (2-10%) and the operating costs (1-7%), depending on plant size. The higher price of conventional fuel in Alaska therefore contributed significantly to the economic performance of GTL plants at all size ranges since the products can be sold for more money. The economic value, estimated as internal rate of return, could be greater than 100% for natural gas-fueled plants, providing that markets could be found at the higher prices for all of the products (naphtha, GTL fuel and electricity). We note, however, that even the smallest sized plant would supply fleets as large as 10,000 light duty vehicles or 800-900 heavy duty vehicles, which is larger than what would likely be found in remote communities, and that naphtha is valuable as a product only if it can be used as a fuel itself (e.g., in an HCCI engine), or as a feedstock for a reformer (H_2) or chemical process (e.g., to make ethylene). Therefore, to realize the full emissions and economic benefits of a small footprint plant will require export of fuel.

Finally, our analyses indicated that biomass-fueled plants would be much more expensive to construct than natural gas-fueled plants, implying that, even in Alaska, the products from a small footprint GTL plant would require significant subsidies ($3-5/gal) to compete with conventional fuel and power.

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[1] A recent lifecycle analysis commissioned by Sasol Chevron, ConocoPhillips and Shell International notes that quantities of CO_2 produced by GTL processes are much more similar to those of conventional refineries for large scale GTL plants whose overall energy efficiency is greater than 55% and whose effluent streams are integrated into standing utilities for cooling, heat and power ("Gas to Liquids Life Cycle Assessment Synthesis Report", Five Winds International, 2004). For a small footprint plant, integration opportunities are much more limited since the enthalpy and even electricity output of the plant will typically be much greater than what can be used within an economic radius.

INTRODUCTION

This study is part of a larger effort directed by the Integrated Concepts Research Corporation, on behalf of the US Department of Energy to assess the impact of the introduction of ultraclean fuels produced by small footprint Gas-to-Liquid (GTL) processes on air emissions, cost and energy use. The particular processes and scale of production were selected as a way to exploit under-utilized domestic resources of hydrocarbons, including stranded petro-resources and biomass, as transportation fuels, with the ultimate goals of increased energy security and decreases in criteria pollutants. It was recognized that the potential benefits of small scale production would be magnified if the resources could be tapped close to the point of use since the costs, emissions and risks associated with transportation of the fuel itself would therefore be minimized. However, it was also recognized that, to be economic, the distributed production of fuels would require technology that could be operated reliably with a very small staff and, in instances where the resource could be exhausted, a physical plant that could be relocated conveniently.

We focused on the GTL process because it can be used to produce very clean-burning transportation fuels from a wide variety of feedstocks. In the GTL process, synthesis gas (carbon monoxide plus and hydrogen) is converted to liquid fuels through Fischer-Tropsch catalysis (Figure 1). The product stream contains a distribution of liquid hydrocarbons plus water, heat and, optionally, electricity (turbine-driven generator). The hydrocarbon products (Figure 2) consist largely of straight-chain alkanes that can be concentrated in the range of medium to heavy distillate fuels (e.g., diesel fuel) by appropriate choice of reaction conditions and post-treatment. Lighter molecules, those boiling in the naphtha range, have value as very clean feedstocks to refinery processes. By themselves, however, they are not useful in today's engines as transportation fuel because they have very low octane numbers. The lightest molecules can be used as a heating fuel in situations where there is a need for liquefied petroleum gas (LPG). Such synthetic fuels have long been known to burn very cleanly in conventional diesel engines—producing significantly lower concentrations of particulates, carbon monoxide and nitrogen oxides compared to conventional, petroleum-derived fuels that contain sulfur compounds and aromatic molecules. Moreover, in the event that they can be used locally, the heat and electricity that come as side-products of the GTL process can increase the overall energy efficiency of the process, thereby helping to offset the cost of the process equipment, which is large compared to that of mere combustion systems.

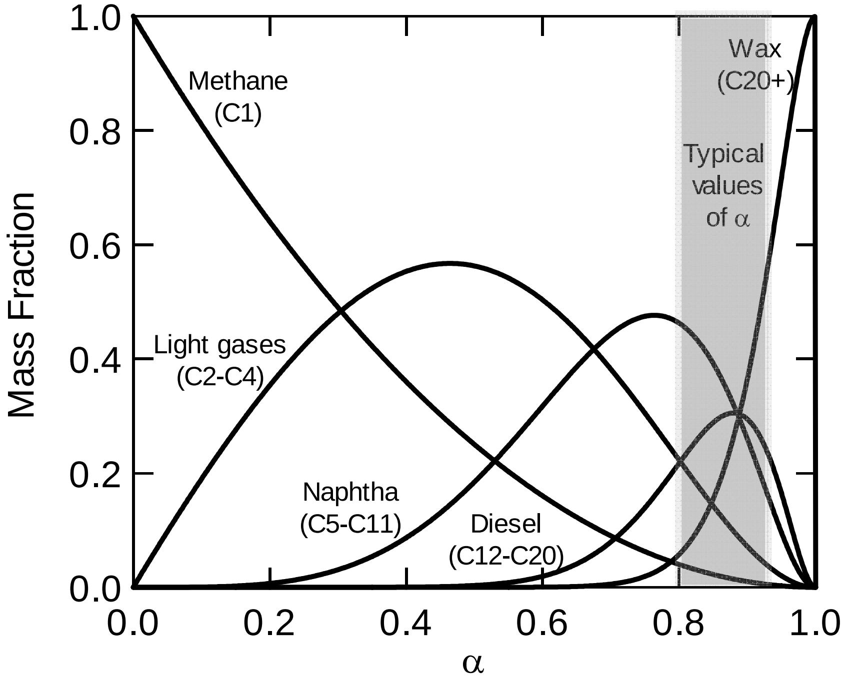
Figure 1. Transformation of CO and H_2 into hydrocarbons by the Fischer Tropsch Process

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$$

The GTL process has great generality because synthesis gas (syngas) can be generated from a wide range of carbon-based feedstocks, including coal, coke, producer gas, natural gas and biomass, although each feedstock requires its own conversion process (varying in temperature, pressure and concentrations of water and oxygen) to achieve an acceptable process efficiency and effluent composition. GTL processes that use natural gas as the feedstock are now being commercialized at large scales (>100,000 barrels/day) in parts of the world were natural gas is abundant. The goal of this study was to determine the feasibility of using similar, down-scaled and repackaged technologies for fueling the local needs using locally available feedstocks.

We limited our study to "small footprint" plants, meaning facilities that produce less than 10,000 barrels per day of product, so that we could focus on resources that would fail to satisfy the economic criteria of large energy companies but that could have a strong appeal to small, remote communities and industrial operations like mining and to situations that could exploit non-conventional feedstocks like biomass.

Figure 2. Typical distribution of hydrocarbons produced by the Fischer Tropsch process as a function of the chain propogation parameter, α [1]. In practice, the catalyst and operating conditions are chosen so that α is in the range of 0.8 to 0.95 so as to minimize the amount of methane and light gases that are produced. The heavy fractions (wax) can be hydroprocessed improve the yield of fuel range products.



Approach

The market potential of a particular fuel chain involves four closely linked considerations: fuel availability, economics of production and delivery, overall energy efficiency and overall environmental footprint. Because we envisaged small footprint plants generating only small quantities of fuel, we estimated market demand based on existing distillate usage by transportation, residential customers, industrial customers, commercial customers and in electricity generation. We estimated the economics of production of GTL fuels based on a multifactor, scaling method rather than a detailed costing exercise. While the results must therefore be viewed circumspectly, our experience suggests that they are useful for discriminating among technologies and fuel chains. More refined analyses and sensitivity analyses (to identify significant parameters and assumptions) could be the focus of future work. The overall energy efficiency of the GTL processes were estimated by multiplying the energy efficiencies of the individual unit operations while taking into account plausible heat integration. The well-to-wheels comparisons were based on a combination of our own analyses and publicly available estimates for the emissions and energy efficiencies of the well-to-tank and tank-to-wheels conversions for both conventional and GTL diesel and for a representative range of vehicles.

We have, in addition, attempted to localize the results to conditions relevant to Alaska by taking into consideration market size, costs of fuel and electricity along with estimates of the costs and quality of available feedstocks.

As a first pass, to classify the availability of various feedstocks we assumed that there was an equivalence between the heating value of the inlet and outlet fuel streams, with a conversion efficiency of 40-50%

(i.e., to create an outlet stream whose heating value is X kJ requires an inlet fuel equivalent to about 2X kJ), which is a conservative estimate of the efficiency of a small scale plant. The upper end of the efficiency range applies when electricity is exported. Table 2 shows the amount of feedstock required to generate a given amount of distillate fuel.

Table 1. Nominal conversion of carbon-based feedstocks into distillate fuels

Conversion of 1 million standard cubic feet (1 MMSCF) of natural gas to distillate products at 50% energy efficiency

For diesel (36.4 MJ/liter [2])

$$1050\frac{BTU}{scf}\times 10^6\,scf\times 0.50\frac{BTUproducts}{BTUgas}\times 1055\frac{J}{BTU}\times\frac{1}{36.4\times 10^6}\frac{liter}{J}\times\frac{1}{159}\frac{bbl}{liter}=95bbl$$

For Naphtha (32 MJ/liter [2])

$$1050\frac{BTU}{scf}\times 10^6\,scf\times 0.50\frac{BTUproducts}{BTUgas}\times 1055\frac{J}{BTU}\times\frac{1}{32\times 10^6}\frac{liter}{J}\times\frac{1}{159}\frac{bbl}{liter}=109bbl$$

Conversion of 1 ton of dry biomass to distillate products, assuming 20 GJ/t [2] and 35% energy efficiency

For diesel (36.4 MJ/liter [2])

$$20GJ\times 0.35\frac{GJproducts}{GJfeedstock}\times\frac{1}{36.4\times 10^6}\frac{liter}{J}\times\frac{1}{159}\frac{bbl}{liter}=1.2bbl$$

For Naphtha (32 MJ/liter [2])

$$20GJ\times 0.35\frac{GJproducts}{GJfeedstock}\times\frac{1}{32\times 10^6}\frac{liter}{J}\times\frac{1}{159}\frac{bbl}{liter}=1.4bbl$$

We have considered plants as small as 100 bpd and runs as short as 2 years between plant relocations, to account for the possibility of a non-traditional plant architecture. With these criteria, we identified 2997 gas resources in the lower 48 states of a suitable size and location for relocatable, small footprint GTL plants sized for 100 bpd of production. All of these proven reserves are located within 150 miles of a wholesale diesel outlet, suggesting that conventional fuel suppliers could serve the potential markets for GTL products so the GTL products would have to compete on the basis of price, possibly subsidized to reflect the clean nature of the fuel and its purely domestic provenance.

To estimate the economics of a small footprint GTL plant we extrapolated the results of a techno-economic analysis carried out for a much larger scale plant (>50,000 bpd), using standard allometric relations (power-law scaling). Our method produced economic estimates for both capital and operating costs that compared very well to those provided by Syntroleum for a much more detailed analysis of two sizes of plants (100 and 1700 barrels per day). The analysis estimated the capital cost each of the important components required in the GTL process (heat exchangers, reactors, separation units, compressors), each sized according to the desired scale of the plant. Operating expenses combined the costs of the feedstock, expendables and labor. We assumed that the plants were built with 100% equity.

With the assumptions we used, the preliminary results suggest that a small GTL plant (1000 bpd) would be able to generate profit (10% internal rate of return) under circumstances of sufficiently cheap feedstock ($0.00 to $0.40 per million BTU) if conventional fuel maintained its historical pricing levels (wholesale price of $0.74/gal). While the results depend sensitively on scale of operation, cost of gas, location and market price of the fuel it is fair to infer that remote locations, for example in Alaska, may benefit the most from this technology. Indeed, in Alaska, where fuel and electricity prices can be high, we estimate that the IRR for small footprint plants can exceed 100%.

METHODS

Resource Identification

To identify suitable starting resources we employed the GASIS database [3], which includes data on small and unconventional resources in the lower 48 states. Release 2 of the GASIS Reservoir Data System is a national database of geological, engineering, production, and ultimate recovery data for U.S. oil and gas reservoirs. The reservoir data system contains 19,220 reservoir records with 185 data fields per record. These reservoirs represent most of the historical gas production in the areas covered. Included reservoirs are those either meeting minimum cumulative gas production levels (through 1996) or those that were included in the Department of Energy/Gas Research Institute Gas Atlas projects.

Data sources for the GASIS Reservoir Data System include the regional DOE/GRI Gas Atlas data sets, new information from Dwights TOTL (field and reservoir) database, Dwights DOGR (well completion) database, GRI tight gas identification data and gas composition data, and other public domain data [3]. Some data elements included in GASIS are calculated values, such as gas well productive area, recovery per well statistics, and estimated ultimate recovery.

We used the query functions in GASIS to characterize and count gas resources of four types (Table 2). On the upper end, the search was limited to fields that contained less than 10 billion standard cubic feet (bcf) of recoverable gas and that was not currently “in play”, since gas that is being delivered to the grid was deemed to have a value higher than could be attained by converting it to liquid fuel. On the lower end, the search was bounded at 1 bcf, the minimum amount of gas required to keep a 100 BPD SFP in production for 2 years before it would be relocated to another site. For reference, consider that with the assumptions in Table 2 about energy content and energy conversion efficiency, a SFP sized to make 500 BPD of a product stream, consisting of 25% naphtha and 75% diesel fuel, for 10 years would require a gas field containing about 20 bcf of gas:

$$0.25 \times \frac{109}{10^6} \frac{bbl_{gasoline}}{scf} + 0.75 \times \frac{95}{10^6} \frac{bbl_{Diesel}}{scf} = 99 \frac{bbl_{product}}{10^6\, scf}$$

$$500\, bpd \times 365\, d \times 10 = 1{,}800{,}000\, bbl$$

$$1{,}800{,}000 bbl \times \frac{10^6}{99} \frac{scf}{bbl_{product}} = 18\, bcf$$

Table 2. Gas resources considered as possible feedstocks

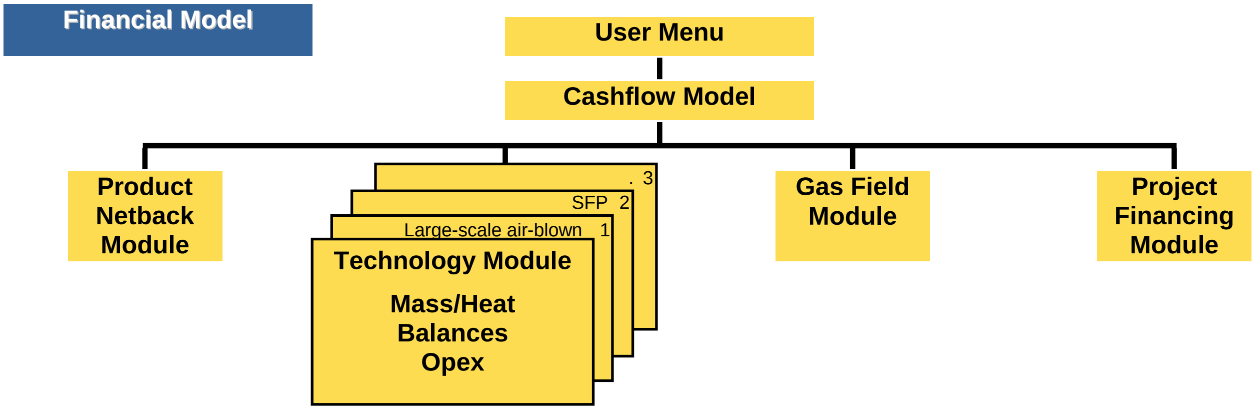
Resource	Description
Conventional	Reservoirs of associated natural gas (dissolved in or lying above oil reservoirs) or non-associated gas
Coal bed methane	Natural gas associated with coal beds
Tight gas	Natural gas from low-permeability (tight) reservoirs, having permeabilities less than 0.1 millidarcies [4]
Shale gas	Natural gas derived from shale deposits

We initially considered but did not pursue the use of coal or biomass as starting materials because the oxygen-fed gasifier required to ensure conversion of those feedstocks would have added inordinately to the price of the overall plant.

Techno-economic analysis of a Small Footprint Plant.

Initially, we based on our analysis of the technical and economic performance of an SFP by extrapolating our previous work on Gas-to-Liquid technology [5]. We constructed a spreadsheet model that included the costs of the unit operations, the nature of the gas and project financing (Figure 3). In that work, we scaled the sizes and costs of the equipment using standard allometric techniques [6] (power law relations between scale and cost).

Figure 3. Schematic of the economic analysis.



The model was then exercised to determine the sensitivity of the results (capital costs, operating costs, internal rate of return, etc) to the values of the input parameters (e.g, plant scale, cost and quality of gas, price of products). The base case (Table 3) was an air-blown GTL plant designed to resemble the technology employed by Syntroleum.

Table 3. Base case parameters used to estimate the economics of an SFP.

Parameter	Value
Feedstock	Natural gas with a heating value of 1050 BTU/scf
Location factor	1
Products	diesel, naphtha, electricity; self sufficient in electricity and steam

The profitability of either sort of plant will also depend sensitively on the price that can be charged for the products. We considered three products: diesel fuel, electricity and naphtha. A fourth product, exported heat (most likely in the form of low pressure steam), was not considered in our analysis since the remoteness of the envisaged applications means that the demand for heat will be very specialized. We considered two scenarios for the market prices for the three exported products, one that represents historical trends in the price of fuel and electricity [7] and the other that takes into account the recent large increases in the prices of those commodities [8] (Table 4). As a conservative measure, we assumed that the GTL diesel will be sold without any premium that might be attributed to its particular properties (e.g., ultralow concentrations of sulfur, high cetane number). Somewhat optimistically, we also assumed that the naphtha fraction of the product stream could be sold at prices comparable to the netback of petroleum-derived naphtha (estimated by regressing world prices for naphtha and petroleum over periods that included both high and low prices of petroleum). The base case of our analyses included natural gas or biomass priced at the production cost ($1/million BTU for natural gas, $20/ton for biomass) but we also considered cases where the feedstock was free. All of the plants were assumed to have useful lives of 20 years with high utilization (95%). The plants were assumed to be owned outright (100% equity). Taxes were set at 35% of revenues and we assumed a low discount rate for the net present value calculations that was low compared to those more typically employed by the petrochemical and oil industry (6% here compared to 10-12%) since the applications here would likely be driven by external factors (convenience, regulations) rather than pure economics. Because we are judging profitability of enterprises for a 20-year lifetime where costs and prices are not only inherently uncertain, but expected to change, we also ran Monte Carlo simulations on the base case plant to assess the uncertainties in our estimates of process economics under the two scenarios.

Table 4. Price scenarios for the products for small footprint GTL plants

Component	Scenario 1	Scenario 2
Oil price [$/bbl]	24	55
Electricity price [$/kWh]		
Lower 48 States	0.03	0.075
Alaska	0.10	0.110
Naphtha netback	1.00	0.83
Diesel netback	1.3	
Natural gas cost	$1/mmBTU	
Product slate (diesel/naphtha)		
Stickbuilt plant	75/25	
GTL-in-a-Can™	80/20	
Energy efficiency		
Stick-built plant	50%	
GTL-in-a-Can™	40%	
Plant size	500 bbl/day	
Plant life	20 years	
Plant utilization	95%	
Tax rate	35%	
Equity	100%	
Discount rate	6%	

To estimate the effect of geographic remoteness on the perceived value of SFP products we attempted to determine the added cost of delivering fuel from a central depot to outlying locations where one might site an SFP (whose products were assumed to be delivered without cost). Our simple model took into account the costs of storage and transportation:

$$Cost_{overall} = Cost_{transport} + Cost_{storage}$$

$$Cost_{transport} = Cost_{fixed} + Cost_{variable}$$

The storage costs were assumed to be 2 cents/gal; the fixed cost for transportation (driver, vehicle) was assumed to be $700 per day, prorated by the number of deliveries; and the variable cost was assumed to be 38 cents/mile.

We have not attempted to price the fuel as a function of location or time but rather have used that parameter as an input to a sensitivity analysis.

In the latter half of this project, we updated our previous GTL model with costing and scaling factors to estimate the capital costs of the major components of the SFP. We also rewrote the model in a form that permits much easier maintenance and revision. The previous model was an Excel spreadsheet. The current model (Figure 4) is based on Simulink®, a general purpose modeling tool in which the functionality of each unit operation in the small footprint plant can be encapsulated in an independent module. We believe that this is the first such use of Simulink® for techno-economic modeling. An important benefit of this new approach is that the models can be packaged in a way that permits them to be distributed without revealing confidential information.

Our approach uses a multifactor method that has proved successful in work we have done for much larger GTL plants. The cost of a system is constructed from the costs of the individual components, which are divided into equipment costs, construction costs and installation costs. The latter two are estimated by multiplying the equipment costs by factors (hence the name, “multifactor”) derived from field experience for the different types of equipment (synthesis gas generator, Fischer-Tropsch reactor, balance of plant) and for the ancillary services that lie outside the “battery limits” of the core process (e.g., roads, housing, safety services).

We have constructed models for plants sized between 100 and 10,000 barrels per day capacity, operating with an air-blown synthesis gas generator and an operating pressure of 170 psi. A major assumption is the overall energy efficiency of the plant, defined to be the heating value of the products divided by the heating value of the input feed gas. We used a value of 50% for the energy efficiency, a number that has been validated by Syntroleum as being appropriate for this size range of plants. The conventional small footprint plant technology, as employed by Syntroleum, produces 75/25 diesel/naphtha split, whereas with GTL-in-a-can$^{©}$, discussed below, the split was assumed to be 80/20.

In order to measure the overall cost and emissions of GTL technology and fuel we elected for the analysis to reflect a scenario wherein Fischer-Tropsch diesel accounts for 1% of the annual U.S. diesel consumption, (14.4 million barrels per year of diesel fuel). This level of diesel consumption (and, likewise, production) was chosen because it is small enough to be supported for 20 years by stranded gas in the lower 48 and large enough to show reasonable cost and emission effects. As the analysis will show, this level of production can be accomplished by a very reasonably sized fleet of GTL plants.

The result was used to compare the effect of varying plant size and differing technologies on the total cost per gallon of diesel produced. The method of assembling the total cost of this level of production was done by first assuming a plant size (100-10,000 BPD), then calculating how many of that size plant would be required to produce 14.4MMbbl/yr. Once the number of plants was known, our cost model was exercised to find the CAPEX, OPEX, feedstock cost and relocation cost for a single plant. The feedstock, since it varies by location, was assumed constant at $1.00 per MMSCF—a most-likely conservative estimate. The numerator of the following formula is the total cost of production, which is then normalized by the production to get the per gallon cost:

$$\$/gal = \frac{\#ofplants \times (CAPEX + 20yrs \times (OPEX + feedstock)) + (\#ofrelocations) \times relocation\_\cos t}{14.4M \,\frac{bbl}{yr} \times 20yrs \times 42\,\frac{gal}{bbl}}$$

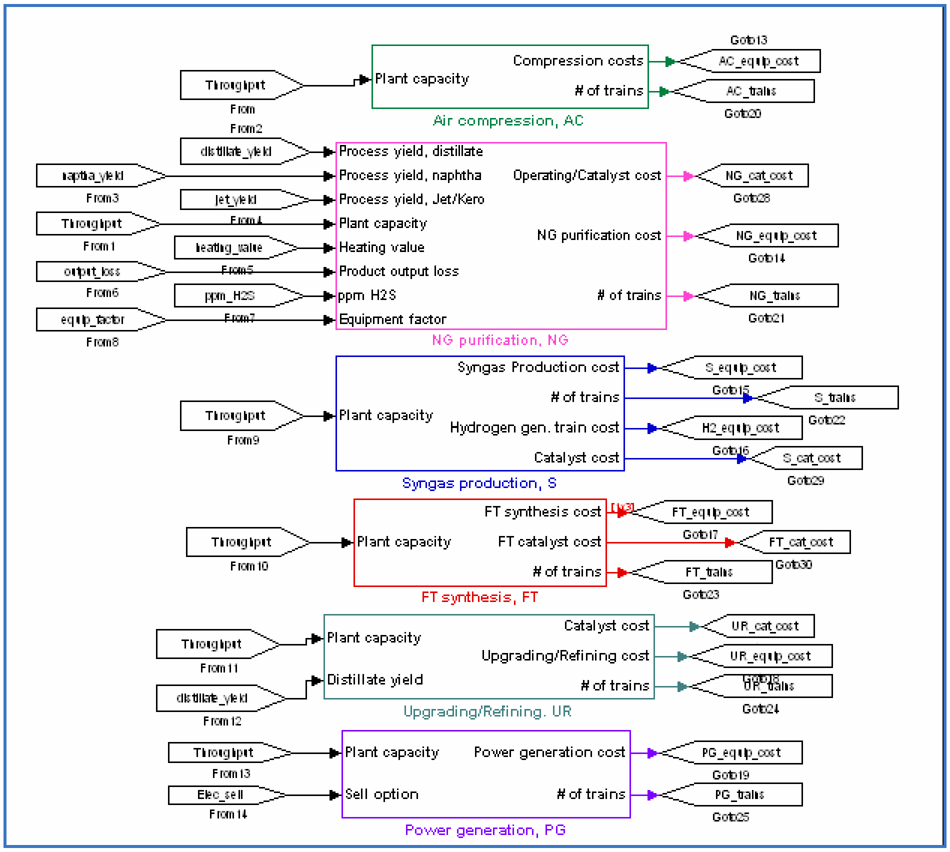
The cost of relocating was calculated as a sum of disassembly/reassembly costs and moving costs, which were 70% of the initial installed cost and 2% of the CAPEX, respectively. The relocation cost is only an estimate based on best-guess values. The number of times a plant was required to relocate (which appears as *#ofrelocations* in the equation above) depended on the size of the gas field from which it was drawing its feedstock. Whenever a plant was required to relocate because it depleted its field’s gas a relocation cost would be incurred along with three months of zero production from that plant.

The plants were given a credit for their production of naphtha. Per gallon of naphtha produced the overall cost (numerator of above equation) would be decreased by $0.65. This price of naphtha reflects the low end (conservative) of the naphtha market. The average naphtha price from May04-Aug04 was closer to $1.00. If the price of naphtha increases, the resulting trend would be a lower net production cost of diesel. The lower net cost is more pronounced in the technologies that have a higher naphtha product split, whereas the effect is parallel for different plant sizes within the same technology.

The analysis shows that with increasing plant size, the cost to produce a gallon of diesel decreases. For conventional stick built plant there is a large benefit in increasing the plant size from 100 BPD to 1000 BPD, with diminishing benefit as plant size increases from 1,000 to 10,000 BPD. We also note that as plant sizes increase, the cost of relocating probably will not scale directly with CAPEX, but rather would increase greater than linearly because of the costly demands outside the battery limits, which we have shown to be very significant.

More important than the trend of decreasing cost with increasing plant size is the actual cost of producing a gallon of Fischer-Tropsch diesel. For a $1.00 per MMSCF feedstock cost and a 10,000 BPD plant, the cost to produce a gallon of diesel fuel is $0.66. This number has the potential to be lower in most actual applications because conservative estimates have been made in both the feedstock cost and the price of naphtha.

Figure 4. Top level of the Simulink® model that incorporates the revised economics for the small footprint plants.



Well-to-Wheel Analysis of fuels produced by a small footprint plant.

The well-to-wheels analysis consists of two parts, well-to-tank and tank-to-wheels. The former includes the costs of producing and transporting the fuel. The latter includes the efficiency and emissions associated with using the fuel. Data for the former come from our understanding of the thermodynamics and kinetics involved in transforming natural gas into liquid fuels, in particular the effective conversion efficiency. Data for the latter estimates come from recent series of tests of GTL fuels in vehicles (Table 5), where the reductions range from 8-15% for NOx and 20-50% for particulate matter.

Table 5. Estimates of abatement in criteria pollutants from using FT fuels compared to conventional ultralow sulfur diesel fuel

Pollutant	Abatement	Reference
NOx	6.2%	[9]
	4-9%	[10]
	9%	[11]
PM	29 to 45%	[9]
	12-45%	[10]
	32%	[11]

The emission reductions indicated in Table 5 are not necessarily indicative of the use of GTL fuels in future vehicles because the combustion technologies that are being employed to meet upcoming emissions standards are highly dependent on the "assumed" nature of the fuel, both its physical and combustion characteristics. We note that optimization of the next generation of diesel engine control systems, both in terms of their architecture and their specific programming to recognize and make the best use of very high Cetane fuels such as F-T fuels, is a likely future development when the potential availability of such fuels increases.

RESULTS AND DISCUSSION

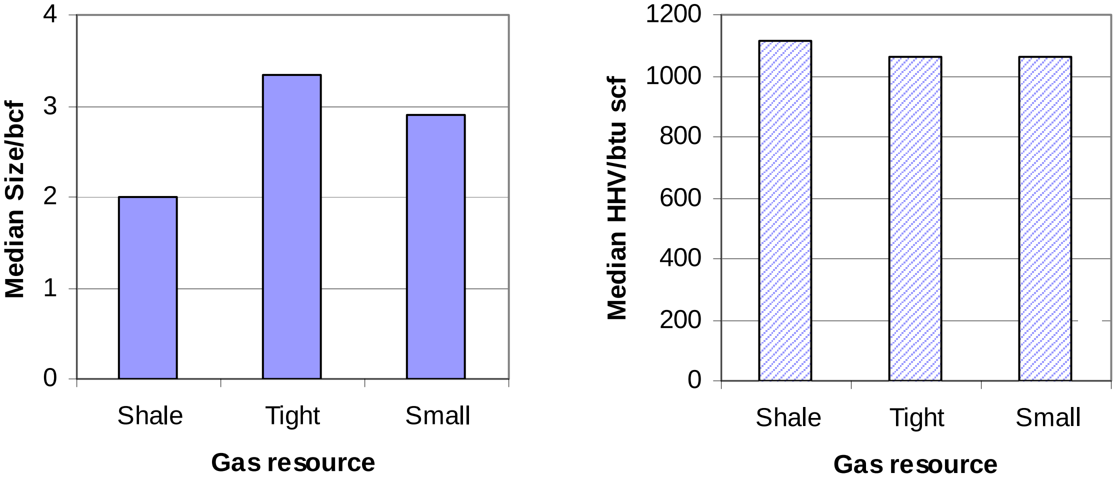
Resources

The data in the GASIS database suggest that the resources for feeding an SFP will come most readily from small reservoirs of conventional gas (associated and non-associated), tight gas and coal bed methane (Figure 5). The database contained no coal bed methane resources, when screened according to the criteria described in the Methods section. Altogether there were 2997 resources that fit the screening criteria.

Whether a particular resource is, in fact, usable will depend on its location proximity to infrastructure and markets, its quality (energy content of the gas, presence of impurities that require extensive cleanup or removal) and whether the resource can be used in other, more profitable ways. The increasing price of natural gas has a direct bearing on the latter criterion.

The selected resources are distributed almost exponentially by size (Figure 6). Small, conventional resources are by far the most numerous (2947 wells), followed by tight gas (43 wells) and shale gas (7 wells). The total amount of gas contained in these wells is equivalent to 800 million barrels of oil at an energy conversion efficiency of 40%. For reference, the US now uses roughly 1.4 billion barrels of diesel fuel per year (US Energy Information Agency).

Figure 5. Results of the screening exercise. Left: Median recoverable ultimate reserves reported in GASIS for the screened resources. Right: .Median higher heating value of reserves of each type.



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The number of small footprint plants required to exploit these resources depends on the size and desired lifetime of the SFP (Table 6 - Table 8). The lifetimes were calculated using the conversion factors presented above. Thus, if the resources were to be exploited by means of 100 bpd plants then hundreds could be in service at once. On the contrary, 1000 bpd plants could only be used for short periods of time (2 years) on even the largest of these resources. Evidently, an economic optimization between plant construction and plant relocation is required to exploit the resources in as profitable way as possible. We will present that sort of analysis after discussing the two forms of plant architectures.

Figure 6. Resource distribution by size for the wells screened according to the criteria specified in Appendix 1. Note that the number of resources of each size for the tight wells and shale gas wells have been multiplied by 10 and 100, respectively, to make them visible on this scale. The curve is an exponential fit to the distribution of small, conventional resources in this size range.

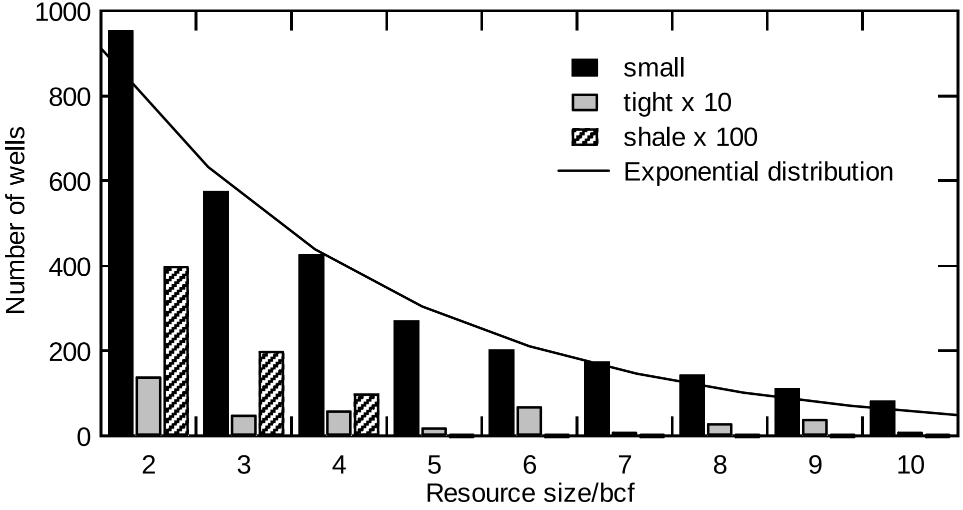


Table 6. Number of SFPs of the specified size that can be supported for the specified lifetime using the screened, small conventional resources of natural gas identified in the GASIS database

	Lifetime/y			
Plant Capacity/bpd	2	5	10	20
100	308	1107	882	650
200	717	1064	595	0
500	606	458	0	0
1000	255	0	0	0

Table 7. Number of SFPs of the specified size that can be supported for the specified lifetime using the screened, small resources of "tight" natural gas identified in the GASIS database

	Lifetime/y			
Plant Capacity/bpd	2	5	10	20
100	5	12	13	13
200	5	18	11	0
500	11	8	0	0
1000	5	0	0	0

Table 8. Number of SFPs of the specified size that can be supported for the specified lifetime using the screened, small resources of shale gas identified in the GASIS database

	Lifetime/y			
Plant Capacity/bpd	2	5	10	20
100	1	5	1	0
200	2	1	1	0
500	1	0	0	0
1000	0	0	0	0

In fact, there is reason to believe that the GASIS database significantly under-represents the amount of gas available in reservoirs containing less than about 10 billion standard cubic feet (Figure 7). The solid curve in Figure 7 shows the amount of gas presumed to be extractable from each reservoir (EUR = estimated ultimate recovery) as a function of the ranking of that reservoir in the database (Well number). The dashed curve corresponds to an extrapolation of the distribution of gas wells to small sizes, assuming that the distribution is fractal, i.e.,

$$R = \frac{C}{N^D} \qquad \text{Equation 1}$$

where R is the size of a feature, N is the number of features having that size and C is an empirical constant. The quantity $1/D$ is called the fractal dimension of the system. Fractals have been shown to be applicable to a number of geological features, including the distribution of minerals and petroleum [12]. For the data in GASIS, the relationship between well size and well number, determined from the largest well to wells containing 10 billion standard cubic feet of gas is:

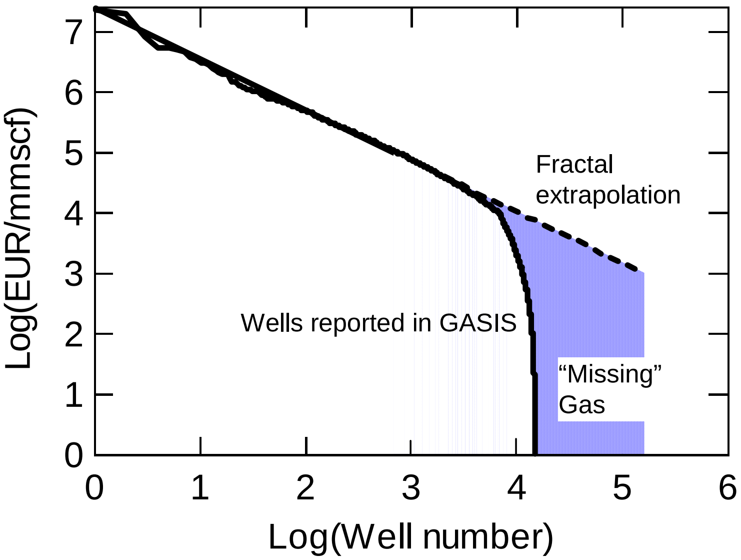
$$EUR = \frac{2.45358 \times 10^7}{Well^{0.84323}} \qquad \text{Equation 2}$$

Integrating this equation over a range of well sizes provides an estimate of the gas that appears to have been undercounted in GASIS (shaded region in Figure 7):

$$\sum EUR_k \approx 2.45358\times10^7 \int k^{-0.84323} dk = 1.3\times\left(k_h^{1.84323} - k_l^{1.84323}\right) \qquad \text{Equation 3}$$

The indices of the wells can be obtained from Equation 1. For wells between 1 and 10 billion standard cubic feet, the shaded region in Figure 7 corresponds 36 trillion cubic feet of gas or the equivalent of 65 billion barrels of distillate fuel at a conversion efficiency of 50%. While this amount of fuel is significant (it is approximately 6 times the economically recoverable petroleum estimated to lie in the Arctic National Wildlife Reserve [13]), we hasten to point out that it assumes all of the "missing gas" is accessible.

Figure 7. Fractal extrapolation of wells in the GASIS database to an EUR of at least 1 billion standard cubic feet.



Very likely, we will likely need advances in seismic imaging to find the "missing gas", drilling costs may be disproportionately large for small reserves, the geologic formations in which the gas lies may not be conducive to complete recovery and the overall relationship may be based on a rather optimistic view of the universe of accessible gas [14]. Still, it is probably safe to say that the amount of gas in the Lower 48 States that might be processed by small footprint plants is larger than the 1.3 billion BOE suggested by GASIS and smaller than the 65 billion BOE indicated by this analysis.

Economic Analysis

Stick built plant

To validate the new model we compared its output to information provided by Syntroleum for two plant sizes, 100 and 1700 barrels per day (Figure 8, solid bars). The overall agreement between our cost estimates is very good. We hasten to point out, however, that the costs of the individual components were not estimated on the same basis since we have allocated utilities like heat exchangers and compressors in a manner different from that used by Syntroleum.

A sensitivity analysis on the model (Figure 9) indicates that the most expensive aspects of constructing a small footprint plant are associated with the infrastructure (services and equipment outside the battery limits, OBL), the natural gas purification step (NG) and the Fischer-Tropsch reactor (FT), with less sensitivity to changes in the cost of the balance of plant (BOP). Consideration of those factors has led us to consider ways to significantly decrease the cost of the plant by combining unit operations into a single module. We call that approach GTL-in-a-Can™ and will discuss it briefly in the later section of this report.

Over the range of plant sizes in Figure 8 the capital expenditure exhibits marked economies of scale. The same trend is true for the operating costs (Figure 10) with labor costs providing the best economy of scale because of there is a minimum operating staff required to run a set of unit operations no matter the operation size. Since our model does not account for the small efficiency effects at different sizes, the amount of feedstock increases linearly with the plant size, and so as plant size increases the feedstock becomes a more dominant cost.

Figure 8. Comparison of capital costs for small footprint plants based on a conventional, "stick-built" architecture across a range of plant sizes. The costs of the individual components are not directly comparable because TIAX has used a different method of allocating process equipment, i.e. heat-exchangers.

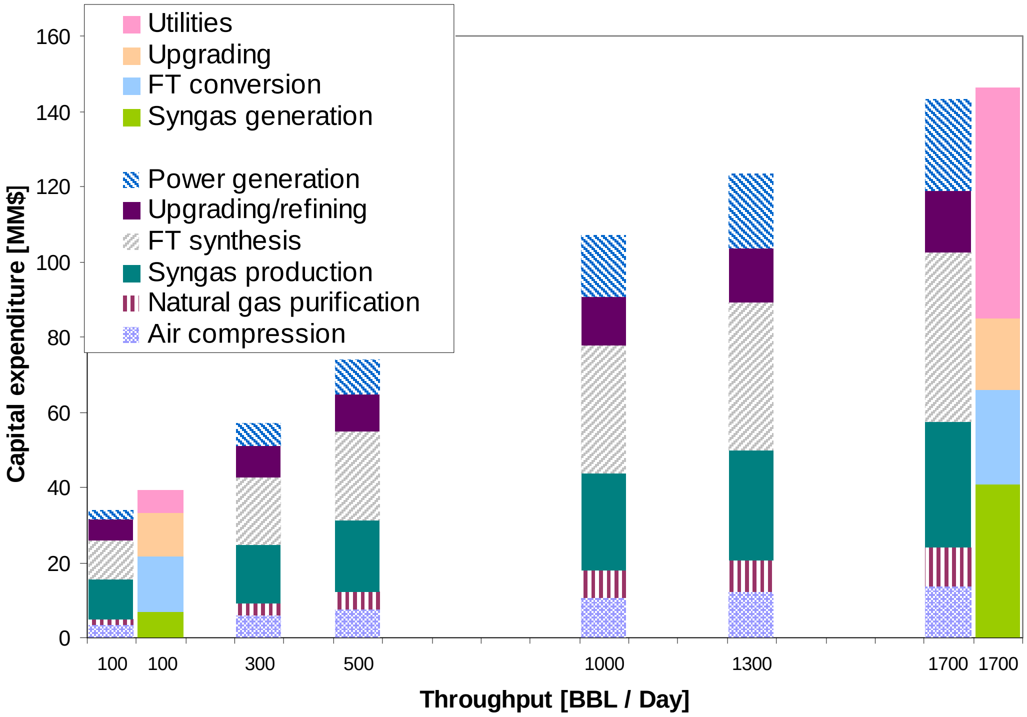
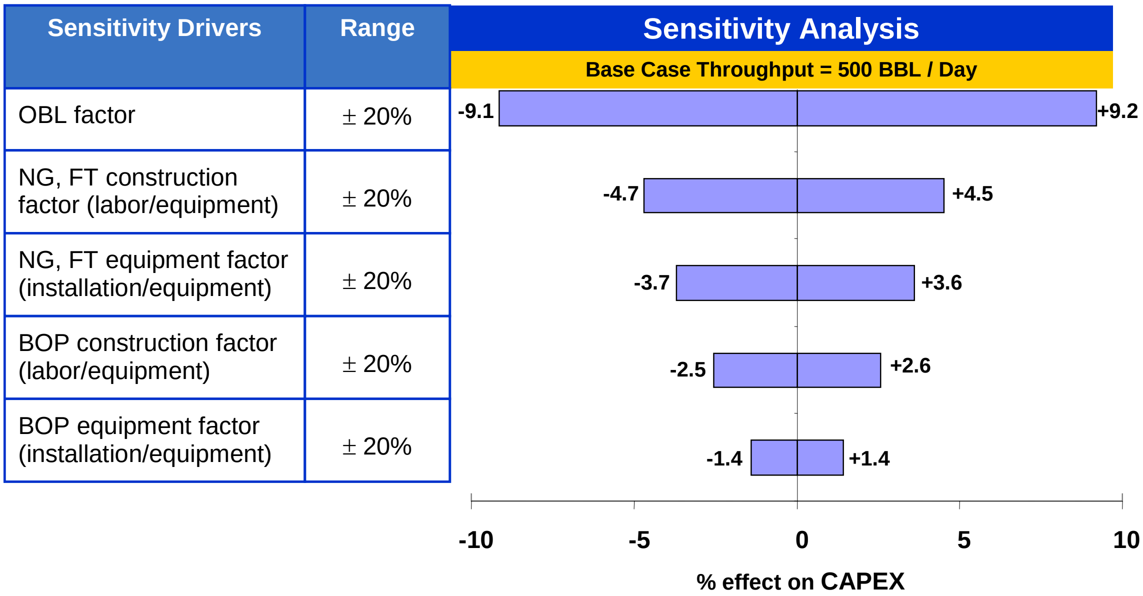


Figure 9. Sensitivity analysis on the capital cost factors for constructing a small footprint plant.



Sensitivity Drivers	Range
OBL factor	± 20%
NG, FT construction factor (labor/equipment)	± 20%
NG, FT equipment factor (installation/equipment)	± 20%
BOP construction factor (labor/equipment)	± 20%
BOP equipment factor (installation/equipment)	± 20%

Figure 10. TIAX estimates of operating costs for stick-built small footprint plants.

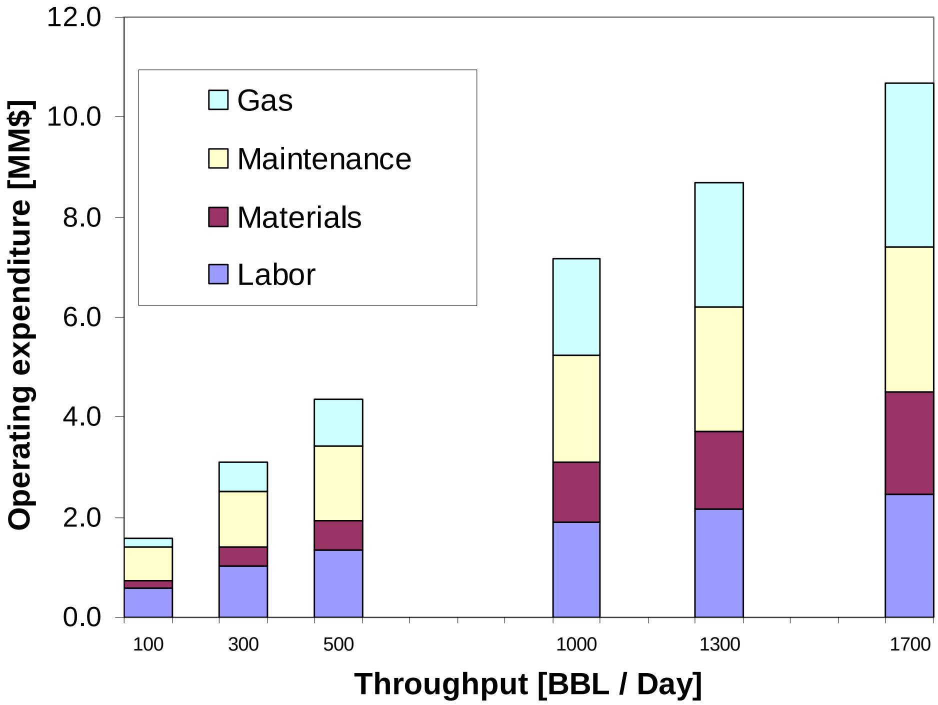
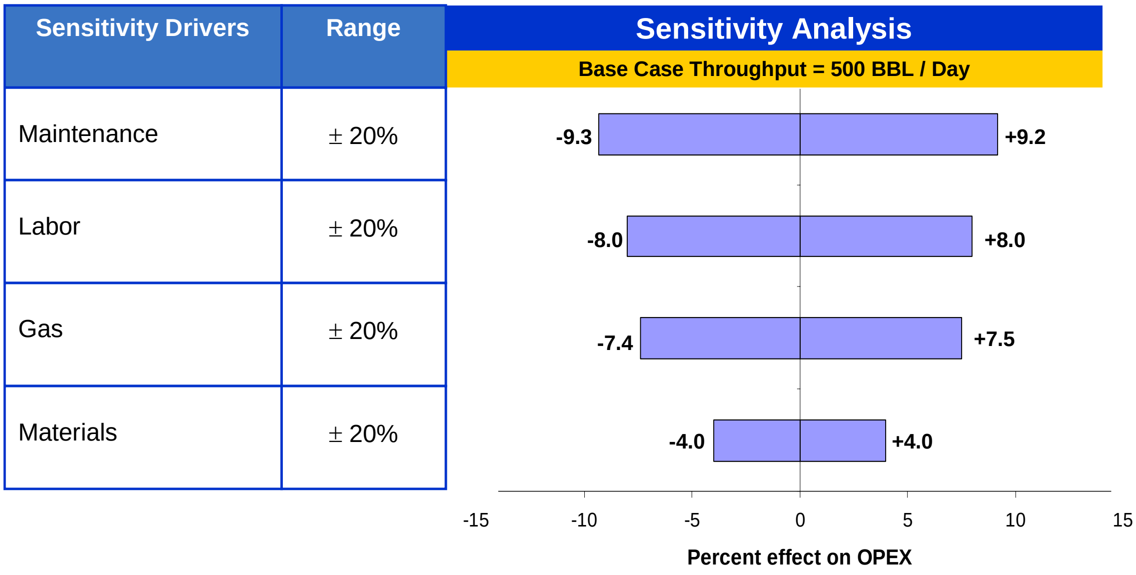


Figure 11. Sensitivity analysis on the operating expenses of a stick-built small footprint plant.



Sensitivity Drivers	Range
Maintenance	± 20%
Labor	± 20%
Gas	± 20%
Materials	± 20%

According to our sensitivity analysis (Figure 11), maintenance, labor and feedstock cost all have roughly the same effect on the operating expenses. Reducing the amount of natural gas (at a set cost for the feedstock) would yield smaller OPEX, but at the penalty of lower throughput and hence less revenue. Only decreases in the maintenance and labor costs could decrease costs while sustaining operation levels.

A possible alternative: GTL-in-a-Can™

The revised economic analysis presented above suggests that a small footprint plant would become significantly more profitable and possibly more robust if a way could be found to decrease capital costs and operating costs in the smaller size range (<1000 bpd). To address those issues, in prior work at Arthur D. Little, the predecessor to TIAX, our staff had investigated ways to integrate the synthesis gas generation reactor and the Fischer-Tropsch reactor in one pressure vessel. The combined unit, which we call GTL-in-a-Can™ appears to be well positioned to become part of a fieldable, modular plant that promises better decreased capital and operating costs as well as increased transportability and reliability than a “stick-built” plant. Our preliminary costing suggests that fuel products could be synthesized for less than $1/gal with a capital cost of $25 million for a 500-1000 bpd plant, about half the costs associated with a stick-built plant. The savings arise from the decreased need for personnel, since we envisage the modular plant being highly automated, and the decreased construction costs, since we envisage the modular plant being produced at high enough volume that it benefits from economies of scale. Such a plant might be used in a number of ways, for example:

- Monetization/utilization of small, remote resources—the topic of this project
- Upgrading/interconversion of fuels—of possible interest to the military
- Alternative to flaring—to permit drilling of exploration wells or monetization of associated gas
- Conversion of gaseous or liquid fuels to hydrogen or methanol, or other alternative transportation fuels—again, of possible interest to the military or remote communities.

A system that incorporates all of these features has not been built or tested however we can still estimate its costs and likely performance based on literature data for the performance of the well-known unit operations and cost estimates that are based on standard literature correlations. We include an analysis of this concept as an adjunct to our analysis of the conventional plan in order to stimulate thinking of novel ways to monetize stranded resources and serve remote communities.

The modular plant incorporates the heart of the GTL plant (Figure 12) in one reactor unit (Figure 13). The reactor unit must be designed to ensure heat integration and the proper flow of species. By arranging the operations concentrically the hottest zone can be located deep inside the can, obviating the need for materials of construction that must withstand both high temperature and high pressure.

In our economic analysis we estimate that a plant that consumes 10 million scf/day of gas (equivalent to about 750 bpd of liquid products) can be built for about $25 million and operated at a cost of about $2.5 million/year. Automating the operation of the plant both decreases the number of operators required to run it and, potentially, makes the plant safer and more robust. The inherently simpler design also allows for more economical relocating the plant, which becomes a viable option if the plant is able to consume the locally available feedstock in only a fraction of the plant's useful life.

Costs and profits

A comparison of Figure 14 and Figure 15 shows that even at the smallest plant size, an integrated GTL-in-a-Can™ process is far more profitable than a stick built plant owing to the much smaller contributions of CAPEX and OPEX to the cost of producing a gallon of diesel fuel.

Figure 12. Schematic of a GTL-in-a-Can™ process showing the components included in the can.

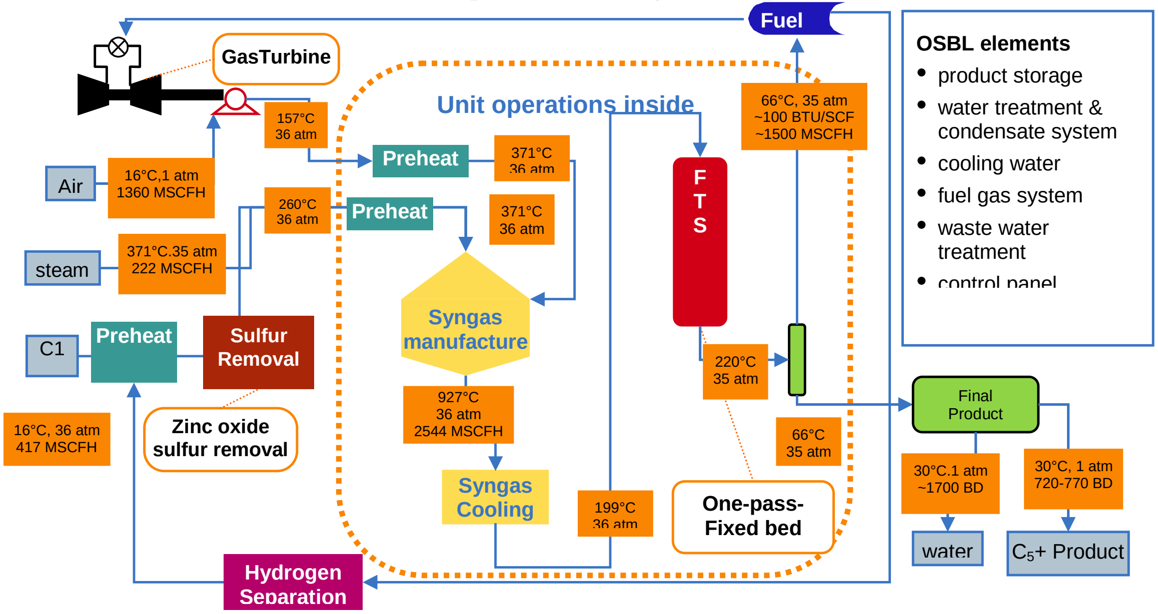


Figure 13. Schematic of the Integrated Modular GTL Technology, GTL-in-a-Can™. The aspect ratio is distorted to show detail.

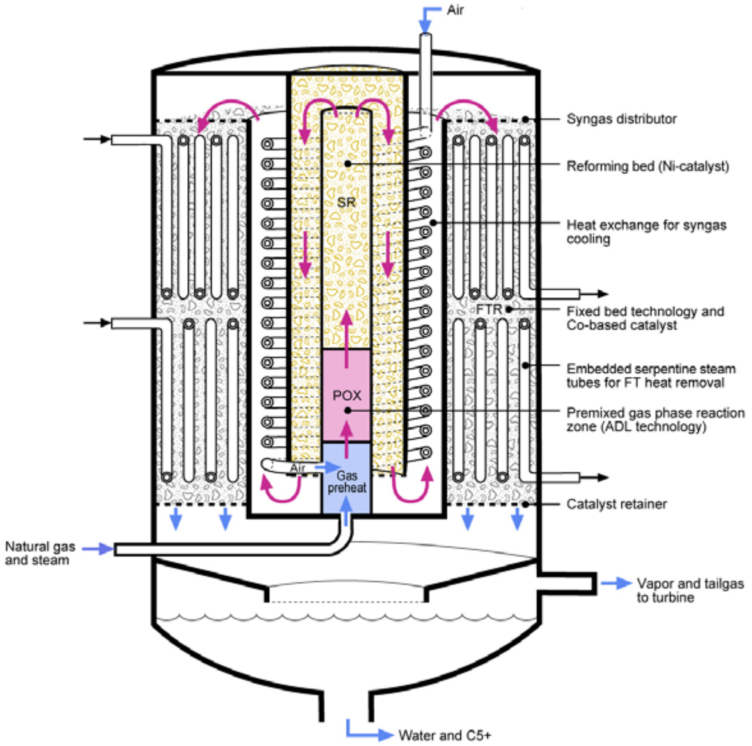


Figure 14. Effect of plant size on profitability for a stick built plant.

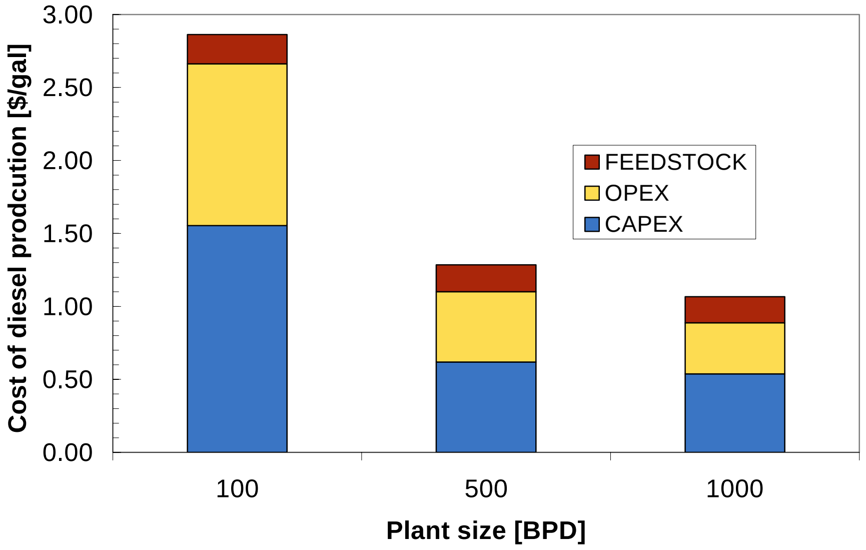
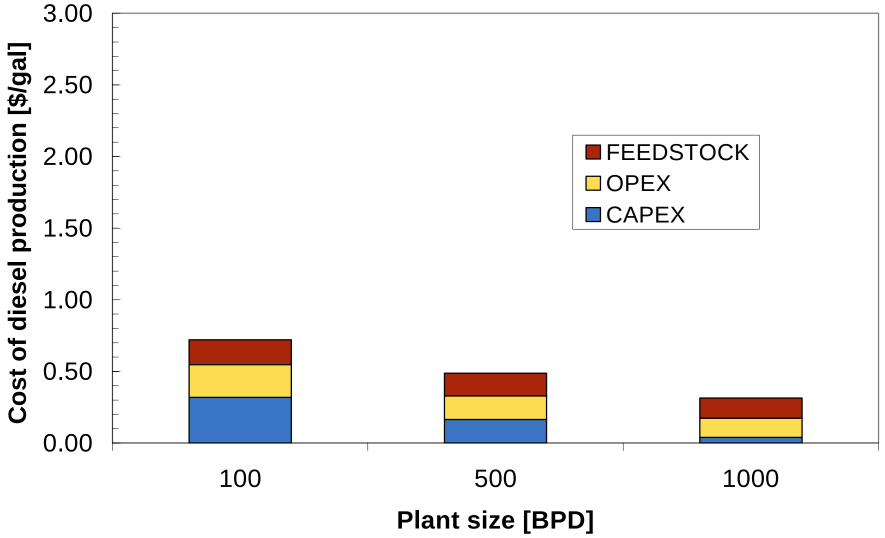
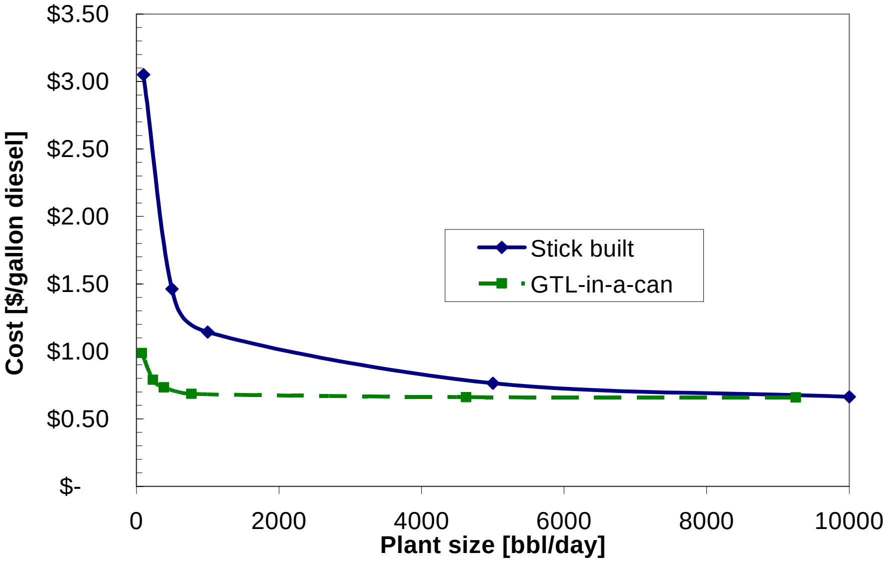


Figure 15. Effect of plant size on the profitability of a GTL-in-a-Can™ plant



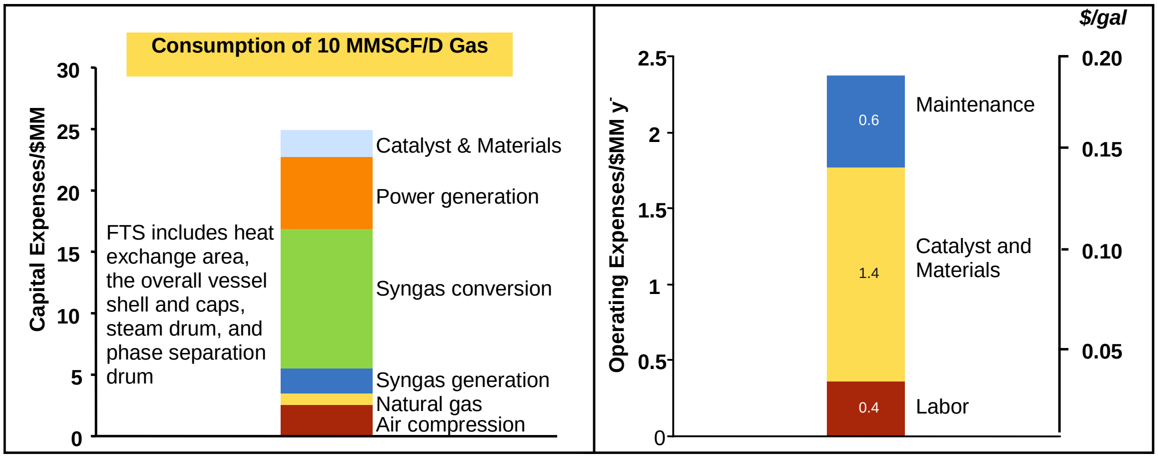
The economies of scale for the GTL-in-a-can™ approach change most rapidly at much smaller throughputs than they do for stick built plants, but there is relatively little to be gained by increasing capacity for plants larger than about 200 bbl/day (Figure 16). Stick-built plants, on the other hand, show significant improvement in their economic performance as the capacity is increased from 100 to 1000 bbl/day. Owing to the lower efficiency (Table 4) of GTL-in-a-can™, at high throughputs, when feedstock costs start to dominate over capital costs, the stick built plant becomes more profitable. This transition occurs at roughly 9,000 bbl/day.

Figure 16. Comparison between GTL-in-a-can™ and stick built plants on the cost of producing 1 gallon of FT diesel



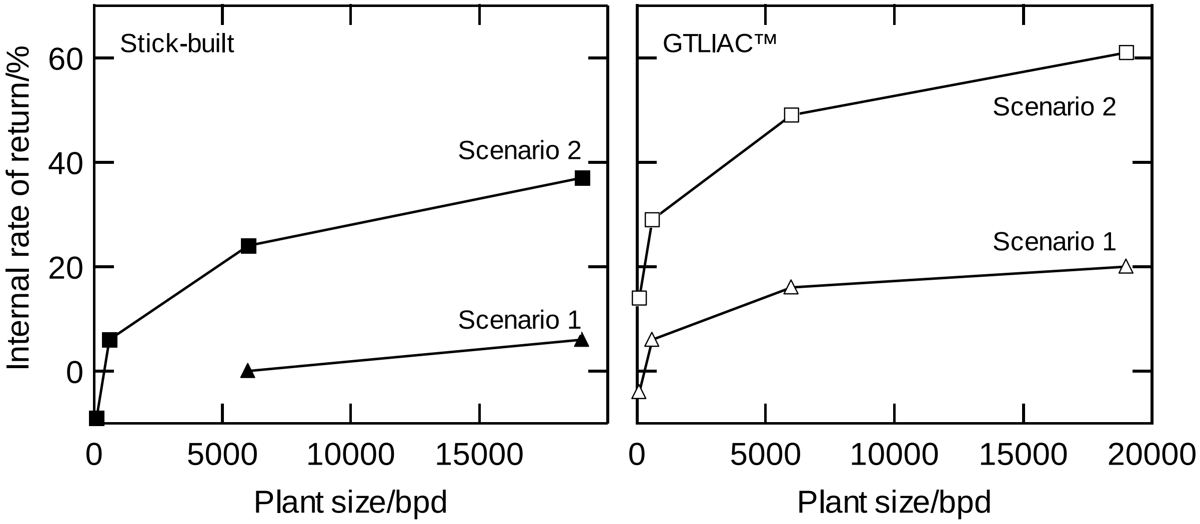
Syngas conversion (the Fischer-Tropsch process) is the most expensive contribution to the capital expense, as it was for the stick-built plant; however, we stress that direct cost comparisons of unit operations can not be made because of the differences in where certain costs were allocated.

Figure 17. Estimated costs of GTL-in-a-Can™ at a size of 10 million scf/day (750 bpd products).



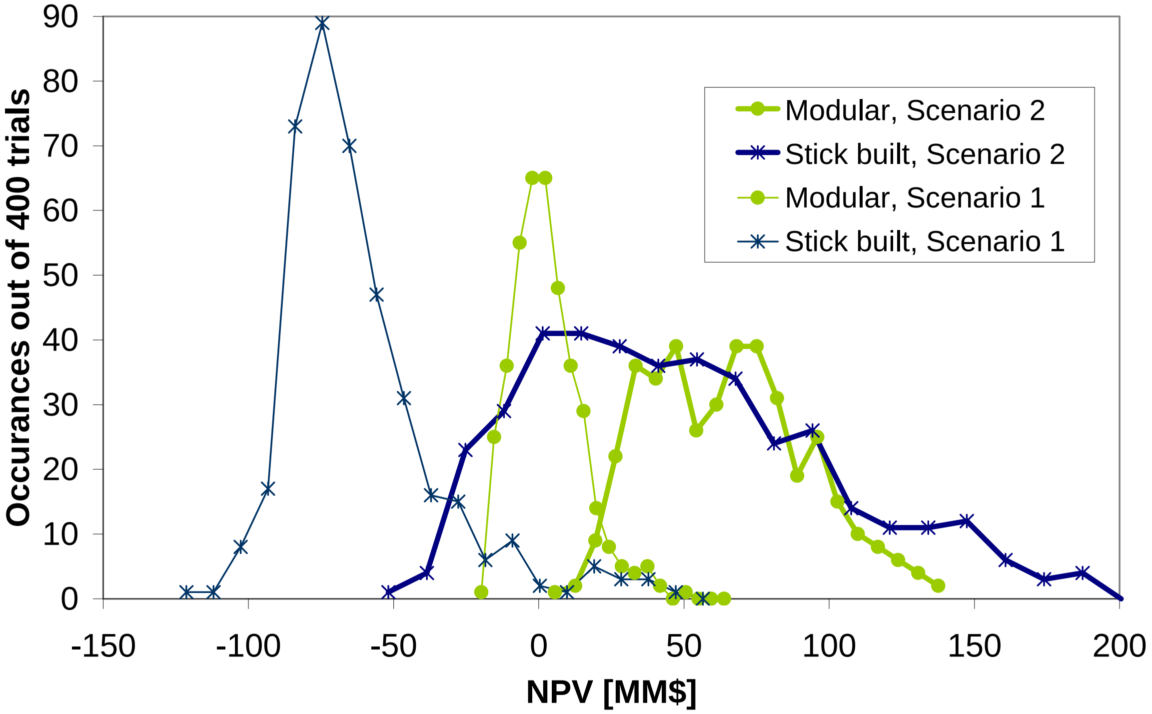
The price of oil is a major, external factor that affects the economics of a GTL plant since we have assumed that the fuel products will be sold without any premium. The finite costs associated with building and operating either sort of small footprint plant imply that there is a throughput below which the plants cannot operate profitably (Figure 18). For a stick-built plant we estimate that the facility must be larger than 6000 bpd for it to return a positive cash flow if the products are to be sold at the low prices assumed in Scenario 1 ($24/bbl oil). For that same scenario, a plant constructed along the lines of our hypothetical GTL-in-a-Can™ would be profitable at much smaller plant sizes. Evidently, both types of plants become more profitable if their products can be sold for more money. Again, however, the envisaged economies that attend the lower capital and operating costs for a unitized plant would suggest that it would be the better investment at these small throughputs.

Figure 18. Comparison of estimated profitability of two small footprint plants



The Monte Carlo analysis (Figure 19) shows that a stick-built plant is more likely to exhibit unfavorable net present values than a modular plant over a wide range of values in the economic and performance parameters. The distributions overlap to a significant extent when the price of the product fuel is high and, as mentioned above, we know from other work that the higher thermal efficiency of a stick-built plant will confer considerable economic advantage at even larger throughputs.

Figure 19. A Monte Carlo analysis of the NPV20 of the two 500 bbl/day GTL technologies shows that the modular plant always exhibits a higher expected return than does a stick built plant. In all cases, the plants are configured to export electricity.



Looking at the CAPEX breakdown of the GTL-in-a-can plant (Figure 17) one of the biggest costs is power generation. However, this investment yields great returns (Figure 20). The incremental value of selling electricity (i.e. the difference in the height of the respective bars) is almost equal to the NPV of the plant without it. The additional cost of buying a larger gas turbine (operating on tail gas) to not just supply the plant with electricity, but also to export it is easily recovered. There is, however, a discrepancy in the amount of fuel and electricity produced in light of demand. When generating enough electricity to meet a certain market demand, more fuel is produced (by several orders of magnitude) than is consumable by the same market.

This mismatch between fuel and electricity production can not necessarily be solved by exporting the fuel because of the costs associated with transportation. As is shown in Figure 21 the further a plant is sited from the petroleum-product distribution rack, the more profitable it will be. The opposite is also likely to be true for the case of exporting fuel from a GTL process, where the further it must be exported the smaller the margin on the sale. And if it were economical to import the fuel, it would be done preferentially, thus obviating the need for GTL production.

It is just such considerations that suggest that Alaska as a natural host for small scale GTL processes since there two principal differences compared to the situation in the Lower 48 states with respect to the distribution and distributability of fuel and electricity:

1. Virtually all of Alaska is so remote from a petroleum product “rack” that diesel fuel produced in one part of Alaska is still closer to the other parts of Alaska than to any competing “rack”. Therefore, movement of locally produced diesel fuel within Alaska to balance the plant’s output supply and demand (such as along a river in barges as is now done to supply dozens of remote villages, for example) is far more likely to be viable in Alaska than it would be in the lower 48. Conversely, movement of electric power between

remote villages of Alaska is virtually out of the question since there is no electrical grid. However, in the lower 48, with an extensive electrical grid already in place, movement of any excess produced electricity might be possible.

2. There are some mining or other potential industrial projects in remote areas of Alaska that might require such large amounts of electricity that a fairly large-scale F-T plant producing base-load electricity might be the only realistic way to provide the required electric power. With judicious selection of plant location, the associated F-T fuel produced could be moved as described in 1. above. Furthermore, in Alaska, where most remote electricity is currently produced primarily by diesel power, there is some degree of "interchangeability" between electricity and diesel fuel when it comes to meeting variable electrical demand.

Thus, the next section of this report considers the case of deploying small footprint plants in Alaska.

Figure 20. Effect on the NPV20 of selling electricity at $30/MWh for a 500 bbl/day modular GTL plant

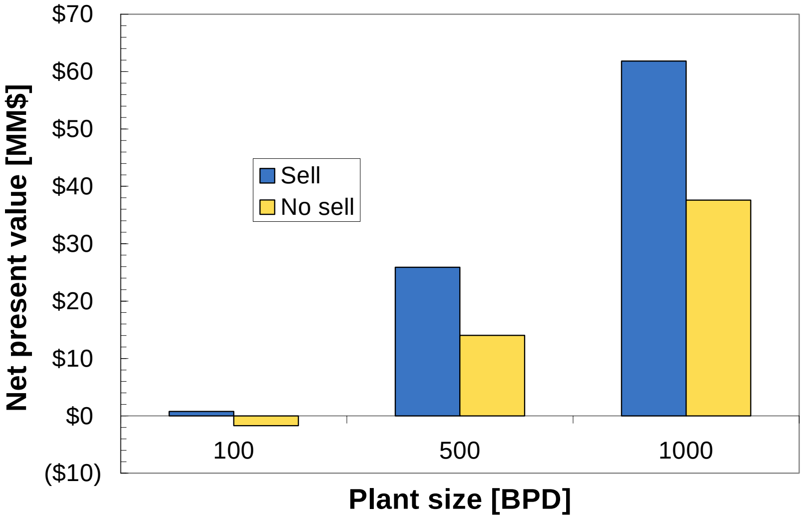
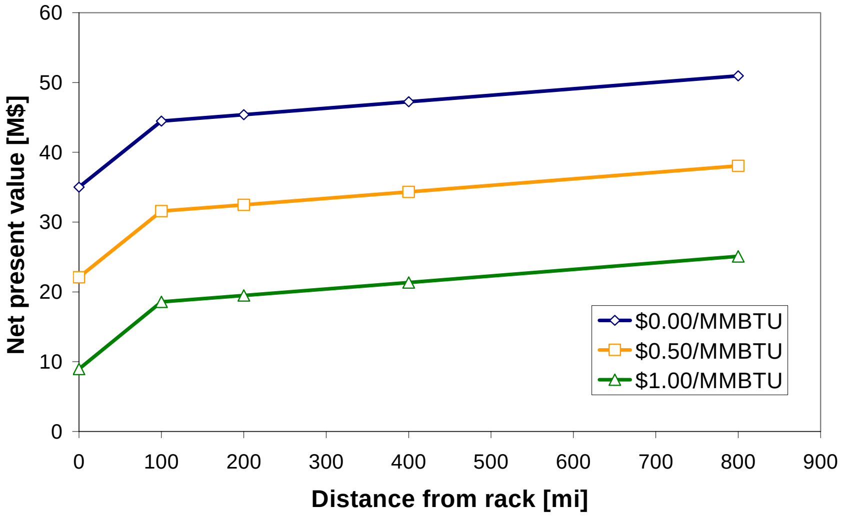


Figure 21. Location effects on the net present value for 20 years of operation of a 500 bbl/day, modular GTL plant



Location dependencies: Alaska

There are substantial economic benefits to be gained by siting a small footprint GTL plant in Alaska. A high number of small natural gas fields and available biomass facilitate the acquisition of raw materials. More importantly, Alaska's remote communities are forced to pay high prices for their fuel and electricity. The high prices are a direct result of distance. Transmission and transportation costs require the fuel and electricity to be sold at double the prices seen in the Lower 48 States. Small footprint GTL plants are thus an economic solution because they can be cited near communities and sell their products with much higher margins.

The following tables show the profitability metrics for GTL-in-a-can™ plants in two locations (Lower 48 States and Alaska) with two feedstocks (biomass and natural gas) and two feedstock costs (baseline and free). All of the cases were run with the product prices of Scenario 2. When electricity is produced for export we assume that we can convert 25% of the heating value of the tailgas to power on the grid. The option without electricity is always cheaper (CAPEX) than the option with electricity because it involves purchase of a larger gas turbine. This extra cost of the turbine adds to the cost of producing a gallon of diesel. The revenue from electricity is not included in this metric, but is included in the IRR and NPV.

The returns shown in the tables assume that naphtha, the other major product from the GTL process, can be sold at a price comparable to its historical mean. For remote plants, monetizing the naphtha will require shipping unless it can be burned locally as a fuel. Evidently, having to transport the naphtha would obviate one of the primary benefits envisaged for a small footprint plant, namely autonomy.

Table 9. Estimates of investments and returns from modular GTL plants located in the Lower 48 States as a function of feedstock (natural gas) price.

$1 / MMBTU

BPD	**100**		**600**		**6000**		**19000**	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	9.173	8.496	29.24	26.13	157.5	135.6	385.4	326.9
OPEX [MM$]	0.807	0.7954	4.401	4.347	41.6	41.22	129.9	128.9
Diesel [$/gal]	0.84	0.80	0.59	0.56	0.45	0.43	0.42	0.40
IRR	***14%***	***10%***	***29%***	***23%***	***49%***	***42%***	***61%***	***53%***
NPV [MM$]	***6.64***	***2.7***	***69.5***	***45.0***	***822.3***	***570.8***	***2708.0***	***1901.0***

$0 / MMBTU

BPD	**100**		**600**		**6000**		**19000**	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	*9.173*	8.496	29.24	26.13	157.5	135.6	385.4	326.9
OPEX [MM$]	*0.3126*	*0.301*	1.434	1.381	12.01	11.64	36.12	35.12
Diesel [$/gal]	0.41	0.37	0.15	0.12	0.02	0.00	-0.02	-0.03
IRR	***18%***	***14%***	***34%***	***29%***	***57%***	***52%***	***71%***	***65%***
NPV [MM$]	***9.9***	***6.0***	***89.0***	***64.5***	***1017.0***	***765.4***	***3324.0***	***2518.0***

Power gen. [MW]	*1.09*	6.56	65.6	207.8

Table 10. Estimates of investments and returns from modular GTL plants located in Alaska as a function of feedstock (natural gas) price.

$1 / MMBTU

BPD	100		600		6000		19000	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	*10.08*	*9.404*	31.58	28.48	165.5	143.5	400	341.5
OPEX [MM$]	*0.8225*	*0.8109*	4.441	4.38	41.73	41.36	130.1	129.1
Diesel [$/gal]	0.89	0.85	0.61	0.58	0.46	0.44	0.42	0.40
IRR	***15%***	***9%***	***30%***	***21%***	***52%***	***40%***	***65%***	***51%***
NPV [MM$]	***8.0***	***1.9***	***80.1***	***43.0***	***941.7***	***563.8***	***3095.0***	***1888.0***

$0 / MMBTU

BPD	100		600		6000		19000	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	*10.08*	*9.404*	31.58	28.48	165.5	143.5	400	341.5
OPEX [MM$]	*0.3281*	*0.3165*	1.474	1.421	12.15	11.77	36.37	35.37
Diesel [$/gal]	0.46	0.42	0.18	0.15	0.03	0.01	-0.01	-0.03
IRR	***18%***	***12%***	***34%***	***27%***	***60%***	***50%***	***75%***	***63%***
NPV [MM$]	***11.2***	***5.2***	***99.6***	***62.5***	***1136.0***	***758.5***	***3712.0***	***2505.0***

Power gen. [MW]	*1.09*	6.56	65.6	207.8

Table 11. Estimates of the investments and returns from modular GTL plants located in the Lower 48 States as a function of feedstock (biomass) price.

$20 / ton

BPD	100		600		6000		19000	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	*74.29*	*74.24*	292.3	289.2	1731	1709	4259	4201
OPEX [MM$]	*2.15*	*2.139*	10.21	10.16	81.61	81.24	237.6	236.6
Diesel [$/gal]	4.88	4.87	3.37	3.34	2.19	2.17	1.81	1.79
IRR	***-14%***	***-21%***	***-8%***	***-11%***	***-1%***	***-4%***	***1%***	***-1%***
NPV [MM$]	***-68.8***	***-72.7***	***-226.8***	***-251.1***	***-861.0***	***-1114.0***	***-1400.0***	***-2092.0***

$0 / ton

BPD	100		600		6000		19000	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	*74.29*	*74.24*	292.3	289.2	1731	1709	4259	4201
OPEX [MM$]	*1.437*	*1.423*	5.932	5.879	38.92	38.54	102.4	101.4
Diesel [$/gal]	4.26	4.24	2.74	2.71	1.57	1.54	1.19	1.17
IRR	***-9%***	***-12%***	***-4%***	***-6%***	***2%***	***0%***	***5%***	***3%***
NPV [MM$]	***-61.1***	***-65.0***	***-180.8***	***-205.0***	***-478.8***	***-670.3***	***-369.5***	***-920.0***

Power gen. [MW]	*0.7*	4.2	42	133

Table 12. Estimates of the investments and returns from modular GTL plants located in the Alaska as a function of feedstock (biomass) price

$20 / ton

BPD	100		600		6000		19000	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	*75.83*	*75.15*	294.6	291.5	1739	1717	4274	4215
OPEX [MM$]	*2.166*	*2.154*	10.25	10.2	81.75	81.38	237.9	236.9
Diesel [$/gal]	4.97	4.93	3.39	3.36	2.20	2.18	1.82	1.80
IRR	***-13%***	***-22%***	***-7%***	***-12%***	***0%***	***-5%***	***2%***	***-1%***
NPV [MM$]	***-67.7***	***-73.7***	***-216.5***	***-253.8***	***-742.0***	***-1123.0***	***-1107.0***	***-2110.0***

$0 / ton

BPD	100		600		6000		19000	
	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
CAPEX [MM$]	*75.83*	*75.15*	294.6	291.5	1739	1717	4274	4215
OPEX [MM$]	*1.452*	*1.441*	5.972	5.919	39.05	38.68	102.6	101.6
Diesel [$/gal]	4.34	4.30	2.76	2.73	1.57	1.55	1.19	1.17
IRR	***-8%***	***-12%***	***-3%***	***-6%***	***3%***	***0%***	***6%***	***3%***
NPV [MM$]	***-60.0***	***-66.1***	***-170.5***	***-207.8***	***-392.9***	***-678.4***	***-107.0***	***-933.8***

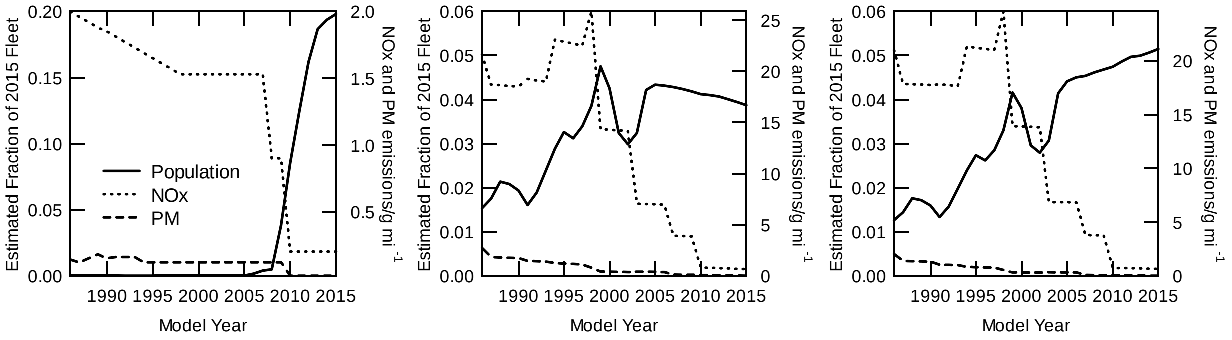
Power gen. [MW]	*0.7*	4.2	42	133

The biomass option in these tables is based on a published estimates for the costs of constructing stick-built biomass gasifiers [15-17]. If gasification proved to be a popular option then the front end equipment would be designed for large-scale manufacture, much as we envisage for GTL-in-a-Can™. In that case, the cost of the gasifier might fall as much as 50%, leading to very significant improvements in the overall economics. For example, we estimate that the net present value of a 600 bpd plant with a 50% cheaper gasifier increases from a loss of $82 million to a profit of about $40 million. Evidently, this option should be explored in more detail.

Well-to-Wheels Analysis

By combining published studies on the emissions benefits from using ultraclean GTL-derived fuels and our previous work on future powertrains, we have constructed well-to-wheels comparisons of the emissions and fuel economy for vehicles fueled with Fischer-Tropsch diesel and conventional diesel. The tank-to-wheels fuel economies of the two fuels are similar (differing primarily because of the slightly different specific and volumetric heating values) and we ignored the difference. There is a consensus that older style engines (pre-2004) fueled with Fischer-Tropsch diesel emit significantly less particulate matter and nitrogen oxides (we assumed 9% less NOx and 32% less PM). On the contrary, the compression-ignition powertrains that will be produced starting in 2007 will derive much less benefit from special fuels unless their control systems are capable of recognizing and taking advantage of the properties of ultra-clean high-Cetane fuels. Indeed, there are preliminary indications that the use of high cetane fuels in engines whose duty cycle includes homogeneous charge compression ignition may increase NOx emissions. Although this situation will likely be rectified in the future, to make our analysis conservatively realistic we assumed that the benefits of FTD accrued only to the fraction of the 2015 fleets containing pre-2007 model year vehicles. The vehicles we chose, a light duty pickup truck, an urban bus and a utility vehicle (refuse truck) were consistent with the idea that GTL-derived fuels from small footprint plants would be used in the immediate vicinity of the plant. For that reason, we did not include any long haul trucks.

Figure 22. Age distribution of compression ignition-powered vehicles projected to 2015 (the three graphs are for pickups, buses and refuse haulers, from left to right).



Three types of emissions were estimated: nitrogen oxides (NOx), particulate matter (PM) and carbon dioxide (Table 13). Because of the very long life and slow turnover of heavy duty vehicles, the older vehicles comprised almost 80% of those fleets (Figure 22). Because there are so few light duty diesel vehicles in the current fleet, the benefits of using GTL-derived fuels are projected to be very small in this category. Significant savings in NOx and PM were projected for the two heavier vehicles. Since the GTL process consumes a much larger portion of the feedstock for just the operation of the plant than does a conventional refinery (60% in our model versus about 20% for a refinery), there is a significantly larger CO_2 burden for using GTL compared to that of using petroleum-derived diesel fuel. However, biomass-derived GTL fuels can, in principle, exhibit net zero CO_2 emissions.

Table 13. Emissions benefits of using FTD in vehicle fleets projected to 2015. Emissions that can be attributed to a fleet of each vehicle type whose size could be fueled by the capacity of the indicated small footprint plant. Carbon dioxide emissions for the plant

			ΔNOx (kg)	**ΔPM (kg)**	**ΔCO2 (kg)**	
	Vehicle Type	**Fleet Size**	(DF2 - FTD)	(DF2 - FTD)	(DF2 - FTD(NG))	(DF2 - FTD(Biomass))
100 BPD FTD	Pick-up	1,698	87	41	(608,550)	605,764
	Bus	136	10,608	1,426	(7,763,592)	12,596,586
	Refuse	157	7,512	717	(7,193,835)	10,215,889
600 BPD FTD	Pick-up	10,189	525	246	(3,651,301)	3,634,584
	Bus	818	63,647	8,553	(46,581,551)	75,579,514
	Refuse	942	45,074	4,301	(43,163,008)	61,295,337
6000 BPD FTD	Pick-up	101,886	5,245	2,460	(36,513,011)	36,345,836
	Bus	8,176	636,474	85,534	(465,815,510)	755,795,140
	Refuse	9,419	450,738	43,008	(431,630,076)	612,953,369

Figure 23. Effect on NOx emissions of fueling various fleets in 2015 with DF2 or FTD

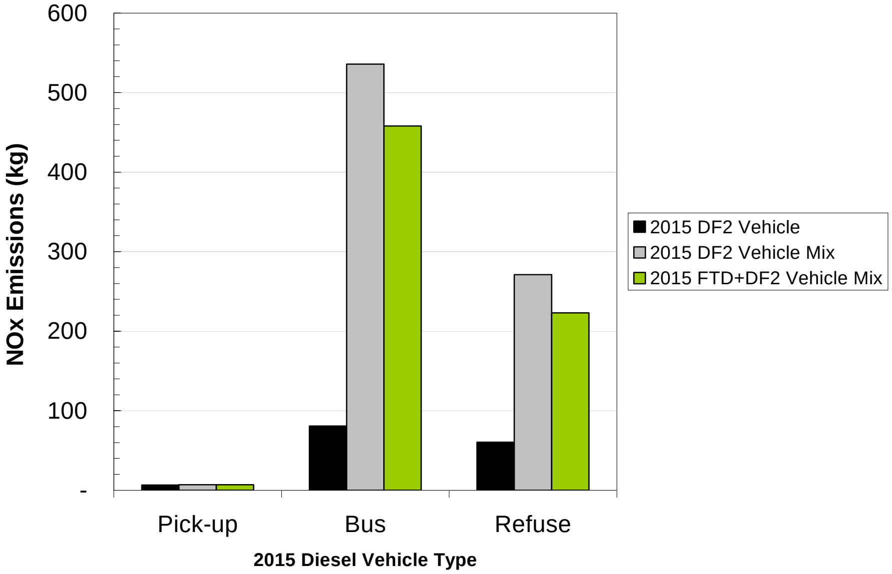


Figure 24. Effect on PM emissions of fueling various fleets in 2015 with DF2 or FTD

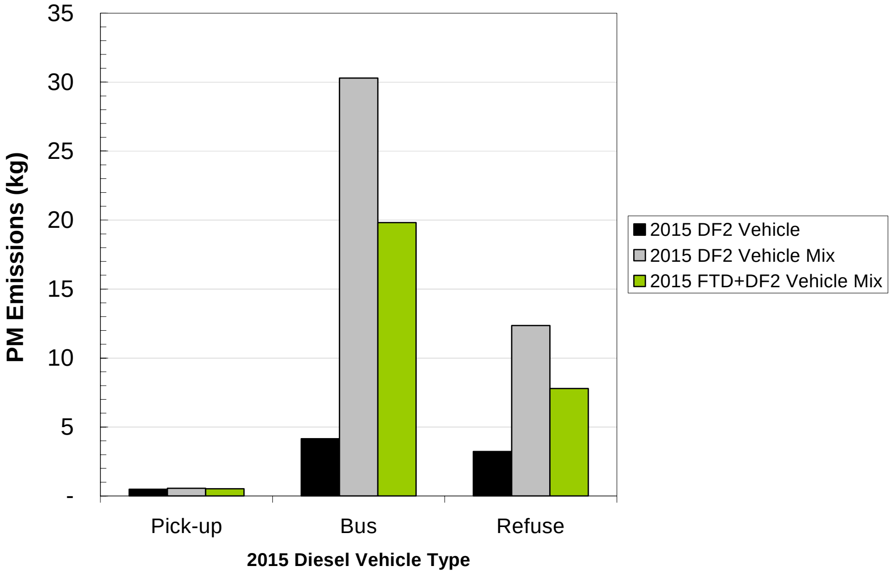
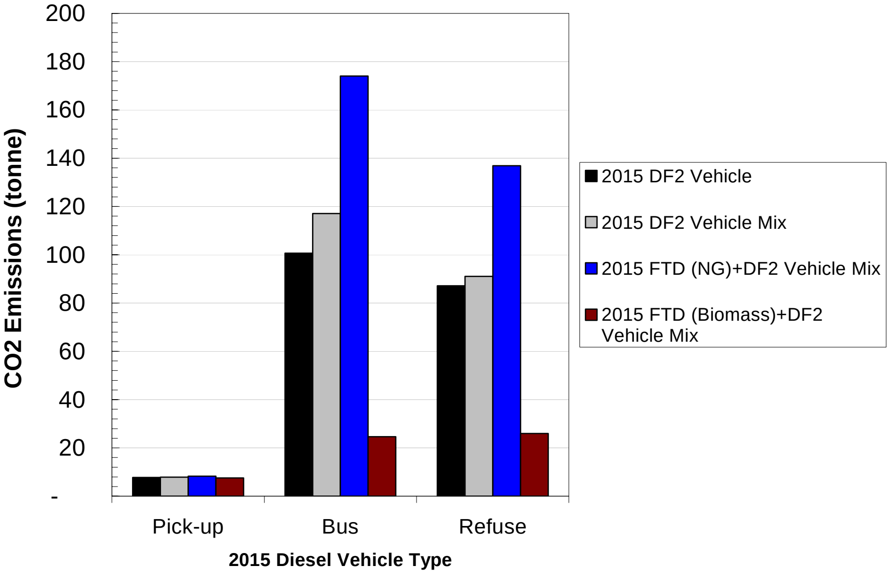


Figure 25. Effect on CO_2 emissions of fueling various fleets with DF2 and FTD derived from two different feedstocks, natural gas and biomass



Finally, by combining the net present value (20-year) of the modular GTL plants with the emission benefits, we estimated the cost of emissions abatement from the projected use of these cleaner fuels (Tables 14-22). These calculations all assumed a feedstock price of either $1/mmBTU (natural gas) or $20/tonne (biomass) and the more favorable product prices of Scenario 2. Since many size ranges of the GTL plants provide positive net present values, negative costs in the tables below signify that the plant is "getting paid" for the emission reduction. In fact, except for the smallest vehicles and smallest plant sizes, even in the cases where the GTL plant does not operate profitably (biomass conversion), it still competes quite favorably with the costs of alternate ways of abating NOx, particulate matter and CO_2 (Table 23).

Thus, the total package of benefits—energy security, energy supply for remote locations and cost-effective (or, profitable) emissions reductions—support the continued development of small footprint GTL plants and the extension of the technology towards biomass feedstocks.

Table 14. Estimated cost per ton for abating NOx using FTD in a 2015 population of light vehicles

Plant size, bpd

Pickup NOx, M$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG	-4	-2	-7	-4	-8	-5	-8	-6
Alaska NG	-5	-1	-8	-4	-9	-5	-9	-6
48 Biomass	39	42	22	24	8	11	4	6
Alaska biomass	39	42	21	24	7	11	3	6

Table 15. Estimated cost per ton for abating NOx using FTD in a 2015 population of urban buses

Plant size, bpd

Bus NOx k$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG	-31	-13	-55	-35	-65	-45	-67	-47
Alaska NG	-38	-9	-63	-34	-74	-44	-77	-47
48 Biomass	324	342	178	197	68	88	35	52
Alaska biomass	319	348	170	199	58	88	27	52

Table 16. Estimated cost per ton for abating NOx using FTD in a 2015 population of utility vehicles

Plant size, bpd

Utility NOx, k$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG	-44	-18	-77	-50	-91	-63	-95	-67
Alaska NG	-53	-13	-89	-48	-104	-63	-108	-66
48 Biomass	458	484	252	279	96	124	49	73
Alaska Biomass	451	491	240	282	82	125	39	74

Table 17. Estimated cost per ton for abating PM using FTD in a 2015 population of light vehicles

Plant size, bpd

Pickup PM, M$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG	-8	-3	-14	-9	-17	-12	-17	-12
Alaska NG	-10	-2	-16	-9	-19	-11	-20	-12
48 Biomass	84	89	46	51	17	23	9	13
Alaska biomass	83	90	44	52	15	23	7	14

Table 18. Estimated cost per ton for abating PM using FTD in a 2015 population of urban buses

Plant size, bpd

Bus PM, k$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG	-233	-95	-406	-263	-481	-334	-500	-351
Alaska NG	-279	-67	-468	-251	-550	-330	-571	-349
48 Biomass	2413	2548	1326	1468	503	651	258	386
Alaska biomass	2375	2586	1266	1484	434	656	204	390

Table 19. Estimated cost per ton for abating PM using biomass-derived FTD in a 2015 population of utility vehicles

Plant size, bpd

Utility PM, k$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG	-463	-189	-807	-523	-956	-664	-994	-698
Alaska NG	-555	-133	-931	-500	-1095	-655	-1136	-693
48 Biomass	4800	5068	2637	2919	1001	1295	514	768
Alaska Biomass	4723	5144	2517	2951	863	1306	406	775

Table 20. Estimated cost per ton for abating CO_2 using biomass-derived FTD in a 2015 population of light vehicles

Plant size, bpd

Pickup CO_2, $/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG								
Alaska NG								
48 Biomass	5680	5997	3120	3454	1184	1533	608	909
Alaska biomass	5589	6087	2978	3491	1021	1545	481	917

Table 21. Estimated cost per ton for abating CO_2 using biomass-derived FTD in a 2015 population of urban buses

Plant size, bpd

Bus CO_2, \$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG								
Alaska NG								
48 Biomass	273	288	150	166	57	74	29	44
Alaska biomass	269	293	143	168	49	74	23	44

Table 22. Estimated cost per ton for abating CO_2 using biomass-derived FTD in a 2015 population of utility vehicles

Plant size, bpd

Utility CO_2, \$/t	100		600		6000		19000	
Electricity option	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec	w/ elec	w/o elec
48 NG								
Alaska NG								
48 Biomass	337	356	185	205	70	91	36	54
Alaska Biomass	331	361	177	207	61	92	29	54

Table 23. Comparison of the cost effectiveness of various approaches to emission abatement

Species	Abatement Credit or Cost \$/t	Comment
NOx	14000	Typical value for California's Moyers Program, TIAX estimate
NOx	2550	2007 SIP trading credit, www.evomarkets.com
PM	5400	Lifecycle cost of a 2007 particulate filter divided by total vehicle pm production, TIAX estimate
CO_2	18-41	Estimated costs of CO_2 sequestration, sequestration.mit.edu/pdf/David_and_Herzog.pdf

We present below two graphs (Figure 26, Figure 27) that indicate our best estimates of the CO_2 emissions from producing and consuming conventional and Fischer-Tropsch diesel fuel. In both cases the tank-to-wheels bars are approximately the same heights since both fuels contain nearly the same energy content. The energy employed, and hence CO_2 emissions, from transporting the fuels and from abating emissions are very small (1-2% of the total) and depend strongly on the actual duty cycle. The largest difference between the two panels is the CO_2 emissions associated with producing the two fuels.

Figure 26. Estimates of well-to-wheels emissions of CO_2 associated with the use of conventional diesel fuel. Well-to-Tank emissions have been derived from EIA estimates.

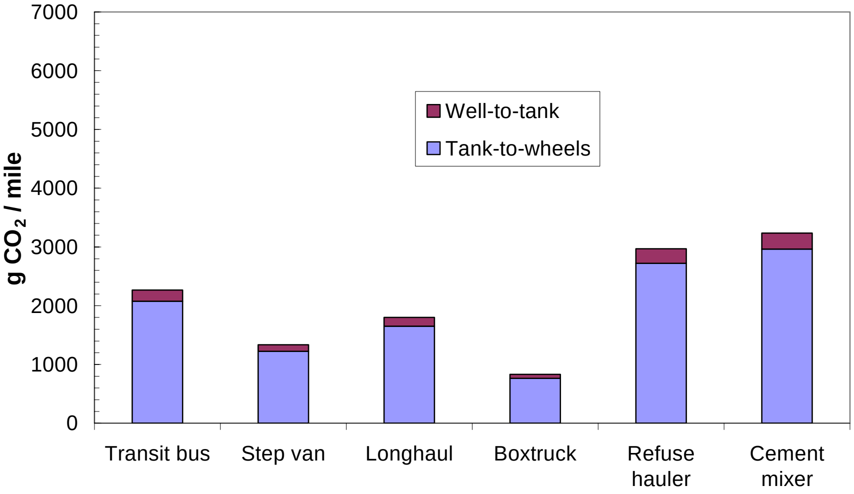


Figure 27. Estimate of well-to-wheels emissions of CO_2 associated with the use of conventional diesel fuel. Well-to-Tank emissions have been derived from our assumptions regarding the energy conversion efficiency of the GTL process.

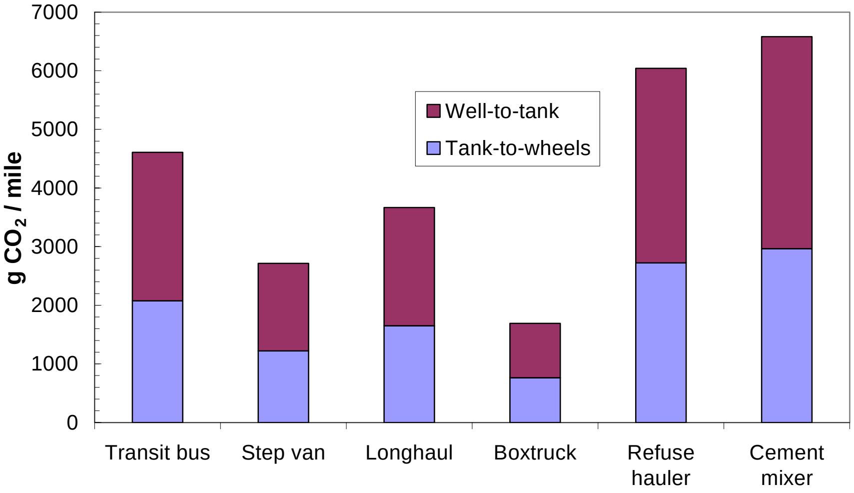
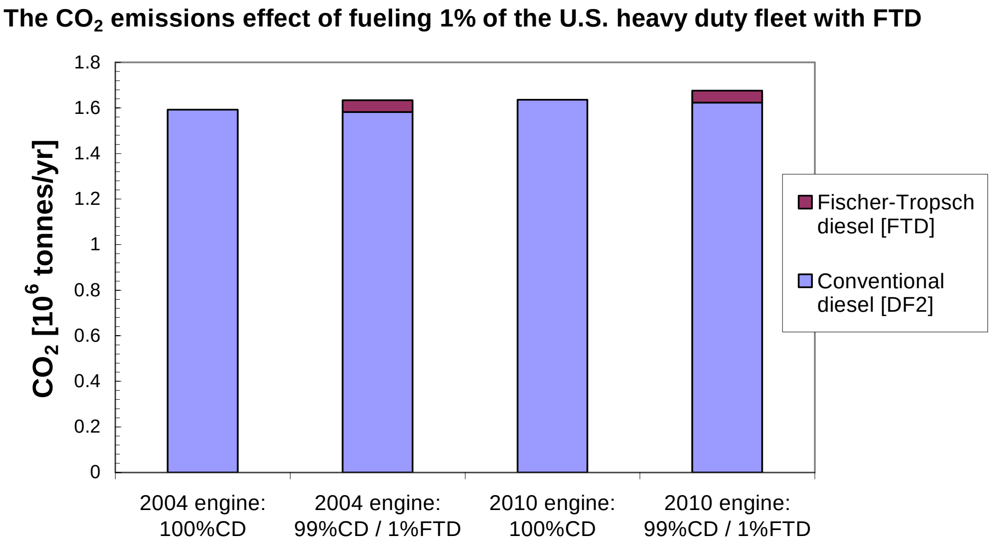


Figure 28. Comparison of our estimates of well-to-wheels emissions of CO_2 associated with the use of conventional diesel and GTL fuel. Consistent with our assumptions on the source of the natural gas (small reservoirs) we have assumed that the GTL fuel comprises 1% of the total fuel used in the US.



We have estimated the consequences for the fleet of using GTL fuel at a rate of 1% of the annual US consumption, which is consistent with both the amount of fuel that might be produced by a battery of small footprint plants and with amount of gas contained in the accessible and economically viable resources in the lower 48 states. The additional CO_2 burden would then be quite small, roughly 0.5% of the national emissions associated with heavy duty transportation and roughly equal to the fuel economy penalties mandated by regulations that commence in full force in 2010.

CONCLUSIONS

The picture that emerges is that there are resources and conditions under which a SFP can be operated profitably. In particular, high cost of oil, long distances from conventional sources and underutilized resources all contribute to the economic viability of the plant. The addition of credits for electricity, steam, water and, in some instances, criteria pollutants, only serve to improve the economic outlook. However, achieving autonomy and profitability require matching the scale of the SFP to local needs and dealing with all of the side products, including naphtha.

We have identified particular resources to refine the economics for constructing and operating small footprint plants. Evidently, the conditions favorable to the economic viability of SFPs prevail in Alaska and it will be interesting to refine the parameters for specific resources and markets there.

A well-to-wheels analysis to estimate the overall economic and environmental impact of the production and use of SFP-produced fuels suggests that the primary benefits of employing GTL fuels derive from both the energy security they confer and the emissions reductions from older vehicles. Emissions benefits from newer vehicles (post 2010) will require tuning of the engines to extract maximum effect. If for some reason this tuning of the engine control systems is not, or cannot be, done, this benefit of GTL fuels from small footprint plants would have only about a 10-15 year window of opportunity (commissioning of the first plants, assumed to be in 2015, until the pre-2010 vehicles have been retired).

We note that modularization of a small footprint plant increases its appeal for both civilian and military applications.

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LIST OF ACRONYMS AND ABBREVIATIONS

BOP	Balance of Plant—utilities required to operate a process whose costs are not considered in detail.
BPD	Barrels per day (roughly 160 l/day of liquid fuel)
BCF	Billion cubic feet
BTU	British Thermal Unit, 1055 kJ
DF2	Diesel fuel number 2—conventional diesel fuel produced from petroleum
FT	Fischer Tropsch—process for converting synthesis gas (H_2 and CO) to liquid hydrocarbons, named after its discoverers.
FTD	Fischer Tropsch diesel—diesel fuel produced by the FT process.
GTL	Gas to liquids; process for converting natural gas or synthesis gas into liquid fuels, typically by means of Fischer Tropsch chemistry
IRR	Internal rate of return (the discount rate that makes the net present value of an investment equal to zero)
NG	Natural gas
NPV20	Net present value (discounted cash flow) over a 20-year period
OBL	Outside Battery Limits—facilities such as roads, housing, schools that are practically necessary but not considered as part of the cost of the plant
RUR	Recoverable ultimate reserve; an estimate of the amount of gas remaining in a well
EUR	Estimated ultimate reserves, an estimate of the total amount of gas that a well contains or contained
SFP	Small Footprint Plant; a facility dedicated to the production of liquid fuels starting with natural gas or other feedstocks, with a production rate in the range of 500-10,000 BPD
Scf	Standard cubic foot; 1 cubic foot at of gas at standard temperature and pressure (often cited as 60ºF, 15.09 psia). 1 scf of natural gas typically has a heating value of 1000 BTU

Fischer-Tropsch Small Footprint Plant Economic Feasibility for Rural Alaska

Report Issued
August 4, 2006

Fischer-Tropsch Fuel Production and Demonstration Project
DE-FC26-01NT41099

Submitted by:
Timothy Bradner

DISCLAIMER

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Executive Summary:

Small Footprint Plant (SFP) Feasibility in Rural Alaska

We have been asked to investigate the feasibility of supplying ultra-clean Fischer Tropsch (F-T) fuels in rural Alaska with possible smaller-scale F-T plants ("Small Footprint Plants") in selected rural locations near natural resource deposits, or in regional locations near resource deposits from where rural communities could be served.

Task 8.1 reads:

"Using readily available sources from government and private industry, gather information on various Alaska resources, such as oil, gas and coal, that could be used as feedstocks for local or regional SFP fuel processing plants. Consider the location, quantities, accessibility and other factors of these resources affecting how much clean fuel can be produced and distributed to rural communities in the area. Examine the feasibility of placing SFPs in the most promising areas to serve rural communities around the state, including the general and economic benefits to be derived. The economic analysis should include the cost of building and transporting the SFPs to Alaska, the cost of assessing and producing the fuels, the cost of transporting the fuels to the surrounding communities and the cost of storing and using the fuels for power, heat and other purposes. Set out findings and draw conclusions about the feasibility of locating SFPs in areas of Alaska to serve the fuel needs of rural Alaska."

The approach:

Task 8.1 asked us to assess Alaska natural resource deposits and potential deposits that could provide feedstock for F-T plants. In approaching the core mission, an assessment of small footprint F-T plants, we decided to first present a discussion of the state of Fischer-Tropsch development and the challenges, in general, facing the development of smaller-scale F-T plants. This is in our "Introduction" in Part 1. Our assumptions in the analyses are also spelled out in the introduction.

In Part 2, we provide an assessment of possible F-T plants in different Alaska locations. In Part 3 of this report we provide a general overview of Alaska's oil and gas, coal, coal-bed methane and biomass (timber) endowment.

In Task 8.1 we were also asked to prepare an assessment of rural Alaska fuel distribution patterns and costs, along with the discussion of issues facing rural fuel distribution, conventional as well as non-conventional (i.e. F-T fuels). It is important to understand how fuel is moved to and around rural Alaska in any assessment of regional F-T plants. This assessment is in Part 4, the final part of this report.

The annual fuel demands of the regions in which we considered sites, and the possibility of exporting fuels surplus to the regions, dictated the size of the F-T plants we considered. Where the regional demand was low, in two small rural communities, we assumed small F-T plants of 300 bbls/day, or 4.5 million gallons per year. Where access to economical water transport was available, such as in coastal locations, we considered larger plants to capture economies of scale.

The sites we considered:

After considerable research we decided to focus on six potential locations as representative of plausible sites for a plant:

- **Nikiski, Alaska** ("Case 1") as a kind of "base case." Nikiski was selected because it is now the point from which much of the fuel bound for western Alaska is distributed. Fuel distribution patterns, and costs, are therefore well understood. Nikiski also has established infrastructure, an experienced local workforce and the presence of other industrial facilities to share infrastructure and utility support.

- **Beluga, Alaska** ("Case 2") as a larger plant site. Beluga was selected as a possible site because there is a large coal deposit very near tidewater.

- **Healy, Alaska,** ("Case 3") with its proximity to a coal mine and the Alaska Railroad.

- **Bristol Bay, Alaska** ("Case 4") because of the potential for large deposits of "stranded" natural gas.

- **Galena, Alaska** ("Case 5") because of the proximity to a small coal deposit and potential for regional bio-mass resources.

- **Fort Yukon, Alaska** ("Case 6") because of proximity to potential coal-bed methane and regional bio-mass resources.

Some initial conclusions:

• **F-T plants in Alaska will require government support.** In almost every scenario we studied, a temporary government support mechanism was crucial in reducing the "tail-gate" cost of F-T fuels to levels that might approach economic viability even if crude oil prices remain high. There are several ways the government could support such plants: (1) An energy credit on F-T fuels for an amount similar to tax credits granted to biodiesel, ethanol and compressed natural gas; (2) A government grant to pay the capital costs of a plant; (3) A government fixed-price purchase contract for F-T fuels to make the plant economic.

In this report we assume a federal energy credit similar to existing energy credits for biodiesel, ethanol and compressed natural gas as a plausible form of federal support. We also do one analysis (Case 5-B) of how a government grant covering capital costs would affect the economics of a small rural plant. We discuss the different methods of possible government support in our Appendix, but a more complete analysis of this is outside the scope of this report.

• **Higher oil prices could make F-T plants more feasible.** While we do not have enough confidence in our estimates to declare that F-T plants in Alaska may or may not be feasible, certainly the continuing rise in crude oil prices and the price of conventional diesel make the possible economics of such plants look better. What must also be taken into consideration are the extra costs required after 2006 and 2010 to supply ultra low-sulfur (ULS) diesel, or conventional diesel with sulfur reduced to 15 parts-per-million (ppm) on top of the cost of conventional diesel. Since F-T fuels will meet the EPA requirements in the 2006 and 2010 regulations, the true comparison will be to weigh possible costs of F-T diesel against conventional diesel with the ultra-low sulfur cost added. We attempt to do this in our report.

• **F-T fuels would meet the requirements of new EPA ultra-low sulfur diesel.** New U.S. Environmental Protection Agency rules requiring the use of 15 ppm ultra-low sulfur (ULS) diesel are effective in 2006 regarding transportation fuels and 2010 regarding diesel used in off-road (construction, mining, etc.) and stationary diesel engines. These rules will have considerable impacts in rural Alaska, mainly because of the cost of making winter-grade ULS diesel and transportation and storage problems that arise if the fuels are segregated from conventional diesel. We believe, as do many in the industry, that by 2010 all diesel used in rural Alaska will be ULS because of the costs of shipping and storing separate fuels. There will still be a premium charged for this fuel in rural Alaska above the cost of conventional ULS diesel and there are various estimates, ranging from 15 cents per gallon to 70 cents per gallon depending on the location. Since F-T diesel meets the requirements of the EPA rules we believe the cost of F-T diesel delivered to rural locations should be weighed against the cost of the ULS diesel.

• **Low-toxicity and biodegradability of some F-T fuels is an advantage.** The low-toxicity and biodegradable nature of F-T fuels is an advantage: Many F-T fuels have low-toxicity and are biodegradable and have been certified as so by the U.S. EPA (see our Introduction section). If these fuels were spilled during handling or because of a rupture of a tank, the environmental impact would be less than that of conventional diesel. We have not attempted to quantify this advantage, but there is a real cost imposed on small rural storage and distribution facilities by spill containment, training and other requirements that arise from the toxic nature of conventional crude oil-based diesel. Use of F-T fuels may not eliminate these requirements, but the nature of the fuel would be weighed by the state and federal government agencies in considering a spill plan and other requirements for a bulk fuel storage facility.

• **The uncertainties in our estimates are considerable.** There are four major risk factors in the estimates we have made. They are:

1.) Technology risks. We know F-T technology works at large scale, such as at 50,000 barrels/day, but there is insufficient industry experience with smaller-scale F-T plants, such as at the 200 bbls/day range. This is a major area of uncertainty, we believe.
2.) Location risks. There are no guidelines for estimating project construction costs in rural Alaska, or even the state as a whole. Project cost estimation is based on past experience and familiarity with site conditions by the project team. We have discussed each location with knowledgeable people and, within the means at our disposal, have attempted to make reasonable assumptions as to local construction costs. However, a realistic assessment of a particular site would take a greater and more focused effort.
3.) Resource risks. We have included a range of estimates for the cost of supplying given resources (coal, biomass, gas) to our locations, but the actual cost will remain unknown until a project is developed. We do have more certainty around the probable cost of biomass and coal at Nikiski and coal at Beluga and Healy, but our estimates for natural gas, coal, biomass and coal-bed methane at the Bristol Bay, Galena and Fort Yukon sites are very speculative.
4.) Operations risks. This is an unquantifiable risk, but a serious one in remote or rural settings. An F-T plant is really a kind of chemical plant. As explained in Part 1, our introduction, its operations are complex and require skilled personnel and substantial off-site support. Given this, we can see that it could be a real challenge to staff and operate such a plant in a remote or rural setting. An illustration of the difficulties involved in actually building and operating an F-T plant is that BP was delayed over a year in startup of the company’s small 300 bbl/day demonstration plant in Nikiski by problems that had little to do with the new technologies being tested and more to do with just the sheer complexity of building and starting up what amounts to a small chemical plant.

- **The four best locations for a possible F-T plant.** A very preliminary analysis indicates that medium-sized (6,000 to 12,000 bbls/day) plants at regional locations, from which F-T products can be distributed to locations in and outside Alaska, offer the best possibilities.

The four locations are:

(1) Healy: There is a producing coal mine at Healy, industrial facilities have been build there, and a F-T plant would have access to the Alaska Railroad for product transportation and the regional power grid for sales of electricity generated with waste-heat.

(2) Beluga: There is a large coal resource and a tidewater location. The opportunity to ship products efficiently in bulk, and near-proximity to the regional power grid makes this location of interest. The major drawback is that a coal mine has not been developed.

(3) Nikiski: There is a functioning gas-to-liquids (GTL) demonstration plant that could be converted, and because local biomass resources are available. The existing GTL plant is too small for commercial use, and using natural gas as a raw material is too expensive in Cook Inlet. There are possible limits to the size of a bio-mass F-T plant.

(4) Bristol Bay: The Bristol Bay basin is very gas-prone and the possibilities of a gas discovery are good. A medium-sized gas-to-liquids plant is a possible option to commercialize a gas discovery that is too small to support a conventional gas pipeline or a liquefied natural gas project.

Of the four sites listed above, the plants that could be developed on the fastest schedules are at Nikiski and at Healy because a source of resource feedstock is available as well as utility support facilities, transportation infrastructure to move products to market and the existence of a local or regional construction workforce.

Rural community locations: We analyzed two rural community locations in Interior Alaska, assuming small-scale 300 bbl/day F-T plants because larger plants would require an extensive transportation system to move the fuel products out of the region. Galena and Fort Yukon were selected because these communities are on the Yukon River, which offers a good, if seasonal, transportation option. Also, we had recent information on resource deposits near the communities that could supply feed for small F-T plants. There is coal and biomass near Galena and bio-mass and coal bed methane near Fort Yukon.

Galena and Fort Yukon are analyzed more or less as proxies for other rural communities where there are resource deposits close by. The information we have on very small-sized F-T plants is very limited, to the point that the analyses done for Galena and Fort Yukon would be similar if the location were at another village near a coal deposit, coal-bed methane or bio-mass resource.

One conclusion we came to is that the state of research and development in smaller-scale F-T plant technology is not advanced enough to adequately assess the potential for such plants in rural community settings. Other, emerging technologies have promise for SFP F-T plants, however, and should be encouraged (see more discussion in our Appendix.)

Capital grant improved economics: We were initially skeptical that a small plant (300 bbl/day) would be even remotely feasible at any rural community locations, and in general our analysis supported this view. However, we were interested when one case we did for Galena (Table 5-B) assumed a government grant to pay the $65 million capital cost of the F-T plant and equipment for wood harvesting. This had a dramatic effect in lowering the required price of diesel products from the plant to at or below diesel prices in late 2004 and early 2005. We did not consider a case like this for the larger projects because the prospects for a government grant for the larger projects – involving several hundred million dollars – seem remote. Our conclusion from this is that alternate ways of financing small F-T projects in rural areas may be worthy of further study.

Bio-mass harvest could stimulate rural industry: One other consideration, we believe, is that in the case of a small rural plant supported by bio-mass from regional timber harvesting, the operation of the plant and the harvesting could provide a considerable economic stimulus to the region, particularly if the harvesting is integrated with a sawmill or some other way to use higher-value wood. This is beyond the scope of this report, but we would observe that small-scale wood harvesting is a very old industry in rural villages along the Yukon River and its tributaries. Harvesting wood to fuel steamboats operating on the river was a major source of cash for the communities, and lasted until diesel-fueled boats began operating on the Yukon system in 1948.

More support is needed for SFP research and development: An overall conclusion is that more support should be given to research and development of SFP F-T technologies, and that if there are potential military applications for SFPs the federal government should take the lead in providing support. As we discuss in our introduction to this report, the direction of private industry's F-T research and development is toward larger plants which enjoy economies of scale. Little effort is being made, within the private sector, on smaller plants, and very little in the micro-plant category (200-600 bbl/day) that we consider in some of our scenarios on this report.

Sources of our information: The bulk of the analyses in this report is from information made public or provided by firms engaged in F-T development, including Choren Industries of Hamburg, Germany; Sasol, of Johannesburg, South Africa; and Syntroleum Corp. of Tulsa, Okla. There is a substantial amount of other information held confidential by companies engaged in F-T development and unavailable to us.

PART ONE: Introduction

The Fischer-Tropsch Process

Different companies have been developing the Fischer-Tropsch (F-T) process throughout the world since the 1930s. While most people associate the F-T process with the gas-to-liquid process (GTL), F-T got its start using coal in Germany and later in South Africa, referred to as coal to liquid (CTL). More recently, bio-mass (BTL) has been used to generate the synthesis gas for the F-T process – creating "green" or bio-renewable energy. All three programs, GTL, CTL and BTL share the same three steps; first, syn-gas generation; second, the F-T conversion; and third, products upgrading. Regardless of the resource input, the second and third steps are identical. Natural gas is reformed (Alaska's Agrium Corp. ammonia and urea fertilizer plant and the BP GTL test plant are examples) while solids; coal and bio-mass are gasified to produce a syn-gas (*hydrogen* $\boldsymbol{H_2}$ *and carbon monoxide* ***CO***). A synthesis gas (or syn-gas) is the common supply for the F-T process, as well as methanol and ammonia processes, and for electrical generation and sulfur reduction in refineries

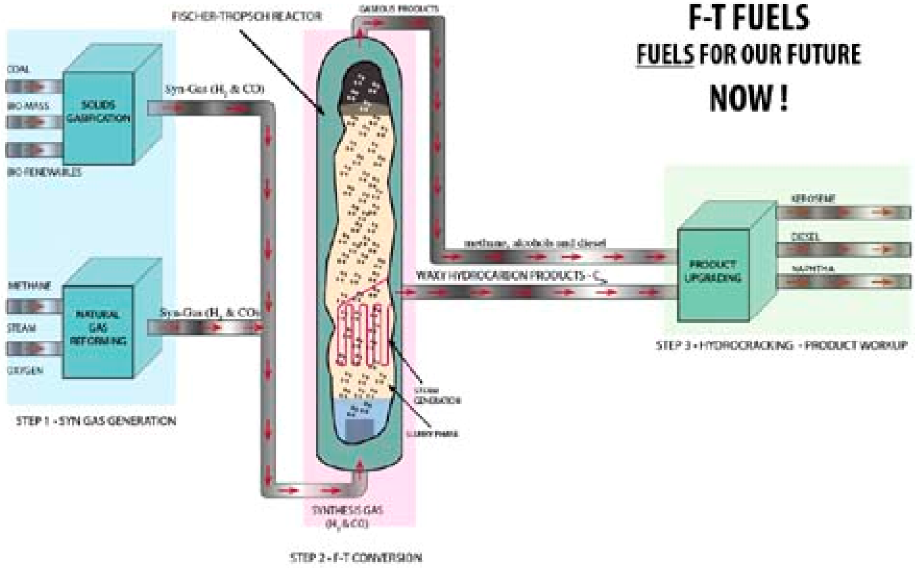


Figure 1

Figure 1 shown here illustrates the F-T process and how different natural resources can be used to make the syn-gas needed in the F-T conversion. The Fischer-Tropsch Process (F-T) has three main processing steps shown here, all of which are commercially proven.

STEP 1:

Syn-gas generation typically represents 50-plus percent of the total cost of an F-T plant.

STEP 2:

F-T Conversion is typically 25 percent of the total cost.

STEP 3:

Product Upgrading is usually 15 percent to 25 percent of the cost.

The type of Syn-Gas Generation, gas reformation or gasification of solids, depends upon the raw material or feed stock available. Around the world stranded natural gas is the choice; however, in the US with the exception of North Slope natural gas, coal, and bio-mass (municipal, timber and agricultural waste) represent the majority of available feedstock for a U.S. based F-T program.

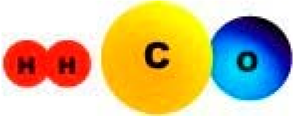
Comparing F-T diesel costs with conventional diesel prices

The estimated cost and resulting wholesale price of producing Fischer-Tropsch (F-T) diesel in a small-footprint F-T plant must be weighed against the wholesale price of conventional diesel fuel available in a given region. To compare Fischer-Tropsch fuel costs with conventional, we consider the plant "tailgate" costs, shown in tables for the respective scenarios, as wholesale prices for the F-T fuel available at the plant.

To compare this with conventional fuel, in each section we report a 2004 average wholesale price of conventional diesel reported from fuel distributors or wholesale purchasers for the region. We also consider an additional cost to conventional fuel for the ultra-low sulfur diesel (ULSD) that will be required by U.S. Environmental Protection Agency regulations effective in 2006 for road diesel and 2010 for all diesel.

Since F-T fuels already meet the EPA 2006 and 2010 clean-diesel standards, we compare the F-T costs with future estimated prices for ULSD conventional diesel.

How the process works:

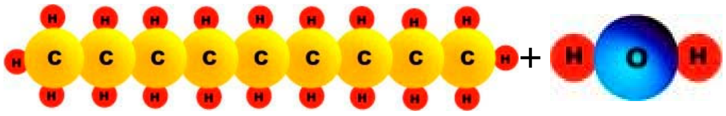


The first step converts natural gas, coal or bio-mass into synthesis gas, a mixture of carbon monoxide (CO) and hydrogen (H_2) – syn-gas.

This mature process technology has been used in many commercial facilities as the first step for producing ammonia, hydrogen, F-T fuels, petrochemicals and methanol. Sasol, a leader in F-T technology uses both gas reformation and coal gasification to produce syn-gas for its F-T production.

Step two, the Fischer-Tropsch conversion, was discovered in Germany in the early 1900's, it upgrades the syn-gas into a waxy long chain hydrocarbon. Simplified, this reaction is:

$$CO + 2H_2 = CH_2 + H_2O$$



The length of the hydrocarbon chain is determined by the composition (ratio of H_2 to CO) of the syn-gas, the catalyst selectivity and the reaction conditions (temperature and pressure.)

Sasol has pioneered several types of F-T conversion technologies to produce over 150 different products from the company's plants in South Africa. The hydrocarbon stream (CH_2) is sent to product workup and the water (H_2O) is sent to a water recovery unit. One disadvantage of today's F-T technology is that for every barrel of product produced one barrel of water is also produced. Water disposal is, therefore, a consideration.

The third step: product upgrading:

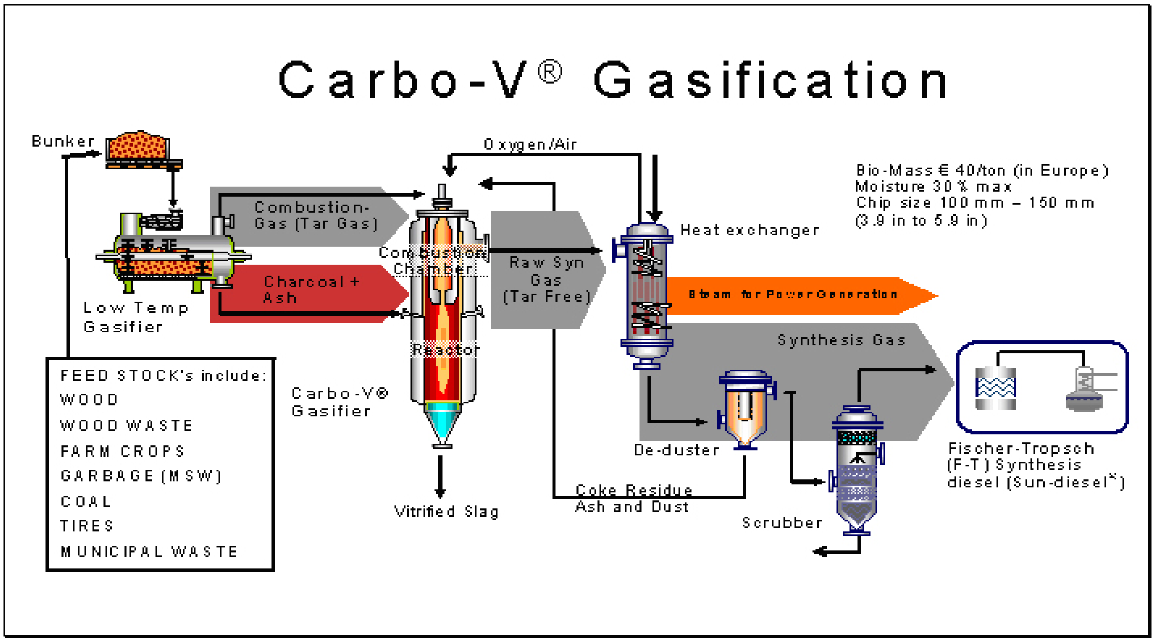
Upgrading can produce a wide range of commercial products including gasoline, diesel and specialty products of use for petrochemical manufacturing. For a U.S. based F-T program we would recommend middle distillate fuels: kerosene, diesel and naphtha. If exports are possible, an Alaska-based F-T plant could also make gasoline, which is in short supply in the U.S. west coast, as well as diesel.

The final product workup makes use of standard hydrocracking and hydro-isomerisation processes commonly found in the refinery world. As with the first step, syngas production, suitable technology is widely available from several licensors around the world.

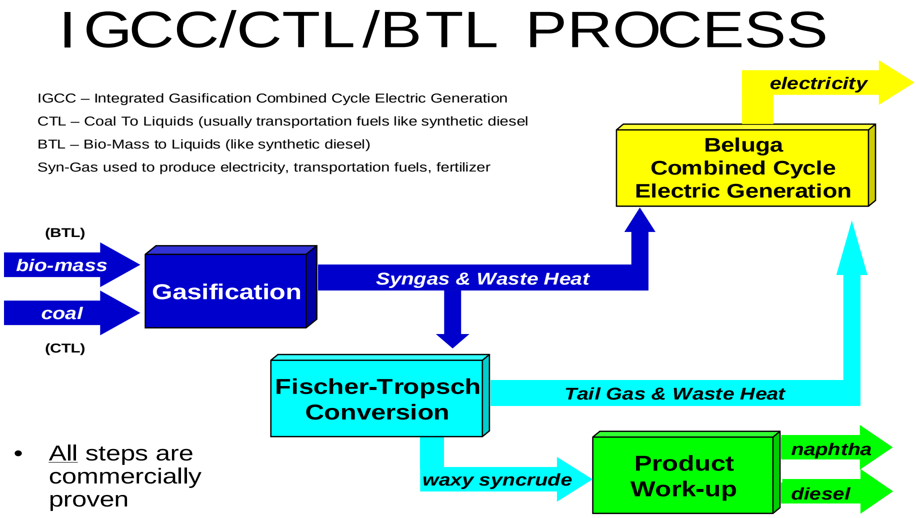
The F-T process produces fuels that contain essentially no sulfur, aromatics or ring chain hydrocarbons that are toxic and harmful to the environment. As with a crude oil refinery, the F-T process does produce CO_2 but it is in a pure stream and is contained so that it can be sold or sequestered through injection into underground storage reservoirs or used in Enhanced Oil Recovery.

F-T diesel may be one of the cleanest motor fuels available. In the early 1990's UNOCAL Corp. asked the U.S. Environmental Protection Agency to approve F-T diesel from the South African Mossgas GTL plant for use as a drilling fluid in offshore waters. As a result of the tests performed by UNOCAL, the EPA determined that this form of F-T diesel is bio-degradable and non-toxic. *Note: The data can be found at EPA Water Docket, EB 57, Reference Docket No. W-98-26, UNOCAL data file 4.A.a, Vol 13.*

Choren, a German company has been operating a bio-mass gasifier to produce syn-gas for methanol and electric power production since the 1970's. This plant is considered one of the world's first bio-renewable gasifiers and has the distinction of producing fuels and electricity with a net zero impact on CO_2 production.

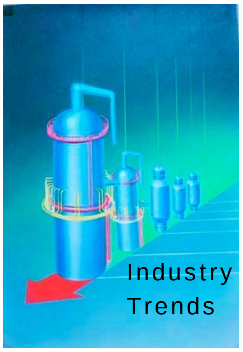


The Choren gasification process illustrated here provides the syn-gas necessary for F-T transport fuels, fertilizer, petrochemicals and electric power generation. It is in essence a bio-renewable generator of higher value energy products. The Choren gasification process has the distinction of being able to gasify coal and bio-mass (such as wood), both abundant in Alaska. One advantage of Choren's gasifier is that it could produce syn-gas from available resources, switching back and forth between coal and biomass on a seasonal basis. The illustration following provides a block flow diagram of the energy conversion process from resource to electricity and or transport fuels.



F-T Plant Size

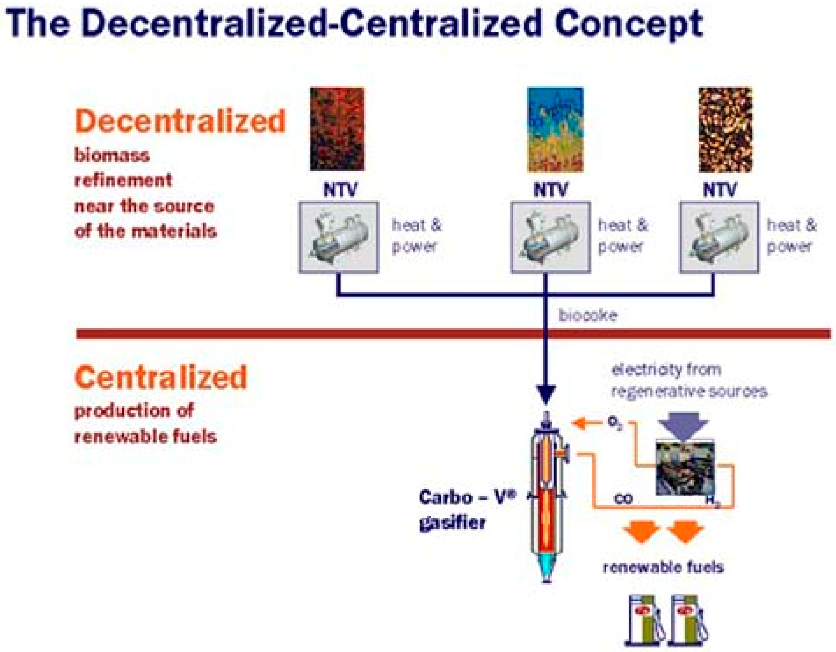
This report will examine the possibility of small scale F-T plants for several Alaska locations that could provide from 1,000 to 6,000 barrels per day of fuel for transport and electric generation. We note that most F-T technology providers started with pilot plants smaller than this, costing $200,000 to $300,000 per installed barrel of capacity. Upon proving their technology most developers have embarked on a program of scaling up plant size to reduce to the $25,000 to $65,000 per installed barrel of capacity. The F-T industry mantra is "bigger is better" because it is more economic. Unfortunately, the F-T industry is moving in opposite direction than the small F-T plants being considered here.



Scale, or size, affects the economics

In the manufacture of F-T, size does matter. There are conflicting issues at play in a chemical reaction, especially those that are highly endothermic or exothermic. When we add or take away large amounts of heat; heat controls the rate and direction of the reaction. Heat transfer in large vessels is difficult to model, thus the reason for scale-up development programs. Outside of these issues the rule-of-thumb is that larger is more economic.

An example with the cost of pipelines illustrates this. The same equipment is used to install a 12-inch pipeline and a 16-inch pipeline. A 16-inch line requires a little more weld time, and a slightly bigger ditch – but we are talking about inches. Typically pipeliners use a rule-of-thumb for calculating the installed cost of a pipeline; "X" dollars per inch of pipe diameter per mile of length. For example, at $15,000 per inch-mile, a 12-inch pipe costs approximately $180,000 per mile. A 16-inch pipe costs $240,000 per mile, a 33 percent increase in cost. The carrying capacity of the two pipelines is considerably different. Under given conditions a 12-inch pipeline can carry 50 million cubic feet of gas, while under these same conditions a 16-inch pipe can carry 106 million cubic feet of gas, more than twice the capacity for a 33 percent increase in costs. The same analogy applies to a flow process in a F-T plant. Small increases in size allow for larger increases in volume, resulting in lower installed costs per unit of volume, or dollars-per-installed-barrel-of-capacity. When we apply the savings across every aspect of a complex plant and the many on and off-site supporting utilities and equipment, we quickly see how "bigger can be better."



In this analysis we are looking at installed costs per barrel of capacity ranging from $200,000 for a 300 bbl/d BTL plant (bio-mass) located at a remote setting to $85,000 for a 6,000 bbl/d facility at Nikiski, an established industrial area. We also consider a case of $35,000 for a 300 bbl/d conversion of an existing BP GTL demonstration to a BTL demonstration plant. We compare these cases to published numbers for a Sasol 33,000 bbl/d GTL plant between $16,000 to $22,000 per installed barrel for a new "Greenfield" site and we quickly see that small plants are at a disadvantage. Size does, however, bring its own challenges. For example, it is one thing to harvest and deliver 250 tons of bio-mass per day, and quite another to deliver 25,000 tons per day. As plant size increases, feedstock handling costs must be controlled. European studies have found bio-mass transport costs limit a plant size to 3,000 tons per day. Above this number, it is preferable to use systems that concentrate feedstocks at remote locations for semi-processing and transporting the material to a central plant location. Choren's two-stage biogasifier illustrated above is designed to deal with this larger-volume bio-mass transport issue.

There are some F-T technology providers looking at micro-plant designs with the hopes that military or space applications will support their development costs (see Appendix). As these technologies mature and micro F-T plants are built, costs will come down. They may even become economic for small volume rural applications. At this point, other than in Choren's BTL program, no one has a small-scale, less-than-300 bbl/d commercial F-T program for producing F-T fuels that costs under $100,000 per installed barrel to construct. At costs in this range, it would seem that none of these F-T programs are economic for rural Alaska when one compares costs with the delivered costs of crude-based diesel from Cook Inlet or Washington State. In our view the fuels market in Alaska is not of sufficient size to economically support, on its own, an F-T plant with today's technology. However, a larger Alaska plant on or near tidewater, that sells 80 percent to 90 percent of its products in the Lower 48 or Asia, will reduce costs to the point that reasonably-priced F-T diesel might be sold in Alaska.

F-T fuel economics

There is no question that F-T technology works. There are F-T plants with over 250,000 barrels per day of production operating in the world today, and another 500,000 barrels per day under construction or in the final design phase. There is also no question that F-T transport fuels are compatible with the existing motor fuels market and infrastructure, with over 40 billion gallons of these fuels sold to date throughout the world. Sasol, of South Africa, secured approval to supply FT-based jet fuel to passenger flights of international airlines refueling at Johannesburg.

The question is whether F-T fuels are economic compared with conventional fuels. If the measure of economics is price at the fuel pump, the answer is generally no. However, as the price of crude oil continues to rise, at some point the cost of manufacturing F-T fuels will equal that of crude-based transportation fuels. The problem in the U.S. is that there are many factors at play that affect overall economics. There are hidden costs in our national energy policy and environmental programs that are not apparent at the fuel pump, for example.

There are generally three economic drivers that impact the real cost of U.S. transportation fuels. They are:

- Strategic, the need to maintain a military presence in the Middle East to insure the free flow of oil to the world. We refer to this as a Security Premium.

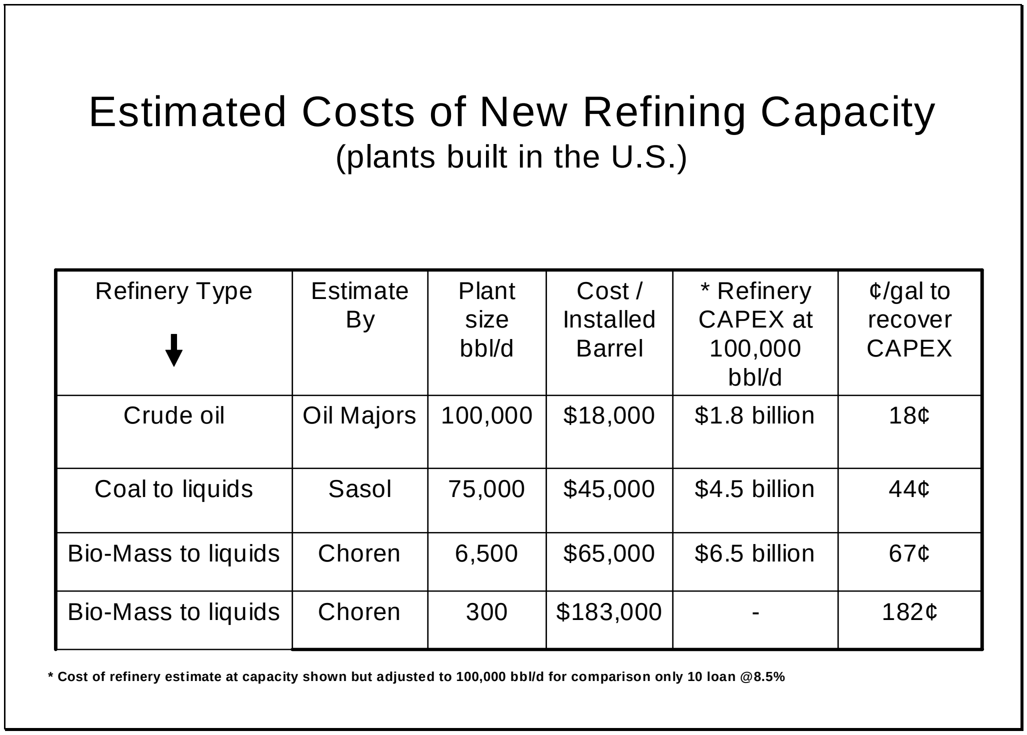
- Shortfall in U.S. refining capacity, which affects availability of fuel. We refer to this as a Refining Capacity Penalty.

- Environmental - Lower Emissions and CAFÉ levels (Clean Cities Programs - lower GHG emissions and better fuel mileage). We refer to this as the Engine Emission and Efficiency Cost.

National policy issues are at stake here. New alternative fuel refineries (F-T) plants cost tremendous amounts to build because they are more like chemical plants than crude oil refineries. However, if environmental laws require crude oil refineries to make fuels as clean as F-T fuels, then F-T plants could be competitive. Alternatively, if the U.S. charged a tax for importing oil or gave credits for refineries that reduced U.S. dependence on imported crude, F-T plants could be competitive. If the U.S. charged a tax for importing gasoline and diesel, it would encourage new refineries to be built in the U.S., helping make new F-T refineries competitive.

Alaska is different than the Lower 48 in that there is currently excess conventional refining capacity in the state. Building new capacity to meet Alaska demand doesn't make sense on a commercial basis. On a national scale there is a shortage of domestic refining capacity and a need to build new refineries, however. The west coast states in particular are short on gasoline refining capacity, and have stringent air quality regulations for diesel. F-T products imported from the Shell GTL plant in Malaysia now sell at a premium in these markets, and would logically continue to do so.

One way of looking at the economics of F-T manufacture is to compare them with the costs of building or adding other new fuel-making capacity. The table included here illustrates the price products must sell for from a new refinery compared with today's fuel prices to recover the new capital investment. As the price of crude oil continues to rise faster than the price of coal and bio-mass remains stable, BTL and CTL plants might be competitive. Once the capital cost of U.S. built F-T plant is recovered, American BTL and CTL plants can be competitive below today's price of crude oil.



Estimated Costs of New Refining Capacity

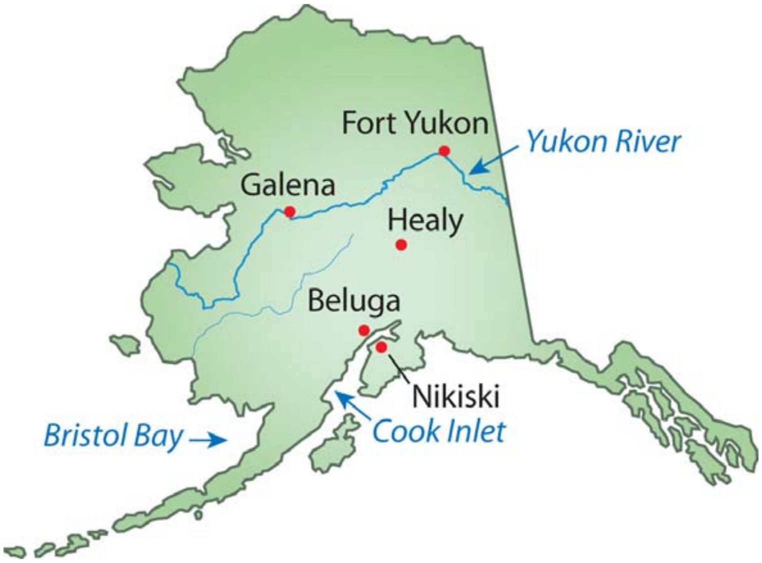
(plants built in the U.S.)

Refinery Type ↓	Estimate By	Plant size bbl/d	Cost / Installed Barrel	* Refinery CAPEX at 100,000 bbl/d	¢/gal to recover CAPEX
Crude oil	Oil Majors	100,000	$18,000	$1.8 billion	18¢
Coal to liquids	Sasol	75,000	$45,000	$4.5 billion	44¢
Bio-Mass to liquids	Choren	6,500	$65,000	$6.5 billion	67¢
Bio-Mass to liquids	Choren	300	$183,000	-	182¢

* Cost of refinery estimate at capacity shown but adjusted to 100,000 bbl/d for comparison only 10 loan @8.5%

F-T Plant Location

A rule-of-thumb in real estate is that there are three most important aspects in the value of a commercial property: Location, location and location. This is just as important in the economics of an F-T plant.



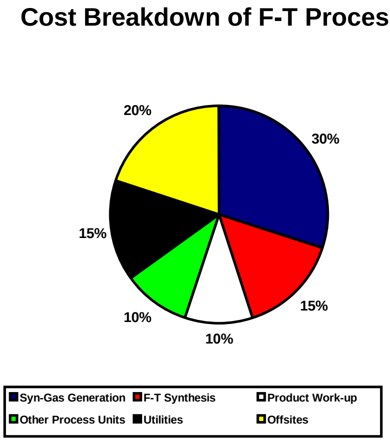
This report looks at the relative economics of BTL and CTL plants at different locations in Alaska, and we include two cases using natural gas, or GTL. Plant construction costs, operating and maintenance costs are estimated very generally, using information made public or provided by firms. We believe these general numbers have a +/– range of 25 percent to 30 percent. Detailed pre-engineering studies that will entail substantial costs will be required to reduce the uncertainty of these estimates.

We briefly discuss six different potential locations in Alaska and outline the impact of each site on the economics, size and function of the F-T plant. The first two examples we consider in the Cook inlet region are (1) at Nikiski, an established industrial area where there is an existing GTL test facility as well a substantial utility infrastructure; (2) a location at the Beluga coal field on the West side of the Cook Inlet near the village of Tyonek (no mine has yet been developed at Beluga, and there is little support infrastructure); (3) a location near the existing Usibelli coal mine in Healy, between Anchorage and Fairbanks along the Alaska Railroad; (4) a potential large gas field in the Bristol Bay region. This region is gas-prone and there is increased industry interest. If a gas discovery is made that is too small for a conventional pipeline or liquefied natural gas project, it could be is a potential location for an F-T plant. We also consider a remote location near Galena (Case 5) on the Yukon River; and a second remote site at Fort Yukon (Case 6) using a potential coal bed methane reserve.

The F-T plants being considered in this analysis are of an order of magnitude more complex and labor-intensive to operate than the small community power plants that now exist in rural communities. Power generation at remote sites usually occurs with small diesel electric generators. If diesel is not available and bio-mass, or wood, is available, a small steam boiler can be used to power a steam-driven generator. Both are conventional technologies that can be operated and maintained with local support. These power units are typically small skid-mounted units, built offsite in industrialized settings and shipped to the location. Engine emissions are manageable, given the state of new diesel generation technology. There is less concern with effluent streams.

Fischer-Tropsch fuel plants, in contrast, are anything but simple to operate and maintain. They are like chemical plants. They operate at high temperatures and pressures and require heavy pressure vessels that can stand 50 to 100 feet tall. They require enormous amounts of power to start up, but once running can supply large amounts of power through excess waste heat. They need specially treated water for use in the process and they produce large amounts of water that must be treated before it can be discharged.

In addition to producing ultra-clean diesel they also produce a range of other products. In all of the cases we consider naphtha is also produced and is considered a heating fuel. The additional products have value but must be stored and shipped in separate containers to realize their value. In addition, government agencies closely regulate emissions of plants like these, which necessitates highly trained plant operators and support technicians available 24 hours a day, seven days a week.



Fischer-Tropsch plants also require typically large investments in utility and offsite support systems which can account for 40 percent 50 percent of the total cost of a plant, as indicated in the illustration below. In our analyses, these support costs are included in the estimates for the three basic F-T steps, syn-gas generation; F-T conversion and finished product manufacture. However, when developing an F-T project in areas where some or all of the utility and support systems are available (such as in Nikiski) there may be significant cost savings available in each of these three steps.

Virtually all the technologies in an F-T plant have a common utility support requirement. Large quantities of energy are needed to drive the air separation processes or the oxygen plant; for the preheat needs of the syngas generation step; for waste heat recovery from syn-gas and its effective utilization; medium/low grade heat generation by the FT process; hydrogen provision for the hydrocracker; and optimum product recovery to maximize yield.

And finally, F-T projects have about 60 percent thermal efficiency, resulting in around 40 percent heat rejection, or waste-heat. There are ways to economically capture this. In addition to heat recovery, offsite support system requirements can be significant, particularly with Greenfield remote locations in Alaska. The offsite systems may include water treatment to support large steam systems and effluent treatment of hydrocarbon contaminated water and system blow downs. Flare systems to deal with high heat flows from the hydrocarbon units as well as high volume flows from the gas processing units, plus firefighting systems to deal with the large volumes of hydrocarbons at their vapor points and process streams containing hydrogen, are very important. Synthetic product tankage and F-T product loading facilities are a significant factor

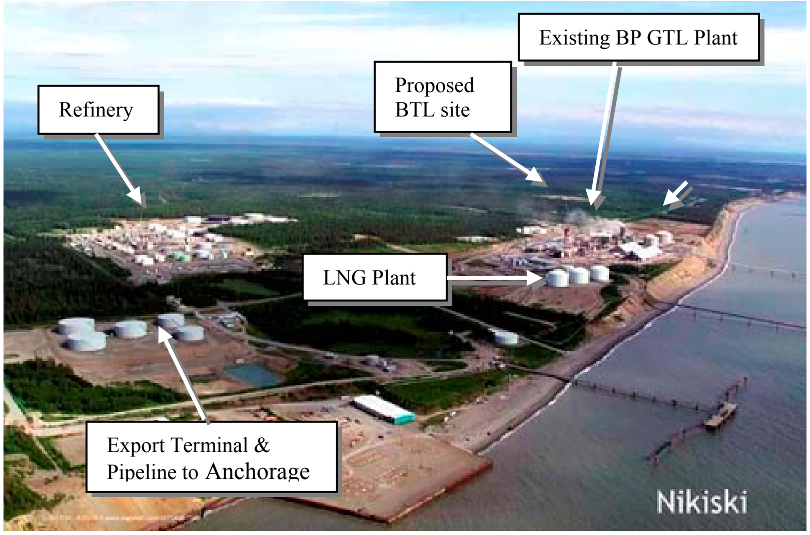
F-T plants are similar to chemical plants where upsets due to contamination, from small amounts of sulfur for example, can occur. Large-scale, reliable electrical systems are required to supply power during startup. The usual support infrastructure of administration buildings, workshops, warehouses, canteens and medical facilities are required, plus temporary construction facilities will be needed for remote locations. While the ultra-clean F-T diesel fuels have generated considerable interest, we must not forget there are equal challenges in the support systems that are needed when considering engineering needs, construction and overall cost.

An F-T facility can be visualized as a chemical plant. There is a major syn-gas generation facility at the front-end, together with a air-separation plant (oxygen plant), the F-T chemical conversion process in the middle and a refinery on the back end, all supported by a power supply system, steam and electrical systems, a wastewater and air treatment facility plus associated supporting infrastructure. Because F-T plants produce so much excess heat, the economics of a plant are severely degraded if offsite use of waste heat cannot be found. Industrial locations where heat, and water, as well as nitrogen and hydrogen can be obtained, will dramatically improve the economics of an F-T project.

As with crude oil refining, the manufacture of F-T fuels produces CO_2 and this gas is becoming increasingly problematic. The advantage of the F-T process is that the CO_2 is in a fairly concentrated stream and is easily sequestered so long as there is a place to dispose or utilize the CO_2. Depleted gas fields and enhanced oil recovery projects offer the best disposal methods, followed by large scale “dry” ice plants, such as those required by the food and fish processing industries. Alaska’s Cook Inlet, with its depleted gas and oil fields, may be an ideal location for an Enhanced Oil Recovery and CO_2 sequestering program.

All of these issues are more problematic in remote locations. The less industrialized the area or region, the fewer the opportunities to share in utility costs, which will hamper the economics of a remote F-T project.

In Alaska, Nikiski represents the best location in terms of supporting infrastructure. The area has a 70,000 barrel-per-day crude oil refinery, a 1.6 million ton-per-year ammonia plant, a LNG export facility, a GTL test facility, three export docks, a tank farm, a products pipeline to Alaska’s largest market and local access to the electric grid, all within a few miles. There is also a large technically-trained and experienced local work force at Nikiski. As for feedstock, the Kenai Peninsula has an abundant amount of bio-mass with road access to support a mid-size bio-mass to liquids plant. There are, however, no large coal resources on the Kenai. Coal would have to be barged across the Cook Inlet and stored locally, adding $3 per ton to $5 per ton to the cost of coal supplied to a CTL F-T plant.



Another potential site location in the area would be on the west side of Cook Inlet near the Beluga coal field. There is, as yet, no mine in this location but the coal resource is identified and proven, and is very large. The location does have a 380 MW electric generating station within 12 miles, and potential access to the electric grid as well as the Drift River oil export terminal for the loading of F-T fuels. Development of a Beluga coal mine would also include a coal export operation, resulting in the sharing of terminal costs. If the F-T plant was capable of using bio-mass and well as coal as resource inputs, wastewood from the region and from Southeast Alaska could be used.

One advantage of a plant at Beluga, as well as Healy, over a Nikiski location is that both would be located adjacent to or near producing coal mines, potentially reducing the feedstock costs by some 20 percent compared with Nikiski.

Both the Nikiski and Beluga locations have access to three large gas fields, each in the 2 to 4 trillion cubic foot (tcf) range, that are being depleted. These could be possible locations to sequester CO_2 produced during the gasification process. The CO2 could also possibly be used in Enhanced Oil Recovery to produce more crude oil from Cook Inlet oil fields. The potential for sequestration will require much more study, but if it is possible CO_2 credit sales might be possible under the Kyoto Protocol. This can add several hundred thousand dollars to tens of millions of dollars per year in revenue, depending upon the size of the F-T plant. None of the other potential sites considered in our analysis – Healy, Bristol Bay, Galena or Fort Yukon – would have this advantage.

PART TWO: Regional F-T plant scenarios

CASE 1: Nikiski, Alaska

300 bbl/d to 6,000 bbl/d bio-mass to F-T (BTL) and coal to F-T (CTL)

Of all of the potential sites evaluated in Alaska for an F-T fuels project, Nikiski is by far the best suited from a plant site point of view in that infrastructure and contractor and labor support is available. Nikiski is also a major shipping point for fuel deliveries to western Alaska, which means F-T products can be shipped via a well-established fuel transportation system. Nikiski's limitations are possible shortages of natural gas for a gas-based F-T project and the costs of supplying coal to a plant if a coal-based project is chosen. If bio-mass is the feedstock of choice, this location is attractive for a number of reasons. However, bio-mass unfortunately limits the size of the F-T plant which adversely affects plant economics.

How the financial analysis was done:

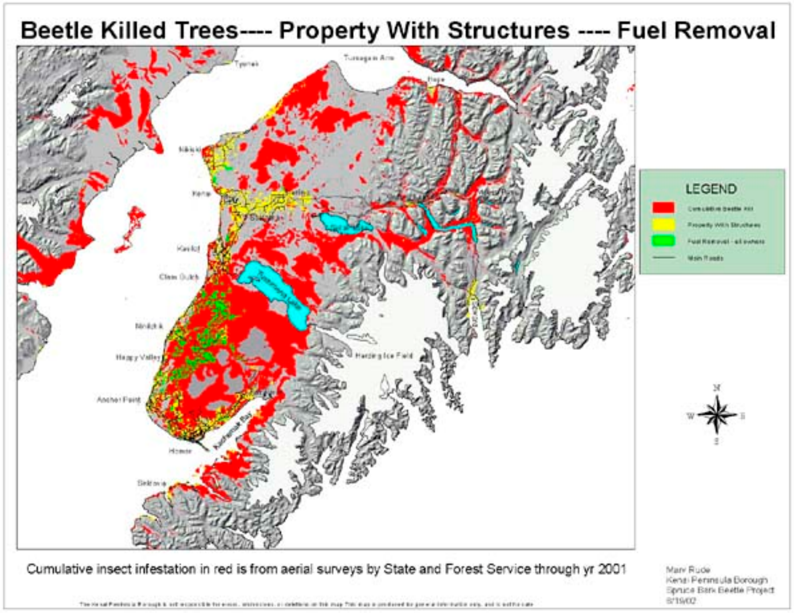
All analyses in the regional scenarios assume a private investor providing between 20 percent to 25 percent equity and earning either 20 percent or 30 percent internal rate of return (IRR) before federal tax. A 30 percent rate of return results in approximately a 19 percent rate of return after federal tax depending on the tax status of the investor. Until several F-T plants, especially small footprint F-T plants, are successfully built and operated, we judge these rates of return to be at the levels required to attract a private investor. Debt is assumed to have a 15-year payback at a 7.5 percent interest rate. The analyses have also reserved 18 percent of net cash flow for local and state taxes. In all cases design and construction is estimated at three and a half years except in the case of the BP gas-to-liquids plant conversion to biomass, in which we assume one year. Capital costs in the case of coal and bio-mass were derived from data made available from Choren Industries of Germany and from Sasol, of South Africa, for a larger coal-to-liquids plant at Beluga. For the Bristol Bay gas-to-liquids plant we use data from Sasol and Syntroleum Corp. of Tulsa, Oklahoma. In the Fort Yukon small gas-to-liquids plant we use published costs associated with the BP gas-to-liquids plant at Nikiski.

We have evaluated three different potential F-T projects at Nikiski. The first is a 300 bbl/d (barrel per day) bio-mass to F-T fuels, the second is a 6,000 bbl/d bio-mass to synthetic gas and F-T fuels, and the third is a 6,000 bbl/d combination coal and bio-mass to F-T fuels.

A prime option we considered is conversion of the 300 bbl/day BP Nikiski GTL test facility to a 300 barrels-per-day (bbl/d) BTL demonstration plant capable of utilizing 250 tons per day of Kenai area bio-mass, from beetle-killed spruce trees, as the feed stock.

The photograph included here is an aerial view of the BP GTL plant site. This is in the heart of the Nikiski industrial area, with ample water, electric power, water treatment facilities, access to an export terminal, pipeline to Anchorage, a refinery, oxygen supply and an experienced work force.

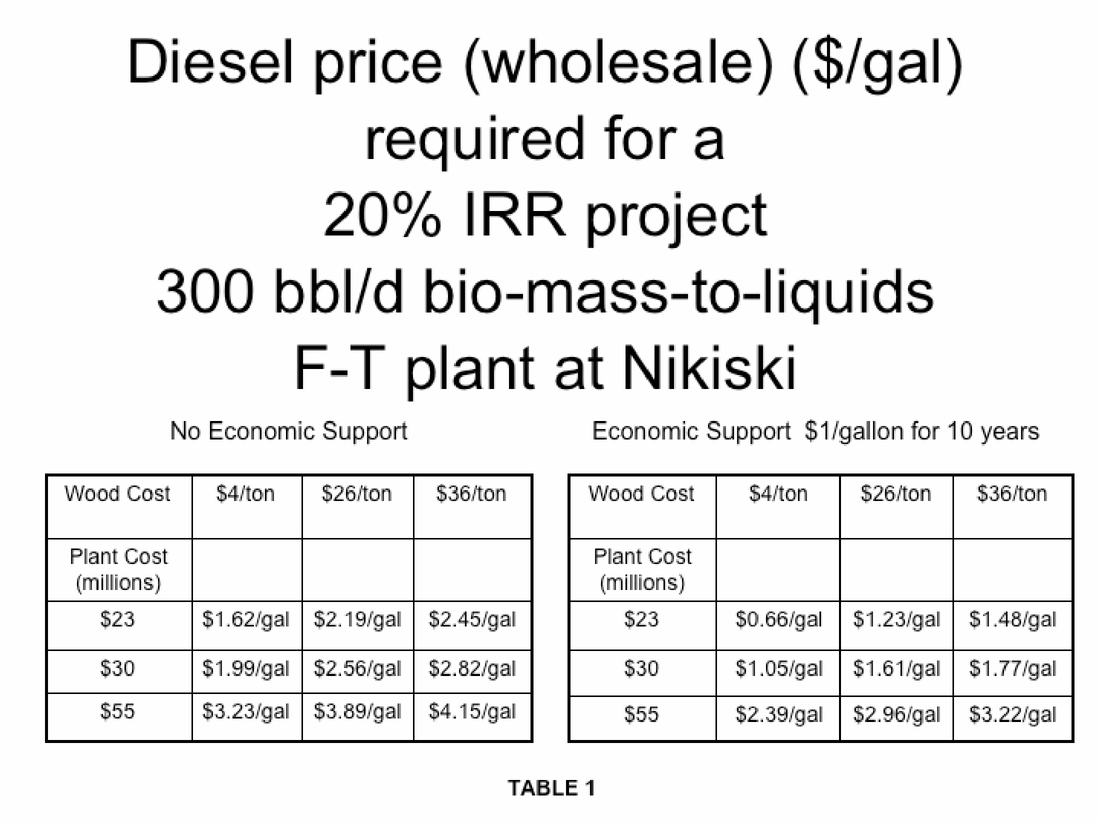
The 300 bbl/d BP test facility, built in 2002, is world class facility containing 80 percent of the F-T and support equipment needed for a BTL program. By using the test facility, if it is available, 50 percent or more of the cost of a new BTL program can be saved, improving the BTL plant economics. If this advantage is combined with the federal forest programs to subsidize the removal of dead spruce trees on the Kenai, a BTL demonstration plant could provide F-T diesel for local and rural Alaska markets. The question is whether it can provide these fuels competitively priced with conventional diesel made at the adjacent Tesoro refinery. The answer to this is generally "no" unless the price of crude oil is above $40/barrel, and unless there is some form of energy credit on a federal level.



The feedstock for this small-scale BTL plant would come from area beetle-killed spruce forests. Estimates from the Kenai Joint Task Force on beetle kill show there is approximately 1.5 million acres of dead or dying spruce trees in the region with between 30 to 50 tons of bio-mass (from waste timber) per acre recoverable (shown in red in the illustration). As with any bio-mass, as years go by the ability to use this resource decreases as the structural strength of the tree decreases. By the time the tree decays to a point where it can longer stand it has lost its value to be gasified and turned into a liquid fuel. One other advantage of a BTL project using a bio-gasifier is that trees damaged in a forest fire that will eventually die can be used in the process. Cost estimates to deliver the Kenai beetle-killed spruce in a chipped form to a Nikiski BTL plant site range from $4/ton if removal is federally subsidized to $36/ton if not. If other, green trees of higher value can be harvested at the same time the dead spruce is removed, private logging contractors indicate that costs could be in the $26/ton range. The 300 bbl/d BTL demonstration plant would require approximately 250 tons per day of wood/wood waste or approximately 10 truck loads a day seven days a week.

300 bbl BTL plant at the BP GTL site

A 300 bbl/d BTL plant at the BP plant site using the Choren bio-gasifier is estimated to cost between $23 million to $55 million. Small plants of this size are more like demonstration plants than commercial plants because the initial cost makes them non-competitive. The Nikiski location, however, does improve the plant economics because of the need to remove the dead spruce trees to reduce area fire hazards and by using the existing BP GTL test facility more than half the costs of the BTL demonstration plant could be saved. Even so, a GTL to BTL conversion plant will require a federal fuel subsidy in some form. We consider the case of an energy credit equal to that of biodiesel, which could keep the plant's "tail gate" price for diesel below $1.60/gal.



Diesel price (wholesale) ($/gal)
required for a
20% IRR project
300 bbl/d bio-mass-to-liquids
F-T plant at Nikiski

No Economic Support

Wood Cost	$4/ton	$26/ton	$36/ton
Plant Cost (millions)			
$23	$1.62/gal	$2.19/gal	$2.45/gal
$30	$1.99/gal	$2.56/gal	$2.82/gal
$55	$3.23/gal	$3.89/gal	$4.15/gal

Economic Support $1/gallon for 10 years

Wood Cost	$4/ton	$26/ton	$36/ton
Plant Cost (millions)			
$23	$0.66/gal	$1.23/gal	$1.48/gal
$30	$1.05/gal	$1.61/gal	$1.77/gal
$55	$2.39/gal	$2.96/gal	$3.22/gal

TABLE 1

Table 1 illustrates the affect of plant cost, feedstock cost and economic support on the wholesale price of F-T diesel at the plant tailgate to achieve a 20 percent Internal Rate of Return (IRR) for a 20 percent equity investor. (Note: Other scenarios we study assume both a 20 percent and a 30 percent IRR if the project is larger and with more risk). The $23 million capital cost represents the expected cost for a BTL conversion using 100 percent of the existing GTL plant facility; $30 million represents this same facility but adding a different product makeup module to make a wider range of products, while $55 million shown represents the cost of a new BTL plant at the same location, without using the BP facility. Wood costs of $4/ton assume a federal program to remove the beetle-killed spruce trees. $26/ton represents a private logging contractor's estimate for logging both green wood and the beetle kill, while the $36/ton shown represents U.S. Forest Service costs estimates to only remove the beetle kill, and to chip and deliver the chips to the Nikiski BTL site. Table 1 shows that without a federal Energy Credit (one option for federal support), the 300 bbl/d Nikiski BTL plant cannot produce F-T diesel competitive with today's Cook Inlet crude based diesel prices. Even with a significant energy credit or some other direct subsidy, the BTL plant will require a subsidized feedstock to sell F-T diesel below $1/gallon.

Frame of reference

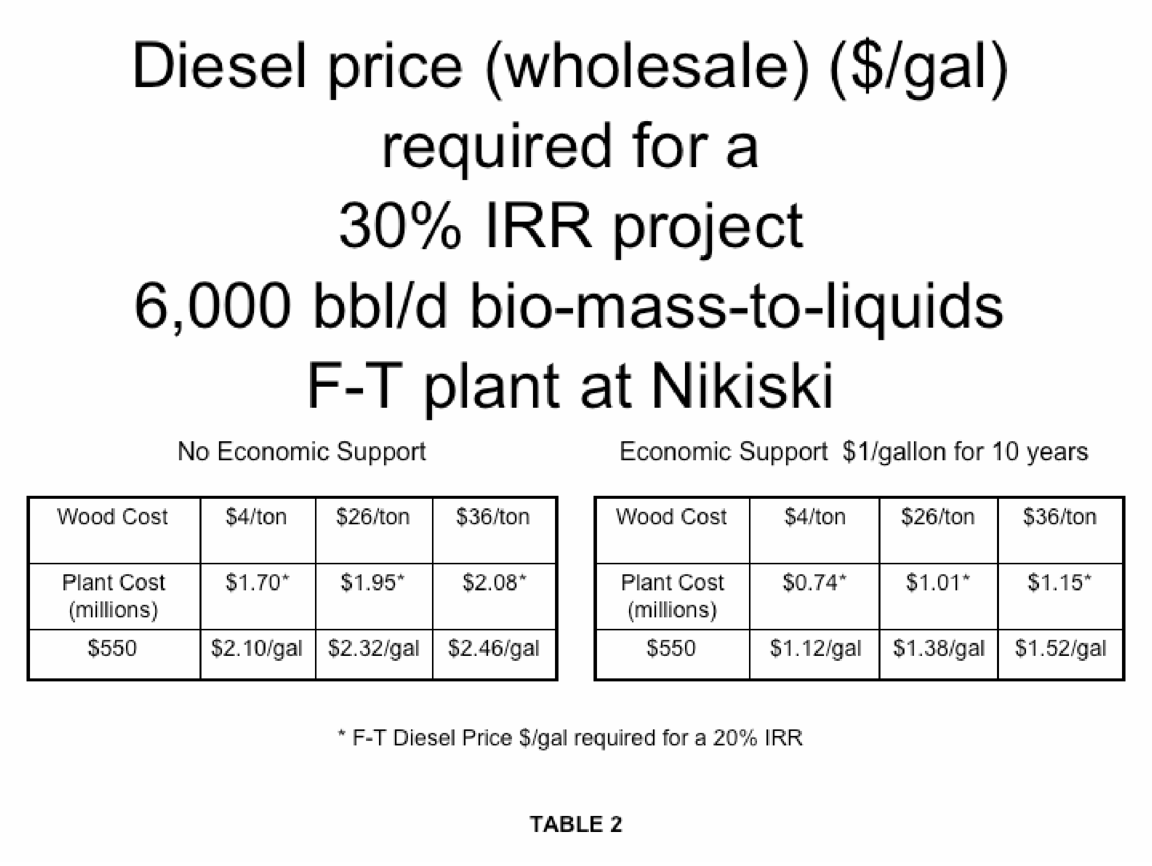
Cook Inlet region:

2004 conventional diesel Oil Price Information Service (OPIS) Pacific Northwest wholesale diesel price during the summer 2004 Alaska shipping period	$1.40/gal.
Estimated premium ULS diesel, post 2006-2010	$0.10/gal.*
Total:	$1.50/ gal.

**ULS diesel premium estimates vary 10 cents/gal. to 75 cents/gal.*

6,000 bbl/day BTL/ CTL plant at Nikiski:

Kenai Peninsula bio-mass resources are estimated to be in the 40 million to 70 million ton range looking only at the beetle-killed spruce. A 6,000 bbl/d Choren style BTL plant would require approximately 3,200 tons per day of bio-mass or approximately 1.2 million tons per year. The area beetle kill spruce resource could in theory support this plant for decades. However, dead trees decay, and long before the trees can be removed even at 1 million tons per year the wood waste would be unusable. One possibility is that the BTL plant could transition from distressed wood to commercial-grade green wood, but this would require paying commercial wood prices. We estimate that for a long term operation, a BTL plant on the Kenai Peninsula would have to pay close to $26/ton.



Diesel price (wholesale) ($/gal) required for a 30% IRR project 6,000 bbl/d bio-mass-to-liquids F-T plant at Nikiski

No Economic Support

Wood Cost	$4/ton	$26/ton	$36/ton
Plant Cost (millions)	$1.70*	$1.95*	$2.08*
$550	$2.10/gal	$2.32/gal	$2.46/gal

Economic Support $1/gallon for 10 years

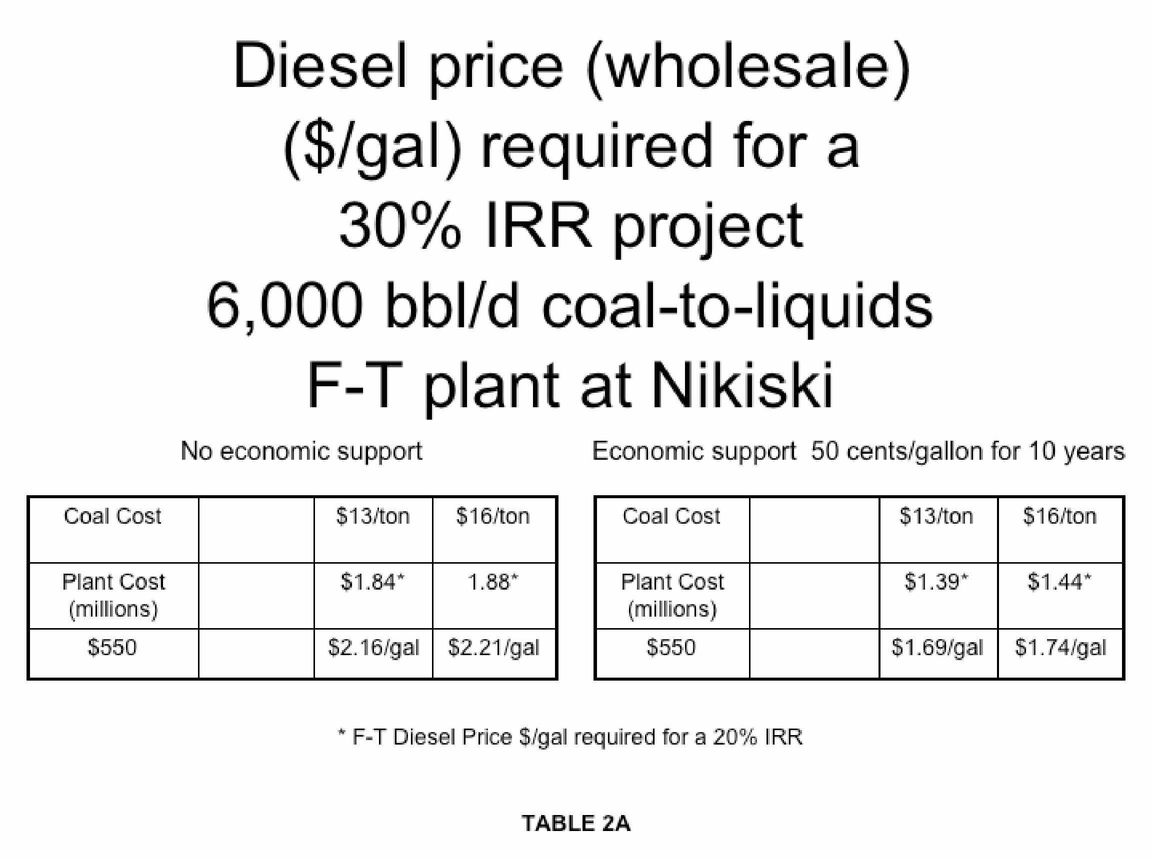
Wood Cost	$4/ton	$26/ton	$36/ton
Plant Cost (millions)	$0.74*	$1.01*	$1.15*
$550	$1.12/gal	$1.38/gal	$1.52/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 2

Table 2 illustrates how a larger size helps the 6,000 bbl/d BTL plant economics significantly, lowering the required plant tailgate wholesale price from $3.89/gallon to $2.32/gallon with no federal support. With an energy credit equal to biodiesel, the larger BTL plant could sell F-T diesel at $1.01/gallon if the investor accepts a 20 percent internal rate of return (IRR) where the wood-gathering cost is $26/ton, and $1.38.gallon for a 30 percent IRR. This F-T diesel price is below recent crude oil-based diesel wholesale prices. Once the capital costs of the BTL plant are paid, the plant could compete at today's diesel prices with no additional support, we believe.

As availability of wood and wood waste decreases, the BTL plant feedstock could be supplemented with coal. While coal costs per ton are considerably lower, $11 per ton for coal compared with $36 per ton for biomass (we assume the energy value per ton is approximately the same for both), the federal energy credit for coal would be half that of the bio-renewable bio-mass, so the economics in the case of coal are not improved until the F-T plant capital has been recovered. As an example, at $36/ton for bio-mass feedstock and a $1/gal energy credit, the required F-T diesel price is $1.52/gallon. The same plant operating with coal priced at $13/ton, but only receiving a $0.50/gallon energy credit, requires $1.69/gallon for F-T diesel to achieve the same IRR.



Diesel price (wholesale) ($/gal) required for a 30% IRR project 6,000 bbl/d coal-to-liquids F-T plant at Nikiski

No economic support

Coal Cost		$13/ton	$16/ton
Plant Cost (millions)		$1.84*	1.88*
$550		$2.16/gal	$2.21/gal

Economic support 50 cents/gallon for 10 years

Coal Cost		$13/ton	$16/ton
Plant Cost (millions)		$1.39*	$1.44*
$550		$1.69/gal	$1.74/gal

* F-T Diesel Price $/gal required for a 20% IRR

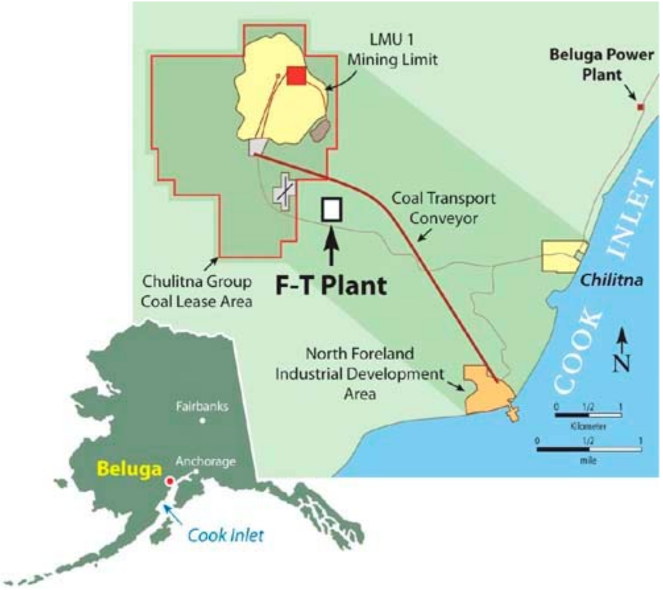
TABLE 2A

At 6,000 bbl/d (250,000gal) of F-T diesel production, such a plant will exceed the local market need and require markets outside the region, such as the U.S. West Coast. However, we believe that by 2010, all diesels fuel, on-road, off-road and marine, will be required to meet the new EPA ultra-low sulfur (15 PPM) standards. At zero sulfur, BTL F-T diesel could be in demand.

One other advantage of a Nikiski location is that it also provides opportunities for the syn-gas produced by the gasifier. It could, for example, provide syn-gas to a fertilizer plant. The Agrium Corp. plant at Nikiski has announced it may close because of an inability to acquire low cost natural gas to make syn-gas for its process. A BTL-based gasifier could help supply this need.

CASE 2: Beluga, Alaska

6,000 bbl/d Coal based F-T plant (CTL) with expansion capabilities beyond 80,000 bbl/d



Located across the Cook Inlet from the Nikiski industrial site is the identified but undeveloped Beluga coal field. The Beluga area contains one of the world's largest surface-mineable reserves of low-sulfur coal close to tidewater and ocean shipping. There are an estimated 2 billion tons of proven and probable sub-bituminous coal but economically recoverable reserves are estimated at 500 million to 750 million tons. The coal's principal attraction is its low-sulfur content. It is a significant natural resource that could supply a coal-to-liquids (CTL) F-T plant. The F-T plant location we assume is at a coal mine proposed by its owners, the Chulitna Group, located 12 miles from the Cook Inlet shoreline. Another company, Placer Dome U.S., owns additional coal resources nearby. The Chulitna Group's leases are approximately 12 miles from existing electrical infrastructure at the 380 Megawatt Chugach Beluga power plant, which is owned and operated by Chugach Electric Association, the regional electric utility. Most of the gas turbines at the plant are simple cycle turbines 25 to 35 years in age.

Little infrastructure: Outside of the Beluga power plant and its connection to the regional electric grid, there is little infrastructure to support the development of the coal mine or an F-T plant. There are few roads in the area, and those that are present are gravel. Chugach's power plant operates as a remote site, with workers housed at the location. There is a dock in the nearby community of Tyonek for use during construction, and there is also an oil export terminal, Drift River, located to the south of the proposed Beluga mine and F-T plant that could be expanded.

Because of this lack of infrastructure, in our analysis we have added an additional $100 million to the capital cost of the 6,000 bbl/d Nikiski BTL project, bringing the estimate cost to $650 million for an F-T plant at this location. A 6,000 bbl/d CTL F-T plant will require approximately 3,000 tons per day of coal, or approximately 1.1 million tons per year. If the existing Beluga power station were converted to a modern integrated gasification combined cycle (IGCC) power station, it could add an additional 1 million tons per year of coal requirement. The owners of the coal leases have said that 750,000 o 1 million tons a year of coal demand might be enough to justify the mine development.

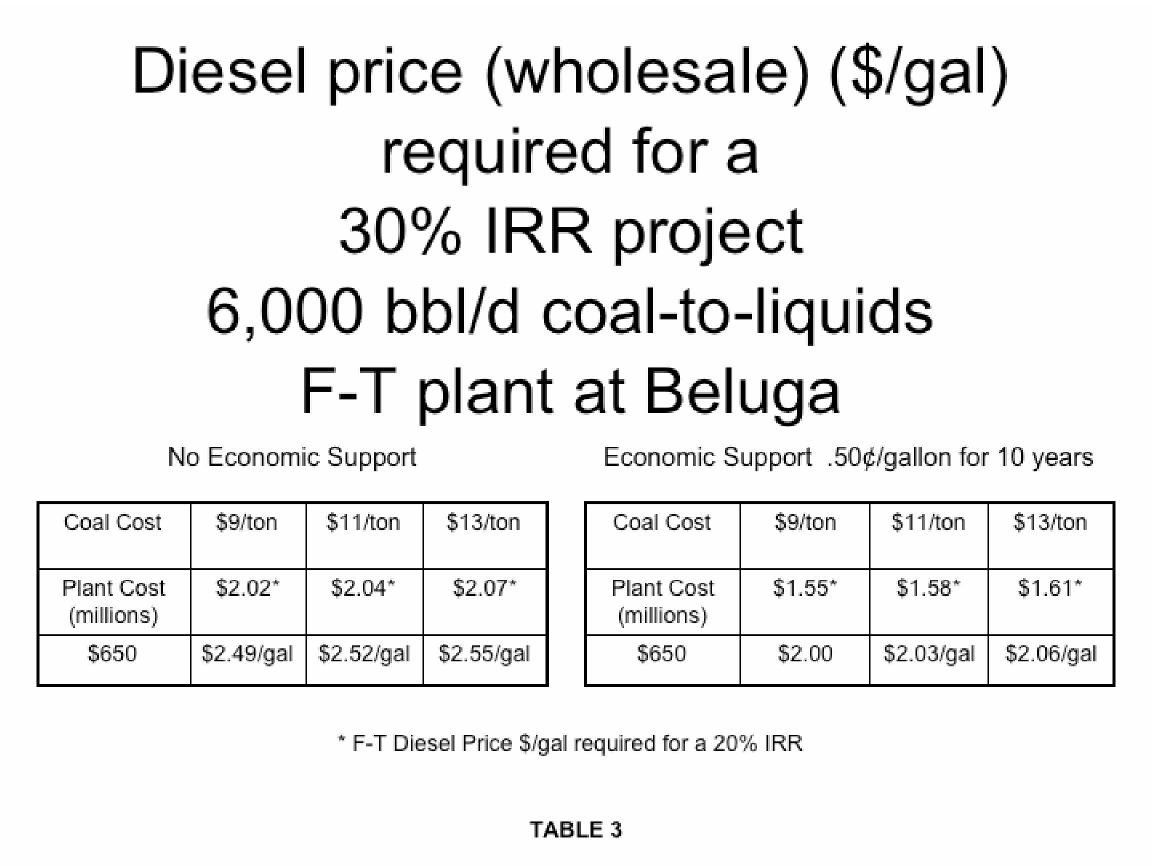
For the purpose of this analysis we will assume that an adequate export market will be found and the coal costs at the mine mouth will be in the $9 to $13/ ton range. The assumed coal prices are for illustration only and do not represent prices that a coal mine developer would actually charge. While the F-T process will also produce large quantities of waste heat for the generation of low cost electric power, we do not consider any benefit from this in the analysis. In addition to the extra costs associated with building the supporting infrastructure, we have also added one additional year to the three-year time estimate for the Nikiski BTL plant to construct the similar sized Beluga CTL project.

Frame of reference

Cook Inlet region:

2004 conventional diesel OPIS Pacific Northwest wholesale during summer season Alaska shipping period	$1.40/gal.
Estimated premium ULS diesel, post 2006-2010	$0.10/gal.*
Total:	$1.50/ gal.

**ULS diesel premium estimates vary 10 cents/gal. to 75 cents/gal.*



Diesel price (wholesale) ($/gal)
required for a
30% IRR project
6,000 bbl/d coal-to-liquids
F-T plant at Beluga

No Economic Support

Coal Cost	$9/ton	$11/ton	$13/ton
Plant Cost (millions)	$2.02*	$2.04*	$2.07*
$650	$2.49/gal	$2.52/gal	$2.55/gal

Economic Support .50¢/gallon for 10 years

Coal Cost	$9/ton	$11/ton	$13/ton
Plant Cost (millions)	$1.55*	$1.58*	$1.61*
$650	$2.00	$2.03/gal	$2.06/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 3

Table 3 illustrates the effect of plant cost, feedstock cost and economic support on the wholesale price of F-T diesel at the plant tailgate to achieve a 30 percent IRR for a plant investor. $650 million represents the cost of a new CTL plant at a mine mouth location. We consider coal costs of $9/ton, $11/ton and $13/ton as representative of a range of expected coal costs provided by the Beluga coal field owners. Table 3 shows that without federal support like an energy credit, the 6,000 bbl/d Beluga CTL plant cannot produce F-T diesel competitive with today's Cook Inlet crude based diesel prices. Even with a significant energy credit, the CTL plant will struggle to sell its F-T diesel unless the price of crude oil stays above $45/bbl, our analysis indicates. Lower feedstock costs at Beluga compared with Nikiski, coupled with a lower energy credit, do not offset the higher costs associated with the Beluga "Greenfield" site.

A larger plant would achieve economies of scale

Expansion of the CTL plant at Beluga provides an example of how bigger might be better. The Beluga mine mouth site represents a good location to expand the size of the CTL F-T plant to take advantage of scale-up economics. While it is outside the scope of this analysis, which is focused on smaller F-T plants, we believe an 80,000 bbl/d CTL plant at this location could support development of the Beluga coal mine by itself while reducing the unit cost of the installed facility, especially the necessary support infrastructure. We estimate that the Beluga 6,000 bbl/d CTL facility will cost over $100,000 per installed barrel while an 80,000 bbl/d facility could cost under $65,000 per installed barrel. In addition, the 10 million tons per year of coal supply needed for an 80,000 bbl/d plant could enjoy a coal price of $9/ton or less because of the larger quantities purchased. Expansion of the supporting pipeline, tank storage and export terminal capacity at the Drift River terminal will further improve the CTL economics.

Additional facilities built in the area, as development of the mine proceeds, could also support a bio-mass collection point for wood and wood waste produced throughout South-central and Southeast Alaska. With many interior Alaska communities on rivers or currently receiving their annual load of diesel fuel via water, a Beluga F-T site could serve these communities with ultra-clean diesel fuel made from Alaska coal while exporting the majority of the F-T diesel to markets on the U.S. west coast, primarily California where low aromatic diesel fuels are prized

How the financial analysis was done: All analyses in the regional scenarios assume a private investor providing between 20 percent to 25 percent equity and earning either 20 percent or 30 percent internal rate of return (IRR) before federal tax. A 30 percent rate of return results in approximately a 19 percent rate of return after federal tax depending on the tax status of the investor. Until several F-T plants, especially small footprint F-T plants, are successfully built and operated, we judge these rates of return to be at the levels required to attract a private investor. Debt is assumed to have a 15-year payback at a 7.5 percent interest rate. The analyses have also reserved 18 percent of net cash flow for local and state taxes. In all cases design and construction is estimated at three and a half years except in the case of the BP gas-to-liquids plant conversion to biomass, in which we assume one year. Capital costs in the case of coal and bio-mass were derived from data made available from Choren Industries of Germany and from Sasol, of South Africa, for a larger coal-to-liquids plant at Beluga.

CASE 3: Healy, Alaska

6,000 coal-to-liquids (CTL) F-T site

We examined Healy, Alaska as a potential site for a 6,000 bbl/d coal based Fischer-Tropsch plant. Healy was selected for study because it is has a producing coal mine and because the location has ready access to the Alaska Railroad for bulk transport of liquids along the railbelt. Access to the Anchorage-Fairbanks electric Intertie, a long-distance electric transmission line, is also an advantage. There are two coal-fired power plants at Healy, and the potential for sharing of waste heat, infrastructure and support services, although opportunities for this may be limited.

The principal advantage of Healy is the presence of a producing coal mine with the potential to expand production without major additional capital expense. Usibelli Mine Inc., the owner of the mine, has been producing coal at Healy for over 60 years. The reliability of the operator and its efficiency in supplying coal are well established. The mine currently produces 1.2 million to 1.5 million tons per year of sub-bituminous coal, employs approximately 95, and supplies coal to six coal-fired power plants in Interior Alaska plus exports coal to South Korea via the Alaska Railroad and a coal export terminal at Seward, on the southeast coast of the Alaska Kenai Peninsula. Test shipments to plants in Latin America have also been made.

Existing industrial facilities: Healy has existing industrial facilities, including two coal-fired power plants (one currently closed down) as well as bulk coal-handling facilities that support the coal mine and the loading of coal on rail cars. Industry support services established for the mine and power stations (fire protection, medical, etc.) could also support an F-T plant construction and operation. Power is available from coal-fired power plant at Healy, and any additional power generated from sales of waste heat from the F-T plant can be readily marketed over the existing electric Intertie.

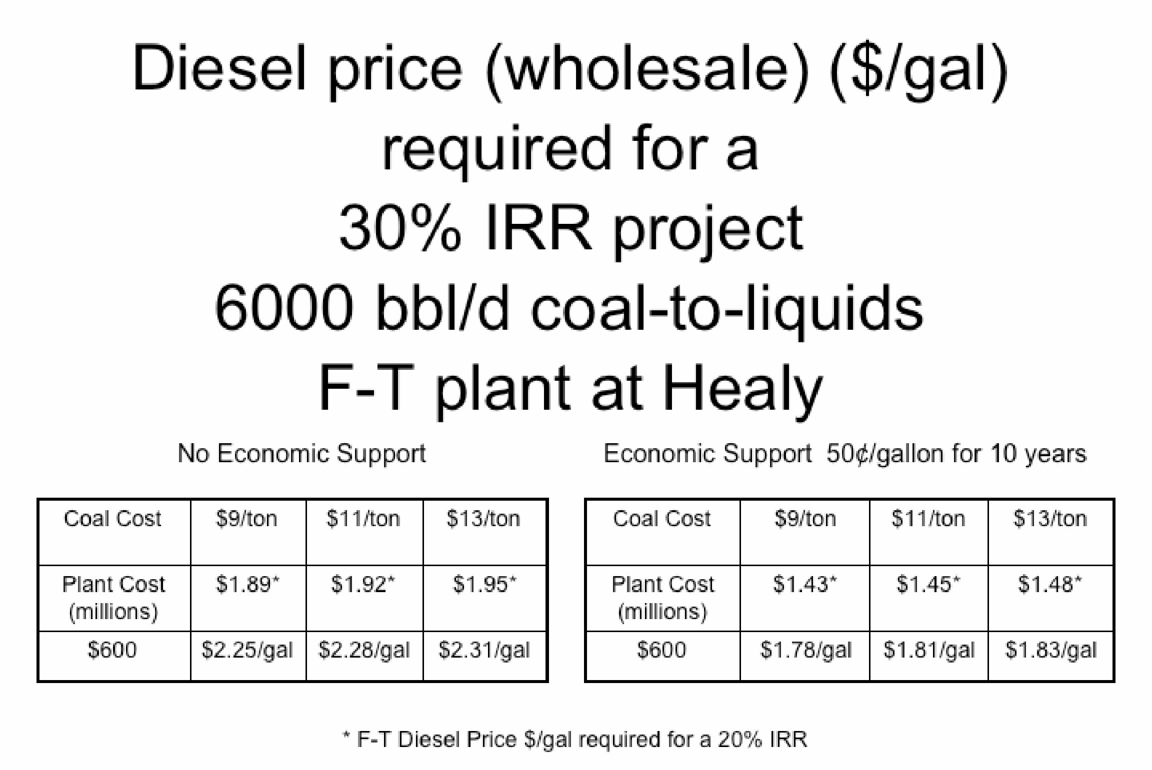
The Alaska Railroad currently operates bulk liquids trains through Healy, carrying fuel products from the Flint Hills refinery from North Pole, near Fairbanks, to Anchorage. The railroad has a long history of reliable service in this regard, lending confidence to our assumption that rail would be an efficient way to transport 91 million gallons a year of liquids products made in a 6,000 bbl/day F-T plant.

Usibelli Mine Inc.'s 1300W Bucyrus-Erie Walking Dragline being moved to the company's Two-Bull Ridge mining area. Usibelli has been mining coal at Healy since 1943.

There is experience in construction of complex industrial facilities at Healy. The 50-Megawatt advanced-technology Healy Clean Coal Project was built in 1996 and 1997 at a cost of over $300 million, so there is a degree of confidence in construction experience in the Interior region. There would be more uncertainty, in contrast, with construction in new "Greenfield" sites such as Galena, Fort Yukon and Bristol Bay. While Healy does not enjoy the same level of infrastructure that an F-T plant in Nikiski would have it is close to a long-term source of feedstock, coal. The regional coal resource may be nearly as large as at Beluga, but with 100 million tons-plus of current proven reserves and an annual need of 1 million tons, the coal reserve life is more than adequate to support the F-T plant. Construction costs at Healy should be lower than at Beluga because of existing road access from the surrounding communities. However, the economics of a plant at Healy would be adversely affected by the need to transport the liquid products by rail to the Anchorage/Fairbanks area, which is where most products would be marketed. For Interior Alaska rural communities Healy is relatively close to Nenana, the major shipping point for seasonal fuel delivery by barge to villages on the Yukon River and its tributaries. From the standpoint of supplying F-T products to Alaska military installations, the plant's location would allow it to supply Elmendorf Air Force Base and Fort Richardson near Anchorage, to the south, and Eielson Air Force Base and Fort Wainwright near Fairbanks, to the north.

Unlike a Nikiski or Beluga F-T plant site, a Healy plant does not have depleted gas reservoirs in the area for storage or utilization of CO_2. Thus, the plant would not be eligible for CO_2 credits, a possible source of revenue. On the other hand, the waste heat from an F-T plant would be considerable and the plant could produce very inexpensive electricity for the regional power grid over the Anchorage-Fairbanks electric Intertie, which comes through Healy. We do not quantify benefits of sales of waste heat.

We estimate that a 6,000 bbl/day F-T plant at Healy would cost approximately $600 million and take 3.5 years to construct. A plant of this size would require a supply of about 1 million tons of sub-bituminous coal per year, which is possible from the present mine with an expansion. We estimate costs of 5 cents to 6 cents/gallon to transport F-T products to Anchorage or Fairbanks by rail, or by rail or truck to Nenana for seasonal shipment to the Yukon River system via the Tanana River. Although beyond the scope of this report, at 5 cents/gallon ($2 per barrel,) shipping costs of liquids to Anchorage, we believe an economic analysis should be made for bringing Healy coal to the Cook Inlet area to take advantage of the depleted reservoirs for CO_2 sequestration, available natural gas for startup, the presence of export terminals and possibly the combining of Beluga and Healy mining capacity for a larger F-T plant.



Diesel price (wholesale) ($/gal)
required for a
30% IRR project
6000 bbl/d coal-to-liquids
F-T plant at Healy

No Economic Support

Coal Cost	$9/ton	$11/ton	$13/ton
Plant Cost (millions)	$1.89*	$1.92*	$1.95*
$600	$2.25/gal	$2.28/gal	$2.31/gal

Economic Support 50¢/gallon for 10 years

Coal Cost	$9/ton	$11/ton	$13/ton
Plant Cost (millions)	$1.43*	$1.45*	$1.48*
$600	$1.78/gal	$1.81/gal	$1.83/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 4

Table 4 included here illustrates the effect of plant cost, feedstock cost and possible federal economic support on the wholesale price of F-T diesel required at the plant "tailgate" to achieve a 30 percent and 20 percent IRR for a 20 percent equity plant investor. The assumed coal prices are for illustration only and do not represent prices that a coal producer would actually charge. Six hundred million dollars represents the cost of a new CTL plant at the location. Estimated coal costs of $9/ton, $11/ton and $13/ton represent a range of expected delivered coal prices. The table shows that without an energy credit or some other form of support, the 6,000 bbl/d Healy CTL plant cannot produce F-T diesel products competitive with conventional diesel prices. With federal support and a 20 percent investor IRR, the Healy CTL plant could not sell F-T diesel competitively unless the price of crude oil is $45/bbl or above.

How the financial analysis was done: All analyses in the regional scenarios assume a private investor providing between 20 percent to 25 percent equity and earning either 20 percent or 30 percent internal rate of return (IRR) before federal tax. A 30 percent rate of return results in approximately a 19 percent rate of return after federal tax depending on the tax status of the investor. Until several F-T plants, especially small footprint F-T plants, are successfully built and operated, we judge these rates of return to be at the levels required to attract a private investor. Debt is assumed to have a 15-year payback at a 7.5 percent interest rate. The analyses have also reserved 18 percent of net cash flow for local and state taxes. In all cases design and construction is estimated at three and a half years except in the case of the BP gas-to-liquids plant conversion to biomass, in which we assume one year. Capital costs in the case of coal and bio-mass were derived from data made available from Choren Industries of Germany .

CASE 4: Bristol Bay, Alaska

12,000 bbl/d barge mounted natural gas supplied F-T Plant

Geologists believe the Bristol Bay region of southwest Alaska is be one of three most promising areas for oil and gas discoveries in Alaska, the other two being the North Slope and Cook Inlet. For years the potential of the area has not been explored because of the concerns of local communities over the environmental danger that offshore oil production could pose to the region's rich fisheries. No federal or state lease sales have been held in recent years, and there has therefore been no attention from industry.

That is now changing, at the initiative of the local communities. The local fisheries have declined and there is now support in the region for onshore exploration or offshore exploration where wells could be drilled from onshore. The state of Alaska plans leasing of state lands in the middle to southern part of the Bristol Bay basin.

We considered a case for a 12,000 barrels/day gas-to-liquids (GTL) barge-mounted plant as an option for Bristol Bay gas commercialization. The GTL barge would require 120 million cubic feet (mmcf/d) of gas or 1 trillion cubic feet (tcf) over 25 years. In the event that gas discoveries are too small to support a conventional gas pipeline or a liquefied natural gas (LNG) export program (a rule-of-thumb is that 5 tcf to 6 tcf are needed for LNG) we believe GTL could be a viable option (only 1 tcf to 2 tcf would be needed.) While export sales would be needed to justify such a plant, its development would also make ultra-clean F-T fuels available in the western Alaska region.

Frame of reference

Bristol Bay region:

2004 conventional diesel Oil Price Information Service (OPIS) Pacific Northwest wholesale during summer season Alaska shipping period	$1.40/gal.
Estimated premium ULS diesel, post 2006-2010	$0.10/gal.*
Total:	$1.50/ gal.

**ULS diesel premium estimates vary from 10 cents/gal. to 75 cents/gal for Arctic-grade ULS diesel.*

In the 1990s, Sasol and Norwegian State owned Statoil considered barge-mounted GTL plants as a way to exploit remote small gas fields. More recently Syntroleum, a U.S. company, has worked on a similar program for the military. This analysis uses data from both the Syntroleum and Sasol programs to evaluate a 12,000 bbl/d barge-mounted F-T plant positioned in a sheltered shallow-water location in a port along the north side of the Alaska Peninsula. This location would be near offshore or onshore natural gas discoveries that we assume could be made on nearby state lands or private lands owned by Bristol Bay Native Corporation.

Our analysis considers a hypothetical $750 million barge-mounted F-T plant capable of producing 12,000 barrels per day of F-T diesel and naphtha; along with a floating products storage system (FPSS) capable of holding up to one month's production of products, or 360,000 barrels. As stated previously, the plant would require 120 million cubic feet per day of gas supply and a gas reserve of at least 1.1 trillion cubic feet. Gas is the assumed feedstock for the plant because of the gas-prone nature of the regional geology, although there are also coal resources in the region.

Coal deposits are known to exist near Chignik and Port Heiden. While it is conceivable that an onshore coal-to-liquids F-T plant could be built near those communities to use coal as a feedstock, in that case the economics of the project would also have to include the cost of developing a coalmine. The mine would have to be large enough to supply approximately 2 million tons per year of coal so the plant could operate at sufficient volumes to achieve economies of scale. It could be possible that a combination of coal and natural gas might be possible.

If a barge-mounted gas-to-liquids F-T plant were built, its liquid products could be directly loaded into a floating petroleum storage facility and then into barges for delivery to communities in the region. An alternative plan could involve transport of products across the Alaska Peninsula to a deep-water port on the south side through a small-diameter liquids pipeline. There are positives and negatives with both alternatives. However, our analysis focuses on the direct loading of barges at a plant on the north side of the peninsula. The cross-peninsula pipeline option requires evaluation beyond the scope of this report.

A shore-based F-T plant is also a possibility, but in our view the additional cost of building a complex plant at a remote location with no onshore support infrastructure would far exceed the costs projected by Sasol and Syntroleum for a similar sized barge-mounted facility.

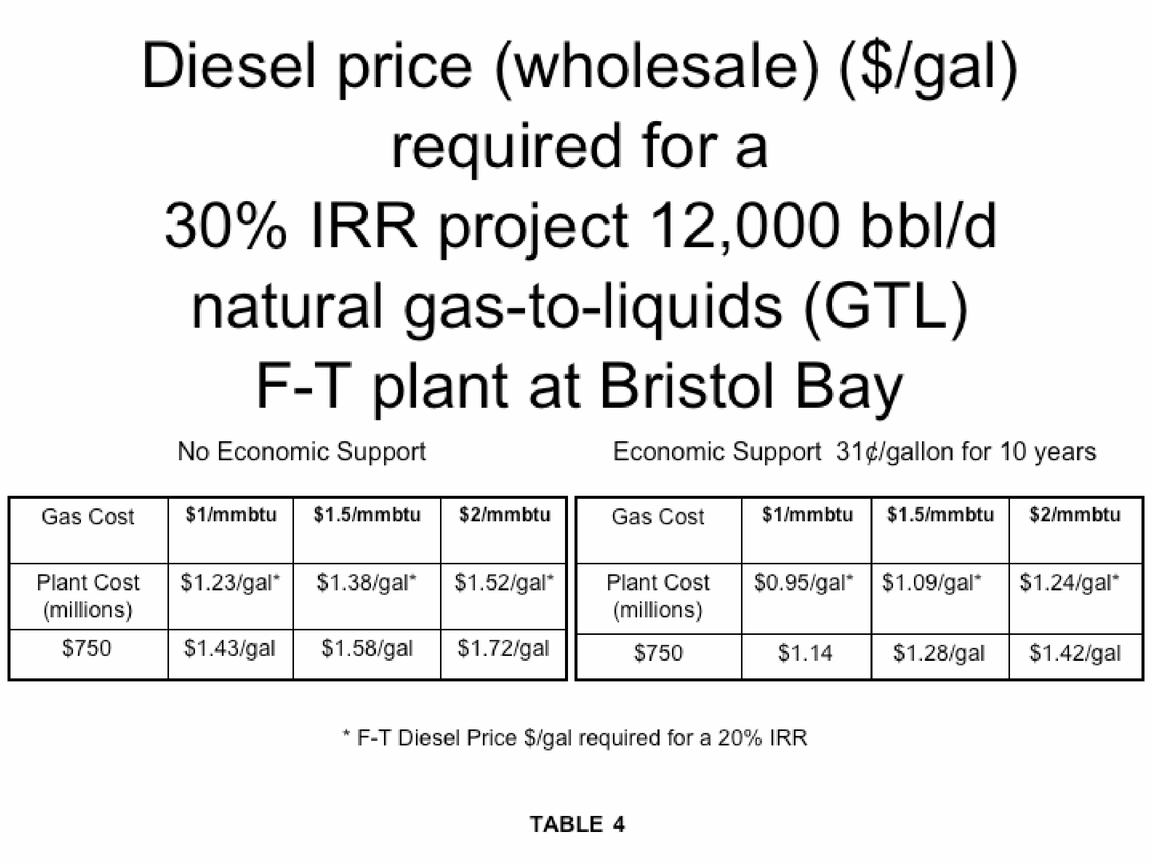
Artist's rendering of a barge-mounted GTL plant of a type being developed by Syntroleum Corp.

Our analysis assumes a barge-mounted F-T plant installed at a near shore location in one of three locations on the northern, Bristol Bay side of the Alaska Peninsula; in or near Herendeen Bay, Port Heiden or Pilot Point would be situated in areas where oil and gas could possibly be discovered nearby. All three locations could support direct-loading operations of barges for fuel deliveries within the region and other western Alaska communities.

FPSS loading operations for larger tankers needed for the export of products outside Alaska will require extensive studies to determine water depth, wind, wave, and ice impacts for specific sites. It may be possible to also locate the FPSS barge in a deeper-water area of Bristol Bay with a products line from the F-T plant to a storage/loading facility.

All three F-T barge locations we consider, Herendeen Bay, Port Heiden or Pilot Point, could also serve a products pipeline built to deep-water port locations on the southern side of the peninsula. Possible routes for a cross-peninsula pipeline from those communities, along with other pipeline routes, were considered in studies by the U.S. Minerals Management Service in the 1980s. The FPSS barge concept could also be employed in one of the deep-water port locations on the southern side of the peninsula where level land is not available to avoid having to build onshore tankage and products export dock.

No one has built a small scale (pilot size) barge-mounted F-T plant upon which to base a good economic model for a 12,000 bbl/d or larger facility. Further, one of the few detailed studies reported uses large volumes of conventional gas processing modules on the F-T barge to extract natural gas liquids, such as propane, butane, natural gasoline and naphtha, from a different gas stream (i.e. “wet” gas as would be produced as solution gas with oil) than we would expect from lean, or dry, gas that may be discovered in Bristol Bay.



Diesel price (wholesale) ($/gal) required for a 30% IRR project 12,000 bbl/d natural gas-to-liquids (GTL) F-T plant at Bristol Bay

No Economic Support

Gas Cost	**$1/mmbtu**	**$1.5/mmbtu**	**$2/mmbtu**
Plant Cost (millions)	$1.23/gal*	$1.38/gal*	$1.52/gal*
$750	$1.43/gal	$1.58/gal	$1.72/gal

Economic Support 31¢/gallon for 10 years

Gas Cost	**$1/mmbtu**	**$1.5/mmbtu**	**$2/mmbtu**
Plant Cost (millions)	$0.95/gal*	$1.09/gal*	$1.24/gal*
$750	$1.14	$1.28/gal	$1.42/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 4

The table above illustrates the effect of plant cost, feedstock cost and economic support on the wholesale price of F-T diesel at the barge plant tailgate to achieve a 30 percent IRR for a 20 percent equity plant investor in the GTL plant. We assume $750 million as the cost of a new 12,000 bbl/d GTL barge-mounted plant at a protected Bristol Bay location. This cost also includes a 400,000-barrel floating petroleum storage system (FPSS) to serve as a storage and export terminal. Essentially, a FPSS is a converted older tanker with the engine removed so that it serves as a floating storage and loading facility.

We assumed a natural gas cost of $1/mmbtu, $1.5/mmbtu and $2/mmbtu as a representative range of expected gas costs needed to economically support stand-alone exploration, drilling and production costs. The table above shows that without a federal support such as an energy credit, the 12,000 bbl/d Bristol Bay barge-mounted natural gas based GTL plant can not produce F-T diesel competitive with today's crude-based diesel prices for export outside of the region but may be competitive with local delivered costs of conventional diesel. With a $0.31/gal energy credit (the same tax credit compressed natural gas (CNG) enjoys in Lower 48 markets) a Bristol Bay barge-mounted GTL plant could be competitive with conventional diesel at today's crude prices.

Assuming that natural gas in the Bristol Bay area could be found, developed, produced and delivered to a barge mounted F-T at the costs shown and with the type of federal tax credit envisioned (what CNG now receives) such a project could help develop the region's resources, stimulate the local economy with jobs and supply the region with clean fuels for electric power generation and transport.

Potential plant sites in the Bristol Bay region:

Regional climate: The climate of the region is northern maritime, with extensive precipitation between July and October. Offshore winter ice is not considered a problem off either the Pacific or Bering Sea coasts. Winter ice is not present off the southern coast, and on the northern Bering Sea coast winter ice coverage seldom exceeds 10 percent.

F-T plant site near Herendeen Bay: From Herendeen Bay (or Port Moller, nearby) on Bristol Bay a 43-mile pipeline could be built across to the southern part of the peninsula to a deepwater port site at Albatross Anchorage on Balboa Bay, which is considered one of the best deepwater harbors on the peninsula. Coastal waters are relatively shallow at both Herendeen Bay and Port Moller, with extensive mudflats and water depths that average less than 12 feet in the bays. There are channels of 60 feet depth in approaches to Port Moller and at low tides vessels of 40-foot drafts can be accommodated. Herendeen Bay's entrances can accommodate vessels of 90-foot draft. While there are challenges, it is possible that a barge with an F-T plant could be positioned in one of these areas.

F-T plant site near Port Heiden: There are two other alternatives for plant sites on the north side of the peninsula near pipeline corridors to the south side. From Port Heiden, a 45-mile pipeline could be built across the peninsula to Chignik Bay. While this is a natural pipeline corridor for terrain reasons, Chignik Bay is shallow. The local area also supports a substantial salmon fishery, which would lead to objections for other reasons to a pipeline terminus at Chignik Bay.

F-T plant site near Pilot Point: In the northern part of the peninsula a natural 50-mile pipeline corridor exists from Pilot Point, on the north side, to Wide Bay, on the south side. Wide Bay is considered to be an excellent port site, although shoals exist at its entrance.

Oil and gas potential of the region:

Geologists consider the Bristol Bay region to be more gas-prone although there is always the potential for oil discoveries. The southern part of the basin, along the western side of the Alaska Peninsula and adjacent offshore lands, is considered to have more potential for oil than the northern parts of the basin, around Bristol Bay itself.

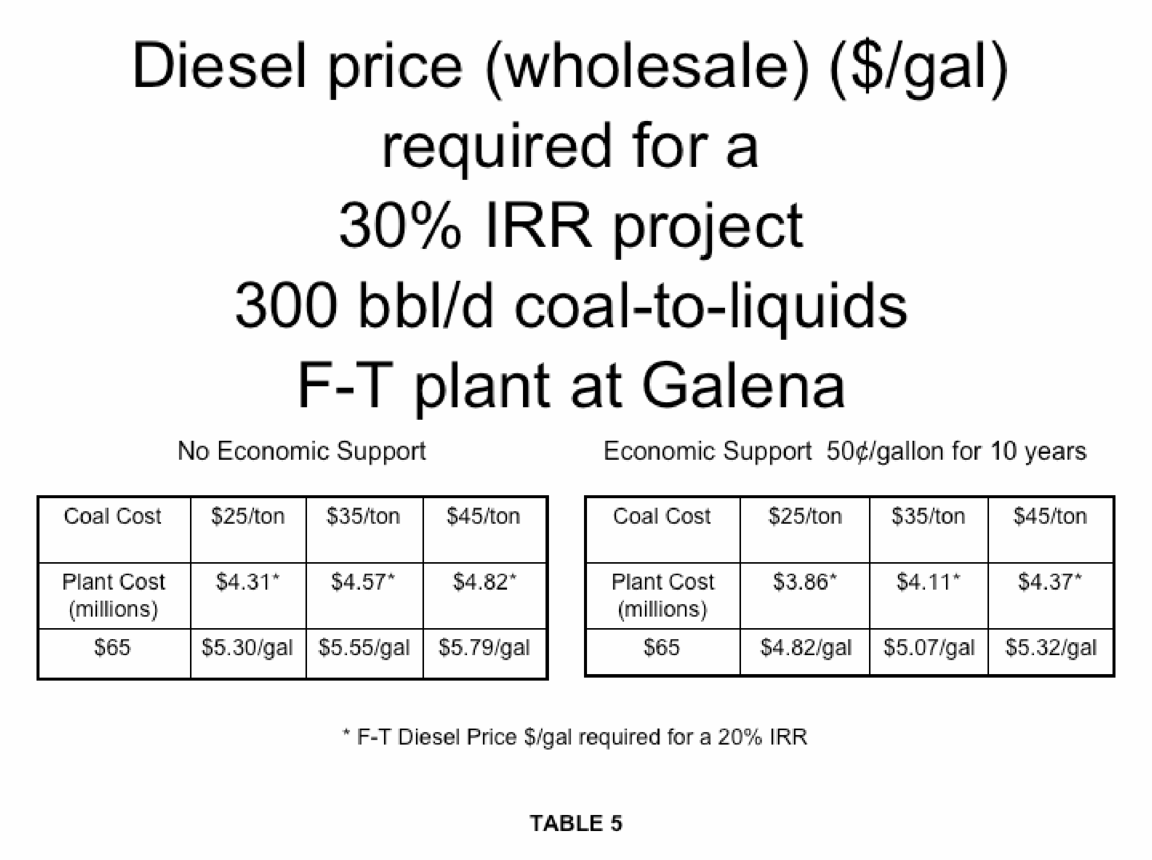
The oil and gas potential of the Bristol Bay Basin has long been known. Oil seeps on the eastern Gulf of Alaska side of the Alaska Peninsula have been known since the early part of the 20th century. There are two oil and gas provinces within the area, one in the northern part of the basin around Bristol Bay itself and the other along the Alaska Peninsula. Twenty-six wells have been drilled in the region between 1903 and 1981. Many of these wells had oil or gas shows but none were considered commercial. The gas shows in many of the wells were quite prominent, however.

How the financial analysis was done: All analyses in the regional scenarios assume a private investor providing between 20 percent to 25 percent equity and earning either 20 percent or 30 percent internal rate of return (IRR) before federal tax. A 30 percent rate of return results in approximately a 19 percent rate of return after federal tax depending on the tax status of the investor. Until several F-T plants, especially small footprint F-T plants, are successfully built and operated, we judge these rates of return to be at the levels required to attract a private investor. Debt is assumed to have a 15-year payback at a 7.5 percent interest rate. The analyses have also reserved 18 percent of net cash flow for local and state taxes. In all cases design and construction is estimated at three and a half years except in the case of the BP gas-to-liquids plant conversion to biomass, in which we assume one year. Capital costs in the case of coal and bio-mass were derived from data made available from Choren Industries of Germany and from Sasol, of South Africa, for a larger coal-to-liquids plant at Beluga. For the Bristol Bay gas-to-liquids plant we use data from Sasol and Syntroleum Corp. of Tulsa, Oklahoma.

CASE 5: Galena, Alaska

300 bbl/d coal-based (CTL) and biomass-based (BTL) F-T plants

Galena is located on the Yukon River west of Fairbanks and northwest of Anchorage. It is a small community of approximately 750 (2000 census) but acts as a regional bulk fuel distribution center. Galena has a small U.S. Air Force forward interceptor base that is used periodically as well as other government facilities. We selected Galena as a site for evaluation of a small F-T plant in a rural location because of its remote location but also its well-established fuel transportation and storage infrastructure. Galena also has an identified coal deposit on the Yukon River 8 miles from the community that we consider in our analysis of a small (300 bbl/day) coal-to-liquids (CTL) F-T plant, as well as extensive timber resources in the region that could possibly supply wood to a small (300 bbl/day) bio-mass-to-liquids (BTL) F-T plant.



Diesel price (wholesale) ($/gal) required for a 30% IRR project 300 bbl/d coal-to-liquids F-T plant at Galena

No Economic Support

Coal Cost	$25/ton	$35/ton	$45/ton
Plant Cost (millions)	$4.31*	$4.57*	$4.82*
$65	$5.30/gal	$5.55/gal	$5.79/gal

Economic Support 50¢/gallon for 10 years

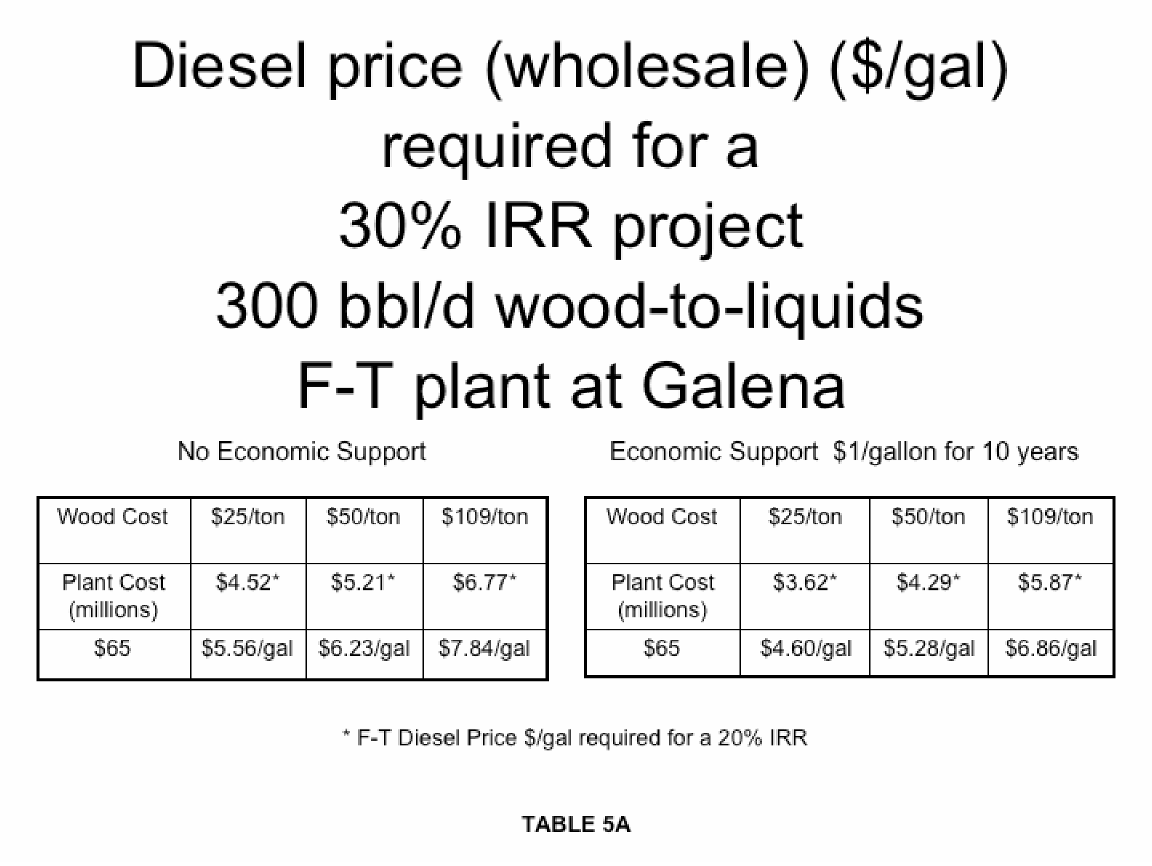
Coal Cost	$25/ton	$35/ton	$45/ton
Plant Cost (millions)	$3.86*	$4.11*	$4.37*
$65	$4.82/gal	$5.07/gal	$5.32/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 5

Table 5 illustrates the effect of plant and feedstock cost and the level of required economic support on the wholesale price F-T diesel at the plant tailgate to achieve a 30 percent IRR for an equity investor, assuming the plant is privately-owned. We assume $65 million as the cost of a new 300 bbl/d CTL plant built in modular form and transported to a location near Galena, at a high ground site near the Yukon River (preferably at the coal deposit.) Coal costs of $25/ton, $35/ton and $45/ton represent a range of costs used in our analysis. These coal costs are very speculative, and assume that the F-T plant would be the only customer in the area. Table 5 shows that without federal support like an energy credit, the 300 bbl/day Galena CTL plant cannot produce F-T diesel at costs competitive with today's crude-based diesel prices delivered to the region. Even doubling the energy credit, a private Galena GTL plant would struggle to sell its F-T diesel unless the price of crude oil is well above $60 per barrel.

As with other Interior Alaska locations, bio-mass, in the form of timber in the region, presents a potential feedstock for an F-T plant. To this end, we have evaluated a potential 300 bbl/day bio-mass (BTL) plant for a Galena location.



Diesel price (wholesale) ($/gal) required for a 30% IRR project 300 bbl/d wood-to-liquids F-T plant at Galena

No Economic Support

Wood Cost	$25/ton	$50/ton	$109/ton
Plant Cost (millions)	$4.52*	$5.21*	$6.77*
$65	$5.56/gal	$6.23/gal	$7.84/gal

Economic Support $1/gallon for 10 years

Wood Cost	$25/ton	$50/ton	$109/ton
Plant Cost (millions)	$3.62*	$4.29*	$5.87*
$65	$4.60/gal	$5.28/gal	$6.86/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 5A

An alternative to coal as feedstock is bio-mass from timber harvesting in the region, however, but having to deliver 250 tons per day of bio-mass (trees or wood-waste) at $25 per ton could be a challenge even using the Yukon River as a method of transportation. In a very simplified analysis of the bio-mass option we relied on a 1981 study of a regional timber harvesting operation, with the further assistance of one of the study authors. The study was the Yukon Basin Timber Survey by Alaska Information and Research Services and Northern Forests, Ltd.

The 1981 study showed green wood chips being delivered from harvesting areas in the middle-Yukon region to the mouth of the Yukon, a 1,000 mile round trip. The costs are over 3 times higher than costs of delivering wood to the Nikiski BTL site discussed in the Nikiski section of this report. Delivering the green wood chips to an F-T plant near Galena would reduce transportation costs, but the extent of the cost-savings would require further study as well as an update of the 1981 estimate of timber harvesting costs. Authors of the 1981 study also note that there have been changes in regional land ownership as well as increased barge construction and fuel costs, which mean that relying on the 1981 study of timber harvesting and delivery can only give very general indications for the BTL option.

Table 5A illustrates the effect of plant and feedstock cost and the level of required economic support on the wholesale price F-T diesel at the plant tailgate to achieve a 30 percent IRR for an equity investor, assuming the plant is privately-owned. We assume $65 million as the cost of a new 300 bbl/d BTL plant built in modular form and transported to a location near Galena, at a high ground site near the Yukon River. Wood costs of $25/ton, $50/ton and $109/ton represent a range of costs used in our analysis.

Table 5A shows that without federal support like an energy credit, the 300 bbl/d Galena BTL plant cannot produce F-T diesel competitive with today's crude-based diesel prices delivered to the region. Even doubling the energy credit, a private Galena BTL plant would struggle to sell its F-T diesel unless the price of crude oil is above $60/bbl.

In any event, the cost of BTL F-T diesel from a plant at this location would appear greater than $6/gallon because the initial cost of the BTL plant as well as the high wood costs. The economics would be improved by approximately 10¢/gallon with a CO2 emission credits at $15/ton using bio-mass instead of coal as the feedstock. Even so, the cost appears well above current fuel costs in the region. One other possibility is that of delivering dry wood rather than green wood, which could reduce transportation costs. Green wood contains up to 40 percent moisture, which is removed when the wood dries. Harvesting trees and stacking them in a wood yard near the river for a period, possibly several years, could accomplish this. However, even if the cost for the delivered wood is $50/ton and the plant owner has a 20 percent IRR, the $4.29/gallon required price will not be attractive.

Yet another possibility is to integrate the wood harvesting with a regional sawmill to use higher-value timber to manufacture building materials, with the waste used for the F-T plant. This would reduce the feedstock cost even further, but even at $25/ton for bio-mass, the price of F-T diesel is $3.62/gallon with an energy credit.

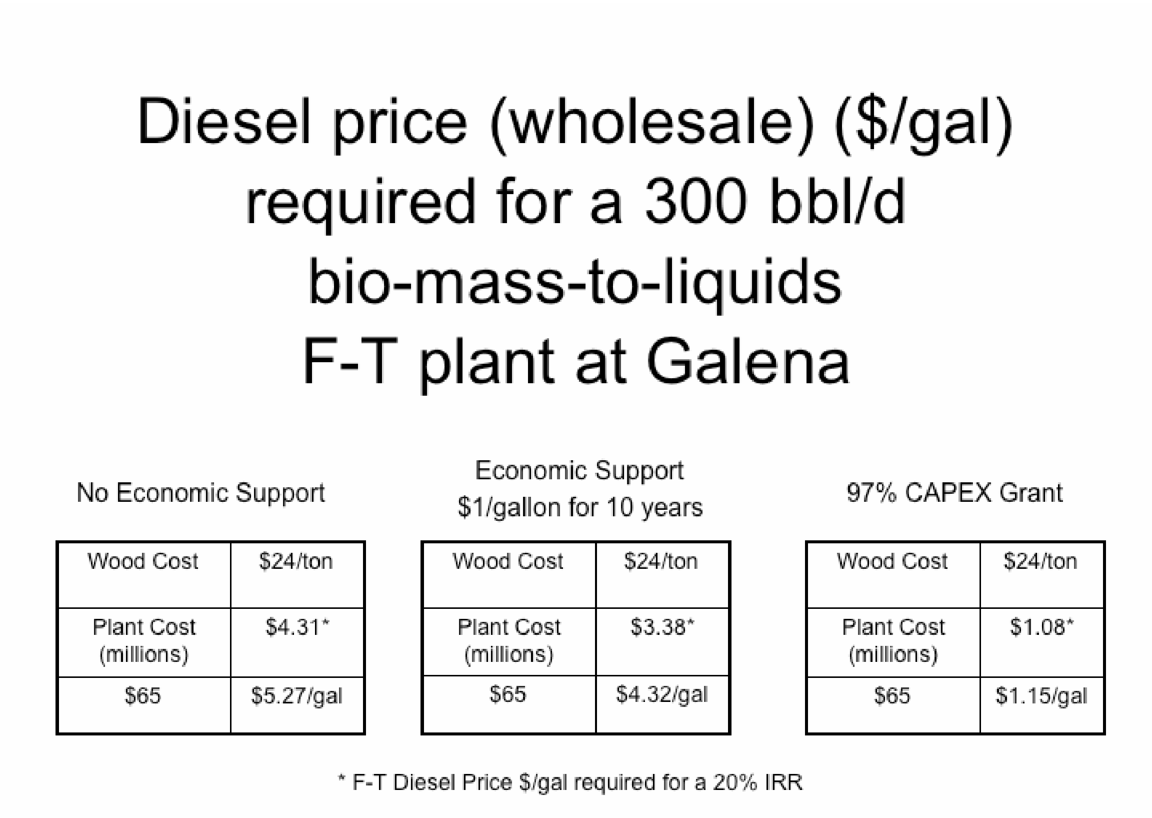
However, the bio-mass BTL plant's economic stimulus to the region is a factor that should be considered. Assuming a wood cost of $25/ton, a Galena BTL project adds $2.2 million to the local economy in wood purchases and $4.3 million at $50/ton. Our analysis also indicates such a plant could pay $600,000 in local and state tax revenue and provide employment at the plant for about 25 people with an annual plant operations and maintenance cost of approximately $2 million. We do not assume any credit for local electric power generation from waste heat, but it is safe to say that with ample waste heat available, electricity could be made available locally at very attractive rates compared with what Galena now pays for power generated with conventional diesel.

Another way to look at a Galena project:

The analysis above assumes a privately owned project that pays a return on investment to the owner. There are other ways a small rural F-T project could be done, however.

Historically the federal government, in recent years through the U.S. Dept. of Agriculture rural economic development programs and the Denali Commission, has helped support projects for rural Alaska that would not be economic on their own due to their small size.

If there was government support for a rural plant in the form of capital grants it might be possible for a 300 bbl/d BTL plant at Galena to supply the diesel requirements for the Interior river and Bering Sea communities for under \$1.25/gallon, on average, FOB Galena and remain under \$1.40/gallon, on average, through 2025. We assume, in the analysis in Table 5-B, that the capital costs of the F-T plant (\$55 million) and the wood gathering/transport costs for a tug, barge and chipper (\$10 million) would be paid for in grants. If this were possible, the revenue stream from the sale of F-T diesel and naphtha produced would pay \$2.2 million annually for wood supply, provide jobs for several hundred people and would have sufficient cash flow to pay operating costs on a sustained basis.



Diesel price (wholesale) (\$/gal)
required for a 300 bbl/d
bio-mass-to-liquids
F-T plant at Galena

No Economic Support

Wood Cost	\$24/ton
Plant Cost (millions)	\$4.31*
\$65	\$5.27/gal

Economic Support
\$1/gallon for 10 years

Wood Cost	\$24/ton
Plant Cost (millions)	\$3.38*
\$65	\$4.32/gal

97% CAPEX Grant

Wood Cost	\$24/ton
Plant Cost (millions)	\$1.08*
\$65	\$1.15/gal

* F-T Diesel Price \$/gal required for a 20% IRR

TABLE 5B

Table 5B looks at a \$65 million total Galena BTL project (not including the saw mill costs) with a \$63 million government grant, a \$1 million equity owner investment and a \$1 million bank loan repaid in 15 years at 7.5% interest. The table shows that with the grant to pay the capital cost, the initial tailgate sales price could be as low as \$1.08/gallon, an attractive price for the region. At an average tailgate price of

$1.25/gallon, the F-T plant could generate enough revenue to sustain operations, covering operations and maintenance, and contingency costs, for 30 years. With the exception of a government grant to pay off the capital costs of a small F-T plant operation, small F-T plants located in remote locations would produce F-T diesel with costs over $4/gallon, and could not economically compete with the delivered cost of conventional diesel today.

How the financial analysis was done: All analyses in the regional scenarios assume a private investor providing between 20 percent to 25 percent equity and earning either 20 percent or 30 percent internal rate of return (IRR) before federal tax. A 30 percent rate of return results in approximately a 19 percent rate of return after federal tax depending on the tax status of the investor. Until several F-T plants, especially small footprint F-T plants, are successfully built and operated, we judge these rates of return to be at the levels required to attract a private investor. Debt is assumed to have a 15-year payback at a 7.5 percent interest rate. The analyses have also reserved 18 percent of net cash flow for local and state taxes. In all cases design and construction is estimated at three and a half years except in the case of the BP gas-to-liquids plant conversion to biomass, in which we assume one year. Capital costs in the case of coal and bio-mass were derived from data made available from Choren Industries of Germany and from Sasol, of South Africa.

CASE 6: Fort Yukon

300 bbl/d coal /bio-mass based F-T plant (CTL/BTL)

Fort Yukon, Alaska, sits at the confluence of the Yukon and Porcupine rivers about 145 air miles northeast of Fairbanks. It is just north of the Arctic Circle in the Yukon Flats National Wildlife Refuge.

The winters in Fort Yukon, population about 600, are long and harsh and the summers are short but warm. Daily minimum temperatures between November and March are usually below zero degrees Fahrenheit. Extended periods of minus 50 to minus 60 degrees are common. Summer high temperatures run 65 to 72 degrees. The Yukon River is ice-free from the end of May through mid-September.

Table 6 illustrates the effect of coal-to-liquids plant and feedstock cost and the level of required economic support on the wholesale price F-T diesel at the plant tailgate to achieve a 30 percent IRR for a plant investor, assuming the plant is privately-owned. We assume $65 million as the cost of a new 300 bbl/d CTL plant built in modular form and transported to a location near Fort Yukon, at a high-ground site near the Yukon River. Coal costs of $25/ton, $35/ton and $45/ton represent a range of costs used in our analysis. These coal costs are very speculative, and assume that the F-T plant would be the only customer in the area.

The table shows that with even with federal support like an energy credit, the 300 bbl/d Fort Yukon CTL plant cannot produce F-T diesel competitive with today's crude-based diesel prices delivered to the region. Even doubling the energy credit, a private Fort Yukon CTL plant would struggle to sell its F-T diesel unless the price of crude oil is above $60/bbl.

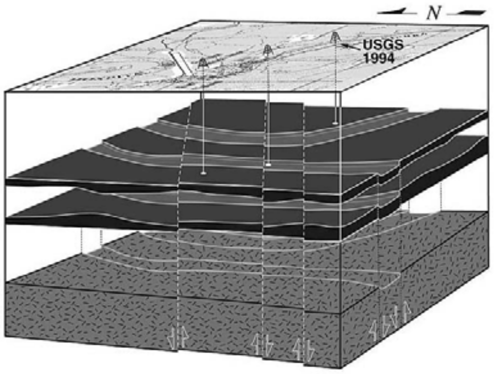
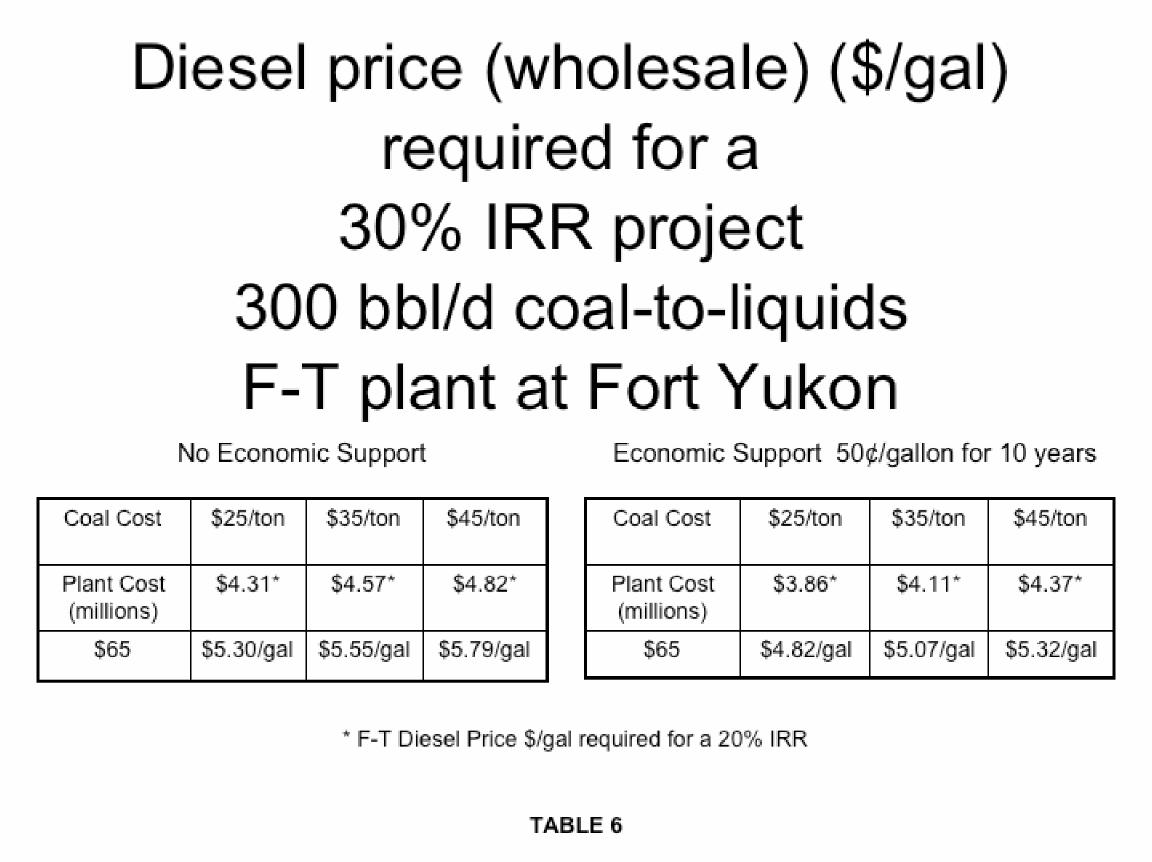


Diagram illustrates coal seams that underlie Fort Yukon at approximately 1,200 feet. Gas was detected in a 1994 test well drilled by the U.S. Geological Survey. The coal could be a source of coal-bed methane, or gas.



Diesel price (wholesale) ($/gal) required for a 30% IRR project 300 bbl/d coal-to-liquids F-T plant at Fort Yukon

No Economic Support

Coal Cost	$25/ton	$35/ton	$45/ton
Plant Cost (millions)	$4.31*	$4.57*	$4.82*
$65	$5.30/gal	$5.55/gal	$5.79/gal

Economic Support 50¢/gallon for 10 years

Coal Cost	$25/ton	$35/ton	$45/ton
Plant Cost (millions)	$3.86*	$4.11*	$4.37*
$65	$4.82/gal	$5.07/gal	$5.32/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 6

An alternative to coal as feedstock is bio-mass from timber harvesting in the region, but as in our Galena case having to deliver 250 tons per day of bio-mass (trees/wood-waste) at $25/ton would be a challenge even using the Yukon River as a source of transportation.

In a very simplified analysis of the bio-mass option we relied on a 1981 study of a regional timber harvesting operation (cited in our analysis of Galena) with the further assistance of one of the study authors.

The 1981 study showed green wood chips being delivered from harvesting areas in the middle-Yukon region to the mouth of the Yukon, a 1,000 mile round-trip. These costs are over 3 times higher than costs of delivering wood to the Nikiski BTL site discussed in the Nikiski section of this report. Delivering the green wood chips to an F-T plant near Fort Yukon would reduce transportation costs, but the extent of the cost-savings would require further study as well as an update of the 1981 estimate of timber harvesting costs. Authors of the 1981 study also note that there have been changes in regional land ownership as well as increased barge construction and fuel costs, which mean that relying on the 1981 study of timber harvesting and delivery can only give very general indications for the BTL option.

In any event, the cost of BTL F-T diesel from a plant at this location would appear greater than $6/gallon because the initial cost of the BTL plant as well as the high wood costs. The economics would be improved by approximately 10¢/gallon with a CO_2 emission credits at $15/ton for using bio-mass instead of coal as the feedstock. Even so, the cost appears well above current fuel costs in the region. One other possibility is that of delivering dry wood rather than green wood, which could reduce transportation costs. Green wood contains up to 40 percent moisture, which is removed when the wood dries. Harvesting trees and stacking them in a wood yard near the river for a period, possibly several years, could accomplish this. However, even if costs for the delivered wood are $50/ton and the plant has a 20 percent IRR, the $4.29/gallon required price will not be attractive.

Frame of reference

Yukon River region:

2004 summer season conventional diesel wholesale price paid, Alaska Village Electric Co-Op system	$1.93/gal.
Estimated premium ULS diesel, post 2006-2010	$0.20/gal.*
Total:	$2.13/ gal.

**ULS diesel premium estimates vary from 10 cents/gal. for conventional diesel to 75 cents/gal For Arctic grade ULS diesel.*

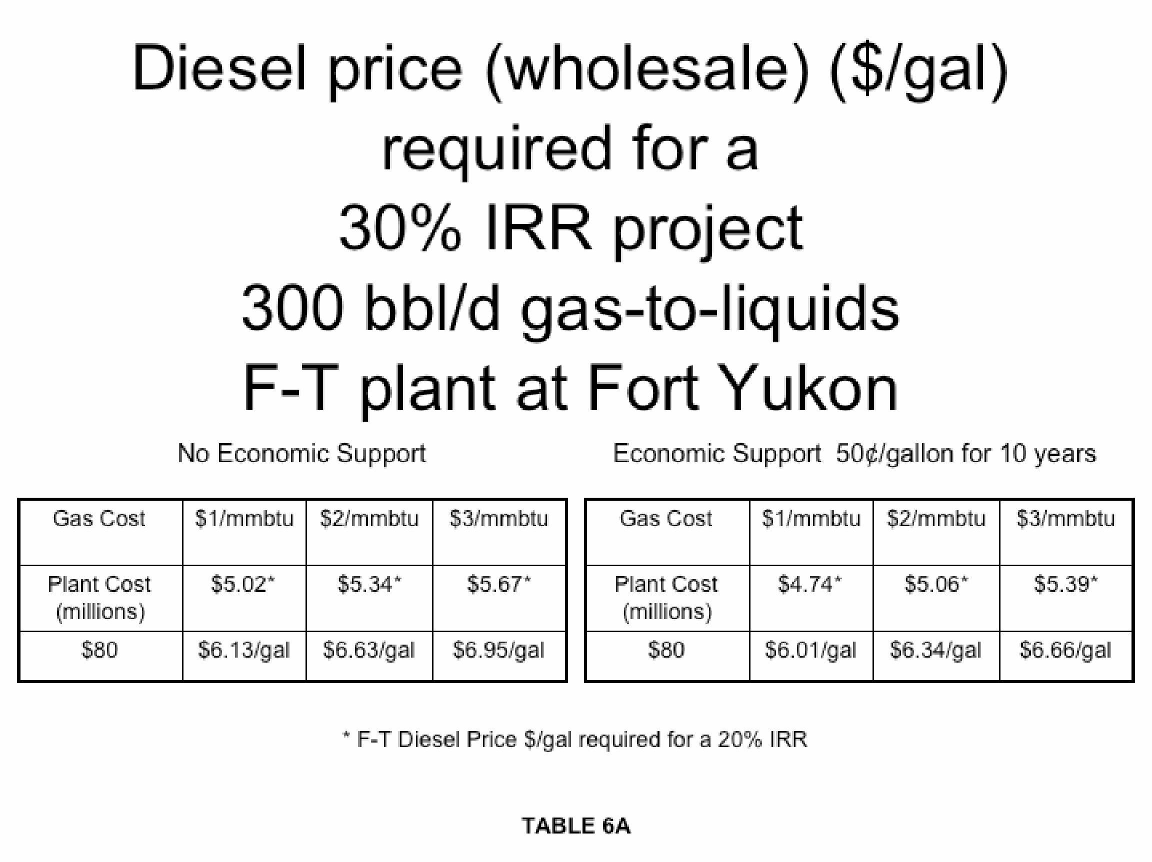
Yet another possibility is to integrate the wood harvesting with a regional sawmill to use higher-value timber to manufacture building materials, with the waste used for the F-T plant. This would reduce the feedstocks even further, but even at $25/ton for bio-mass, the price of F-T diesel is $3.62/gallon.

However, the bio-mass BTL plant’s economic stimulus to the region is a factor that should be considered. Assuming a wood cost of $25/ton, a Fort Yukon BTL project adds $2.2 million to the local economy in wood purchases and $4.3 million at $50/ton. Our analysis also indicates such a plant could pay $600,000 in local and state tax revenue, and provide employment at the plant for about 25 people with an annual plant operations and maintenance cost of approximately $2 million. We do not assume any credit for local electric power generation from waste heat, but it is safe to say that the ample waste heat available could make electricity available locally at very attractive rates compared with what Fort Yukon now pays for power generated with conventional diesel.

Another way to look at a Fort Yukon project:

The analysis above assumes a privately owned project that pays a return on investment to the owner using either coal, coal-bed methane and/or bio-mass. The Fort Yukon area has coal and coal-bed methane (gas from coal seams) potential, according to the Alaska Division of Geological and Geophysical Surveys. Assuming the coal-bed methane resource could be developed for a small gas-to-liquids (GTL) plant we modeled a 300 bbl/d GTL after the 300 bbl/d BP GTL plant at Nikiski, on the Kenai Peninsula in southern Alaska. While this facility was built as a demonstration/test facility, much of the same equipment and infrastructure would be required at a remote village site such as

Fort Yukon. The concept would be to build the GTL plant in modules in Anchorage and transport the GTL plant on a barge up the Yukon to Fort Yukon. The modules would be moved inland outside the flood plain similar to the way oil modules are moved on the North Slope.



Diesel price (wholesale) ($/gal)
required for a
30% IRR project
300 bbl/d gas-to-liquids
F-T plant at Fort Yukon

No Economic Support

Gas Cost	$1/mmbtu	$2/mmbtu	$3/mmbtu
Plant Cost (millions)	$5.02*	$5.34*	$5.67*
$80	$6.13/gal	$6.63/gal	$6.95/gal

Economic Support 50¢/gallon for 10 years

Gas Cost	$1/mmbtu	$2/mmbtu	$3/mmbtu
Plant Cost (millions)	$4.74*	$5.06*	$5.39*
$80	$6.01/gal	$6.34/gal	$6.66/gal

* F-T Diesel Price $/gal required for a 20% IRR

TABLE 6A

We estimate the cost of such a 300 bbl/d GTL plant to be $80 million delivered to Fort Yukon. The GTL plant would require 3 million cubic feet per day of gas or about 35 BCF of natural gas over 30 years. The GTL plant would produce 300 bbl/d of F-T fuels, 75 percent arctic-grade diesel and 25 percent naphtha. With so few people living in the area, waste heat would provide all the needed electric power generation. This still requires that the naphtha be transported and sold in other areas, possibly in Fairbanks as a petrochemical feedstock.

Table 6A illustrates the effect of plant and feedstock cost and the level of required economic support on the wholesale price F-T diesel at the plant tailgate to achieve a 30 percent IRR for an equity plant investor, assuming the plant is privately-owned. We assume $80 million as the cost of a new 300 bbl/d GTL plant built in modular form and transported to a location near Fort Yukon and a range of gas (coal bed methane) costs of $1/million btus (mmbtu), $2/mmbtu and $3/mmbtu in a range of costs used in our analysis. These natural gas costs are very speculative, and we assume that the F-T plant would be the only natural gas customer in the area.

Table 6A shows that even with federal support like an energy credit, the 300 bbl/d Fort Yukon GTL plant cannot produce F-T diesel competitive with today's crude-based diesel prices delivered to the region. Even tripling the energy credit, a private Fort Yukon GTL plant would struggle to sell its F-T diesel unless the price of crude oil is above $60/bbl.

While not part of this study, we are aware of some promising new GTL technology that could possibly dramatically lower the capital cost of a small gas-based GTL plant. One company, TIAX, in Boston, Mass., is working to place all three GTL steps in a single vessel – called "GTL in a Can". TIAX believes that it can achieve capital costs per unit of installed capacity in line with the costs quoted for the 12,000 bbl/day Bristol Bay barge-mounted GTL plant. If so, the cost per installed barrel for a Fort Yukon small GTL plant could drop from $266,000/installed barrel to $60,000/installed barrel. With a capital cost of $20 million compared to the current estimate of $80 million, a Fort Yukon GTL project would look promising. However, technologies like TIAX are still on the drawing boards and years away from being proven.

With the exception of a government grant to pay the capital costs of a small F-T plant operation, small F-T plants located in remote locations would produce F-T diesel with costs over $5/gallon, and could not economically compete with the delivered cost of conventional diesel today.

How the financial analysis was done: All analyses in the regional scenarios assume a private investor providing between 20 percent to 25 percent equity and earning either 20 percent or 30 percent internal rate of return (IRR) before federal tax. A 30 percent rate of return results in approximately a 19 percent rate of return after federal tax depending on the tax status of the investor. Until several F-T plants, especially small footprint F-T plants, are successfully built and operated, we judge these rates of return to be at the levels required to attract a private investor. Debt is assumed to have a 15-year payback at a 7.5 percent interest rate. The analyses have also reserved 18 percent of net cash flow for local and state taxes. In all cases design and construction is estimated at three and a half years except in the case of the BP gas-to-liquids plant conversion to biomass, in which we assume one year. Capital costs in the case of coal and bio-mass were derived from data made available from Choren Industries of Germany and from Sasol, of South Africa. In the Fort Yukon small gas-to-liquids plant we use published costs associated with the BP gas-to-liquids plant at Nikiski.

PART THREE: Resources assessment

Introduction: *We assess Alaska's potential for natural resources that could support Fischer-Tropsch plants in different regions of the state. Alaska has potential for more oil and gas discoveries and development, as well as potential for coal development and use of bio-mass to support the manufacture of alternative fuels.*

Alaska is important to the nation as a supplier of crude oil and, in the future, natural gas. Although production from the large oil and gas fields on the North Slope and smaller oil fields in Cook Inlet is declining, the state still produces about one-fifth of the nation's domestic oil supply.

Alaska has about one-fifth of the proven natural gas reserves in the nation, and if a natural gas pipeline is built from the North Slope of Alaska it will be an important source of domestic gas supply as well as crude oil.

Alaska is considered to have potential for additional oil and gas discoveries and potential for very large unconventional resources, such as gas hydrates. But while reasoned estimates of resource potential have been made, very little exploration has been done across the state. Even the developed basins of the North Slope and Cook Inlet are considered underexplored, and millions of acres of lands in sedimentary basins in the Interior and southwestern parts of Alaska, as well as the Outer Continental Shelf, have seen very few exploration wells.

OIL RESERVES

Discovered to date:	22 billion barrels
Produced to date:	15 billion barrels
Discovered reserves remaining to be produced:	7 billion barrels
Undiscovered resources, Technically and economically Capable of being produced	35 billion barrels

NATURAL GAS (conventional)

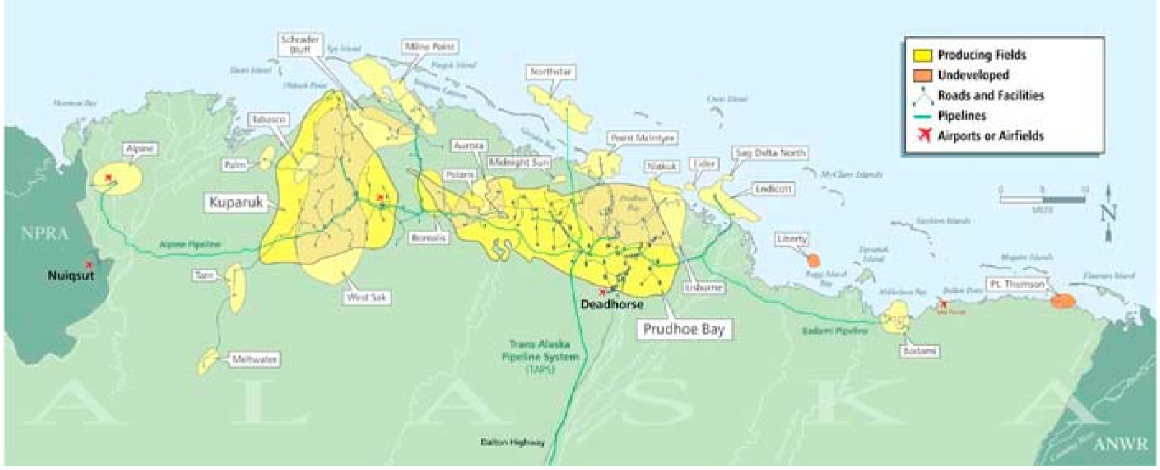
Discovered:	
North Slope:	35 trillion cubic feet
Cook Inlet:	9 trillion cubic feet
Produced to date:	7 trillion cubic feet*

** From Cook Inlet*

Geologists generally believe that many of the onshore sedimentary basins of Alaska have potential for natural gas because the extensive coal fields known to exist in many parts of the state could be a source of natural gas.

There are unconventional resources as well, such as coal-bed methane (natural gas) which could be produced from coal seams. Coal-bed methane is now produced on a commercial basis in other states, but despite the potential there is not yet commercial production of coal-bed methane in Alaska. Also, vast quantities of natural gas are trapped in gas hydrates in the permafrost that underlies much of northern Alaska. It is not known, however, whether gas can be technically or commercially produced from hydrates.

Oil discoveries to date:



To date approximately 22 billion barrels of oil have been discovered in Alaska in fields that are considered economical to produce. About 15 billion barrels have been produced from these Alaska oil fields to date, and it is estimated that about 7 billion barrels of the confirmed resource are yet to be produced, or about 22 percent of remaining confirmed U.S. oil reserves. Some of the oil remaining to be produced is in fields that are currently producing, and some is in known deposits that are considered economic or marginally economic but not yet producing.

In terms of undiscovered resources, it is estimated that there are about 35 billion barrels of oil that remain to be discovered in Alaska, which can be produced economically with known technology. Most of this is on the North Slope. This estimate relates to oil that can be developed from the undiscovered resource at crude oil price ranges between $18 per barrel and $30 per barrel.

The amount of oil that can be technically produced from this resource base is far greater. As technology improves costs are reduced and the amount of oil that can be economically recovered will increase.

The North Slope

Geologic overview:

Because of its geologic history, many geologists believe the North Slope of Alaska is one of the world's great sources of oil generation. The region is defined by its principle formation, the Barrow Arch, a broad geologic formation that generally parallels the northern coast of Alaska. It extends from the Arctic National Wildlife Refuge in northeastern Alaska through the central North Slope and the coastal region of the National Petroleum Reserve-Alaska to Point Barrow and beyond, into the Chukchi Sea.

This broad uplift has provided the trapping mechanisms for numerous oil fields that have been discovered in the central North Slope, including the two largest fields in North America, the Prudhoe Bay and Kuparuk River fields. It is believed that new oil fields will eventually be discovered at other points along the Barrow Arch, including the northern parts of the NPR-A, the coastal plain of the Arctic National Wildlife Refuge, and the offshore Outer Continental Shelf through the entire region.

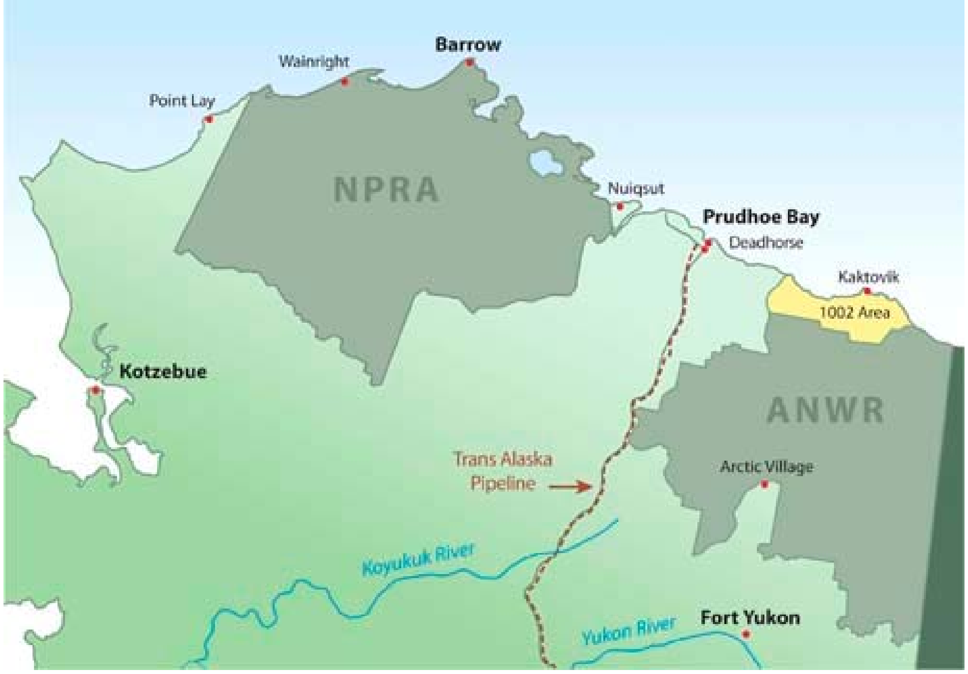
Most of the existing oil fields have been discovered in the coastal region of the central North Slope where lands owned by the state of Alaska were leased in the 1960s and exploration by industry has long been underway. Oil has also been discovered offshore. In the relatively shallow waters of state-owned submerged lands just offshore the central North Slope, the medium-sized Northstar oil field has been producing since 2001 while several other medium-sized and smaller fields, such as Liberty and Tern, have been discovered but not developed.

Oil is also known to exist further offshore, in federal OCS submerged lands. Discoveries have been made at two locations, "Hammerhead" and "Kuvlum." While both discoveries are believed to contain considerable amounts of oil (Kuvlum's recoverable resources have been estimated at approximately 800 million barrels) they are considered too far from the shore to be economic under current circumstances. Prospective geology continues west from the North Slope and National Petroleum Reserve-Alaska into the Chukchi Sea. The presence of oil and gas-bearing formations in the Chukchi Sea was confirmed by 1989 drilling by Shell Western E&P, although commercial discoveries were not made. The U.S. Minerals Management Service recently reevaluated one of Shell's wells and estimated that it had discovered a large gas and gas condensate accumulation, with an estimate of 14 trillion cubic feet of technically recoverable gas and 700 million barrels of technically recoverable liquid gas condensates.

Lands on the North Slope that are south of the Barrow Arch, extending into the Brooks Range foothills region of the southern slope are generally considered by most geologists to be more favorable for natural gas discoveries than oil. This region has seen relatively little exploration and will remain largely unexplored until a natural gas pipeline project is underway.

Central North Slope

The major commercial oil and gas deposits of the North Slope have been discovered in the Central North Slope, or the area of state-owned lands between the Colville River (the eastern boundary of the National Petroleum Reserve-Alaska) and the Canning River (the western boundary of the Arctic National Wildlife Refuge).



Exploration has been underway in this area since the early 1960s. Discoveries have included the super-giant Prudhoe Bay field with 23 billion barrels of oil in place (13 billion estimated recoverable) and the Kuparuk River field with 6 billion barrels of oil in place and 2 billion barrels estimated to be recoverable.

In its 1995 slope-wide evaluation of hydrocarbon resources, the U.S.G.S. estimated there were 2.3 billion barrels of technically recoverable, undiscovered oil resources in the Central North Slope area. There have been discoveries since 1995, and the Alaska Division of Oil and Gas has estimated that, adjusted for the post-1995 discoveries, there are 1.9 billion barrels of technically recoverable oil left to be discovered in the Central North Slope. Of this, about 46 percent, or 916 million barrels, is estimated to be economically recoverable at oil prices between $18 per barrel and $30 per barrel.

ANWR

Area:
1.5 million acres

Technically recoverable oil reserves:
10.3 billion barrels

Economically recoverable reserves:
4 billion barrels*

**Assumes $22/barrel oil price*

Most of the new discoveries have been small discoveries, including Tarn, Meltwater, Tabasco, Midnight Sun and Aurora, although one medium-sized field has been discovered, the Alpine field.

Although these discoveries are smaller than the large Prudhoe Bay and Kuparuk fields, they contain substantial reserves. The Alpine field contains an estimated 429 million barrels of recoverable reserves. Tarn contains an estimated 70 million barrels.

Arctic National Wildlife Refuge

Many geologists believe the coastal plain of the Arctic National Wildlife Refuge has the greatest potential for new major oil and gas discoveries of any onshore region of the U.S. Because of its oil and gas potential a 1.5-million-acre section in the northwestern corner of ANWR was set aside (the "1002 study area") for further evaluation when Congress enacted the Alaska National Interest Lands and Conservation Act in 1980. Congress must approve any exploration, leasing or development of production in the 1002 area, however.

There has been little exploration in 1002 area. One exploration well was drilled in the early 1980s in a privately-owned enclave in the northern part of this area, and limited seismic surveys were done during the winter of 1983 and 1984. The data from the single exploration well is privately-held but the seismic information is held by the government as well as several oil and gas companies which contributed to the surveys.

The western part of the coastal plain has an extreme high probability that discoveries will be made. Its geology is similar to that under state lands just across ANWR's border on the Canning River, where oil and gas have been found. Point Thomson, a very large gas discovery with considerable volumes of gas condensates and two sizeable oil accumulations have been discovered in the area, demonstrating the potential.

Limited seismic exploration done in ANWR in the mid-1980s show numerous large geologic structures in the coastal plain. If one or more of these hold oil, ANWR has the potential become a major source of new production, state oil and gas geologists believe. The U.S. Geologic Survey estimates about 4.4 billion barrels of oil will likely be economic to produce in ANWR at oil prices of $22 per barrel. However, Congress must approve any exploration in the ANWR. The U.S. Energy Information Administration estimates that nine years would pass between any congressional approval for ANWR exploration and first production of oil.

National Petroleum Reserve – Alaska

The National Petroleum Reserve–Alaska covers 23 million acres in northern Alaska. It was created as Naval Petroleum Reserve No. 4 by President Warren Harding in 1923, based on the recommendations of government geologists who had surveyed the region.

Numerous oil seeps were noted in the reserve. The reserve was transferred to the U.S. Bureau of Land Management in 1976 and renamed as the National Petroleum Reserve-Alaska.

There were several phases of exploration, including extensive drilling sponsored by the U.S. Navy following World War II and an exploration program managed by the U.S. Geological Survey in the 1970s. In the 1980s private industry was invited to explore the reserve, and four lease sales were held. Although several oil and gas deposits were discovered through the years, none of them are large enough to support commercial development.

An updated assessment by the U.S. Geological Survey published in 2002 indicates that of 10.6 billion barrels of technically recoverable oil, the NPR-A may hold between 1.3 billion to 5.6 billion barrels that could be economically produced at prices between $22 and $30 per barrel. The discoveries are likely to be spread out over a wide area. The U.S.G.S. estimates that oil reservoirs in the NPR-A will be medium-sized to small, with possible recoverable reserves of 256 million barrels to 32 million barrels. The NPR-A also has potential for the discovery of considerable volumes of natural gas, but its development will depend on the availability of a natural gas pipeline.

The discovery of the Alpine oil field on state lands in the Colville River delta, on the northeast boundary of the NPR-A, has greatly increased interest in the reserve. The federal government resumed its lease sale program, and several small oil and gas discoveries have been made in the northeastern part of the reserve. In general, many geologists believe the northern areas of the NPR-A along the Barrow Arch are more prospective for oil and gas discoveries.

NPRA

Area:
23 million acres

Technically recoverable oil reserves:
10.6 billion barrels

Economically recoverable reserves:
1.3 billion barrels*

Alaska Beaufort Sea

The U.S. Minerals Management Service is responsible for the Outer Continental Shelf submerged lands beyond the state of Alaska's three-mile territorial limit. MMS estimates that there are 8.82 billion barrels of technically recoverable reserves, within which 2.3 billion barrels would be economic to produce at $18 per barrel oil prices and 2.5 billion barrels would be economic to produce at $22 per barrel oil prices.

North Slope Foothills

The North Slope foothills, a region encompassing the southern part of the North Slope north of the Brooks Range, is a little-explored region which geologists believe has potential for major gas discoveries as possibly oil as well. Companies have leases in this region but little exploration has been done in recent years because of the lack of a way to market any gas that is discovered. As progress is made on a gas pipeline to the North Slope, industry will begin exploring the region.

Cook Inlet

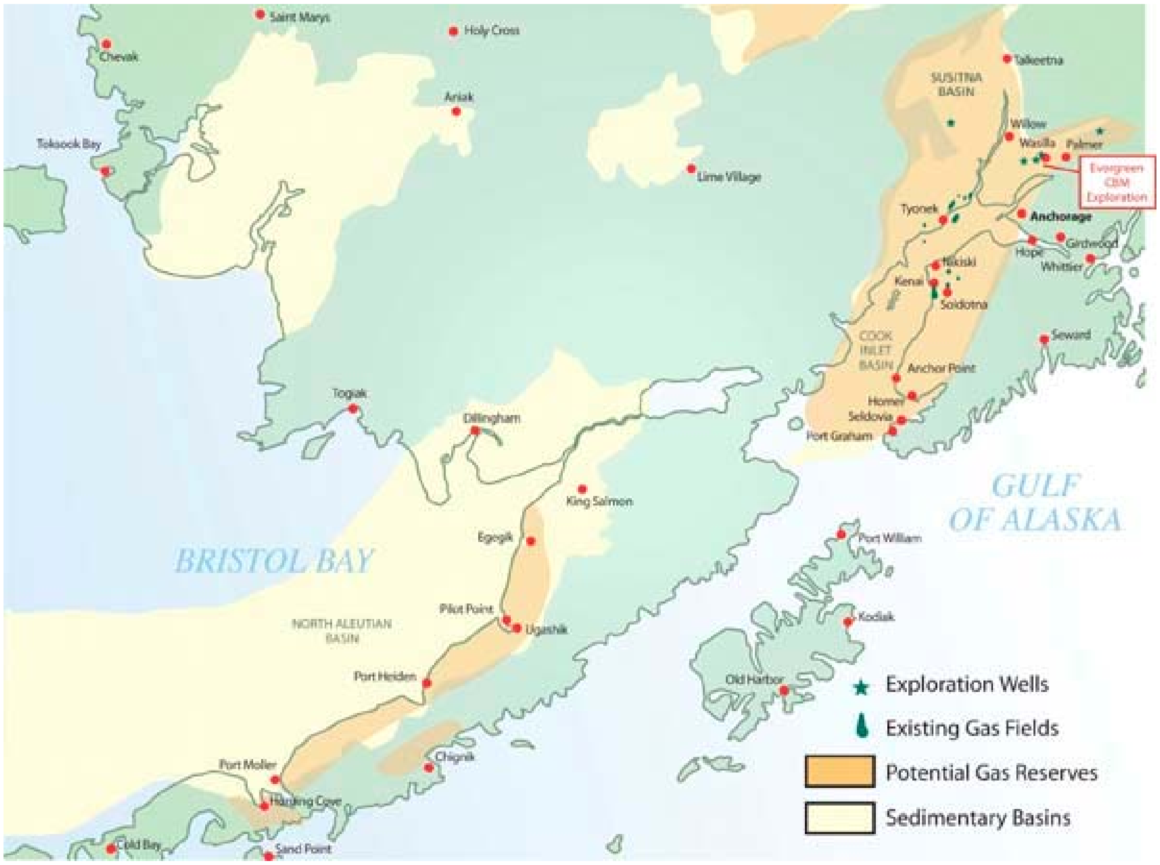
Cook Inlet was where modern commercial oil and gas fields were first discovered in Alaska. The discovery of the Swanson River oil field on the Kenai Peninsula in 1957 helped convince Congress that Alaska had potential for natural resource development sufficient to pay the costs of state government, and led to the approval of statehood for Alaska in 1959. The leasing of state-owned submerged lands in Cook Inlet in the early 1960s led to commercial oil discoveries in the mid-1960s, which contributed substantially to state government revenues and helped develop an industrial tax base and employment for communities in the region.

Geologists believe most of the Cook Inlet sedimentary basin is prone to natural gas because of the widespread coals found throughout the basin. Coals are a primary source for the formation of natural gas, and most of the large gas fields that have been discovered in the region had their origin in coal.

Most of the oil that has been discovered in the inlet, and where the industry's existing fields are concentrated, is in an area of upper Cook Inlet where oil source rocks are present. It is possible that oil source rocks, and commercial oil deposits, may be found elsewhere in the Cook Inlet Basin. It is virtually certain that additional natural gas will be discovered, given the success of recent exploration programs on Kenai Peninsula lands east of the inlet and lands on the west side of the inlet. For many years local natural gas prices were depressed, discouraging exploration for gas. Prices are now increasing, resulting in exploration programs aimed at finding gas. Despite the industry's long presence in Cook Inlet, however, the area is still considered to be underexplored.

Bristol Bay region, southwest Alaska

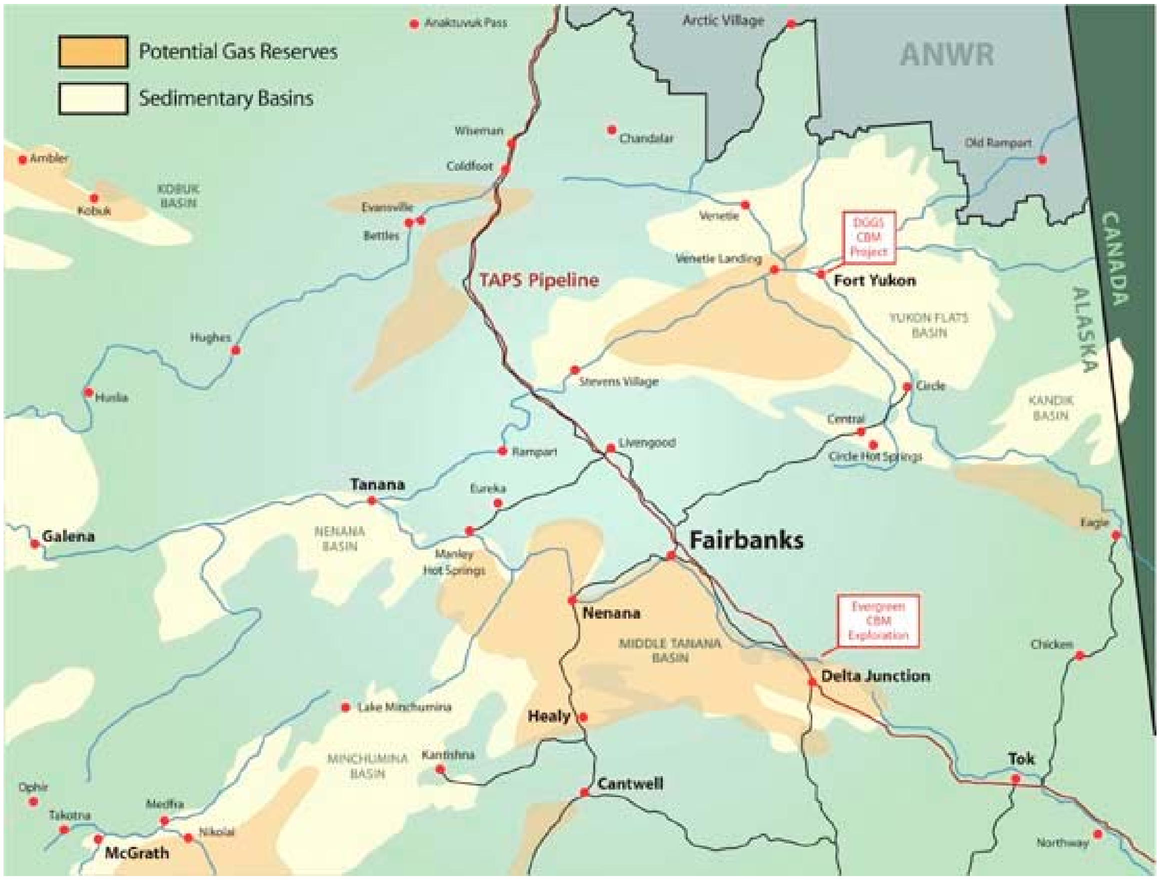
Geologists believe the ingredients for an oil and gas producing region are present in the Bristol Bay basin. The geology of the region is very similar to Cook Inlet, where commercial oil and gas fields have been found. There are numerous oil seeps along the southern half of the Alaska Peninsula, along the Pacific coast side, which indicate that oil has formed in the rocks. Sedimentary source rocks appear to be rich in organic content, which is important to the formation of hydrocarbons.



Twenty six wells have been drilled onshore in the Bristol Bay region, the latest being the Amoco Becharof No. 1 well in 1985. One offshore stratigraphic test was drilled in 1983, the ARCO North Aleutian COST Well No. 1. Oil and gas shows are evident in many of the wells that have been drilled, but no commercial flow of oil has been proven to date.

Alaska state Division of Oil and Gas geologists believe that the geologic setting of Bristol Bay is very good for both structural and stratigraphic traps as well as the likelihood of encountering good to locally excellent reservoir quality rocks. State geologists caution that there is some uncertainty over the quality of reservoir rocks, however.

All of the Bristol Bay basin is considered favorable for natural gas discoveries, but the southern part may also have oil potential, according to the state Division of Oil and Gas. Geologists also believe that Cook Inlet and Bristol Bay were once part of one large sedimentary basin that was split when the North Pacific plate shifted, causing a terrestrial uplifting and the formation of the Alaska Peninsula. In a sense, the Bristol Bay basin could be considered a kind of twin of the Cook Inlet basin.



The state of Alaska and Alaska Native regional corporations in the area are now supporting exploration of state and private (Native) lands in the region, which is a change from their previous positions. Oil and gas leasing in the federal Outer Continental Shelf areas have been under a moratorium since a federal OCS lease sale in the 1980s. The federal lease sale then raised concerns among local residents because of the potential adverse effects an oil spill could have on the region's commercial fisheries, and eventually the leases were cancelled with the lease bonuses repaid to the bidders. There are no plans to resume OCS leasing in the region at this point. A current plan by the state of Alaska to offer leases includes onshore and offshore tracts that can be reached from shore by directional drilling.

Other basins

Yukon Flats Basin:

Nearly all of the Yukon Flats sedimentary basin is within the Yukon Flats National Wildlife Refuge, which at 12 million acres is the third largest refuge in the national refuge system. There are 2 million acres of Native-owned inholdings within the refuge, and 403,000 acres of state-owned lands in the southeastern part of the basin near Circle.

The basin is considered to be prospective because coals capable of generating natural gas are present as well as sandstone and other rocks capable of being reservoir-quality. One estimate of the potential of the basin is for recoverable oil reserves between 350 million and 1 billion barrels. There is no estimate for natural gas. Two wells, LLE Doyon #2 and #3) were drilled in the eastern part of the basin in the early 1970s. The U.S. Geological Survey recently updated its assessment of the basin's potential for natural gas and found the region to be more prospective for gas than in the earlier U.S.G.S. assessments.

Kandik Basin:

The Kandik Basin encompasses about 2 million acres and straddles the Alaska-Yukon Territory border, with about 70 percent in Alaska. The southern margin of the basin is within the Yukon-Charley Rivers National Preserve. Doyon Ltd. of Fairbanks owns 750,000 acres in the center of the basin. In 1976 one well, LLE Doyon #1, was drilled in the basin, with shows of gas and oil-stained strata but no commercial discovery. The basin is considered to have moderate oil and gas potential. Potential source rocks are known to be present, including rocks similar to those of the North Slope, and oil-stained rock outcrops demonstrate that oil has been generated in the region.

Nenana/Tanana Basin:

The Nenana/Tanana Basin covers a large area extending from the Minto Flats area west of Fairbanks to Delta, in the east. It covers approximately 8,500 square miles. There is interest in commercial exploration for natural gas in the western areas of the basin, the Nenana Basin proper, and it is possible that oil may be found as well.

Gravity and magnetic surveys indicate that the sediments are deeper and are more favorable for oil and gas accumulations in the Nenana Basin than in the Tanana Basin to the east. Two shallow exploration wells have been drilled but neither tested the deeper, more prospective areas of the Nenana Basin.

Potential source rocks for gas and oil appear to be present in the basin, and its potential is considered to be moderate to good. State geologists consider the basin to have the potential for discovering "multiple" trillions of cubic feet of gas. The Nenana Basin is thought of have some potential for oil but the large amounts of coal and the presence of shales deem it more likely that natural gas will be discovered.

The state of Alaska has issued an Exploration License for the Nenana Basin and exploration activity is currently underway by a consortium led by a Denver, Colorado independent company and including three Alaska-based firms.

Copper River Basin:

The Copper River Basin covers approximately 3,500 square miles, bordered on the north by the Alaska Range, by the Wrangell Mountains on the east, the Chugach Range on the south and the Talkeetna Mountains on the west. Numerous coal seams extend through the basin and there are sequences of sediments of marine origin, which indicate possible oil potential.

Eleven exploration wells were drilled in the basin between 1957 and 1983, two of which encountered small gas shows. The potential for oil and gas in the basin is considered to be low to moderate, but industry has expressed interest in the region. An exploration well is being drilled in the region

In general, very little is known about the large inland sedimentary basins of Alaska. There has been little drilling or seismic exploration, and only limited gravity surveys. In general these basins are considered to be more prone to natural gas than oil because of the terrestrial origin of the organic material laid down in the sedimentary rocks and the widespread presence of coal in the state, which is a source of natural gas. Gravity surveys have indicated that basins in southwest Alaska may be too shallow for the formation of oil even if marine sediments are present. However, they may have potential for gas.

Coal bed methane

Exploration in Alaska is underway for possible commercial coal-bed methane deposits, where natural gas could be produced from coal seams. Gas is produced commercially from coal in several western states.

Coal is a source of natural gas. In the coalification process, where plant material is converted to coal, large amounts of methane, or natural gas, are generated. Conventional natural gas seeps out of coal and is trapped in reservoirs of porous and permeable rock by an impermeable rock layer, or seal. However, some gas also remains in the coal.

The coal serves not only as the reservoir rock for the gas but is the source of the gas as well. Because of its large internal surface area (porosity), a given volume of coal can contain six to seven times the amount of gas as the same volume of conventional reservoir rock.

Coal-bed methane is composed primarily of methane and unlike conventional natural gas contains no other hydrocarbons, such as ethane and propane. It also contains no carbon dioxide or hydrogen sulfide, which can be found in conventional gas.

Interest in possible coal-bed methane production in Alaska began in the early 1990s. In 1994 the state of Alaska funded and operated an exploratory test well drilled to shallow depths near Wasilla, in the Matanauska-Susitna Borough. The well demonstrated that significant quantities of gas exist in coal seams at shallow depths in the area.

The Alaska Division of Geological and Geophysical Survey has identified 35 Alaska rural communities with local coal deposits and where coal-bed methane could be a source of local energy. Evergreen Resources Inc., a Colorado coal-bed methane producer (now Pioneer Natural Resources), explored in the Matanuska-Susitna Borough, in South-central Alaska. Evergreen drilled test wells but did not establish commercial production.

Gas hydrates

Gas hydrates are crystalline substances composed of large quantities of methane trapped in a crystalline, cage-like structure of water. Potentially, hydrates could be a source of unconventional natural gas because of the large amounts of methane that could be trapped. Hydrates typically occur in permafrost regions and have been found in Siberia, the North Slope and the Mackenzie delta of Canada. Hydrates are found on the North Slope because there is both a source of gas and permafrost at shallow depths.

There are questions as to whether gas can be technically or economically produced from hydrates. An effort by Anadarko Petroleum Corp., assisted by the U.S. Department of Energy, to test the production potential of hydrates on the North Slope was inconclusive. The hydrate turned out not to be present in the interval being tested. However, the presence of hydrates has been confirmed in other areas on the North Slope. In another research effort by BP Exploration Alaska Inc., with the assistance of the U.S. Department of Energy, BP did reservoir simulations of gas hydrate production from hydrates known to exist in the Prudhoe Bay, Milne Point and Tarn field areas of the North Slope. Based on this work, state geologists believe that gas might be produced with conventional well technology where the hydrate occurs over a conventional trap of free gas. Drilling into the gas trap and depressuring the conventional gas might allow gas to come out of the hydrate and into the production well, state geologists believe. The work by BP and DOE has led to a conclusion that there may be as much as 100 tcf of gas in hydrates in the immediate Prudhoe Bay oil field area, according to the state Division of Oil and Gas. It is possible that as much as 60 percent of this might be recoverable, which could add 60 tcf in new gas resources to the known 35 tcf gas reserve base on the North Slope.

If technical problems associated with finding hydrates and producing gas could be overcome, substantial quantities of gas might be produced. The U.S. Geological Survey has estimated that there could be 519 trillion cubic feet of gas trapped in hydrates on the North Slope, and much more in offshore regions of the Beaufort Sea, according to DOE.

Coal

Coal deposits are widespread in Alaska. The state is estimated to have between one third and one half of U.S. coal resources, possibly 5 trillion to 5.5 trillion tons, with approximately 4 trillion tons estimated on the Arctic Slope region of the state. These estimates, however, are based on hypothetical coal resources in Alaska. The hypothetical resource was estimated by extrapolation from a known coal occurrence, such as an outcrop or coal seam identified by drilling.

An analysis of the many known coal occurrences has resulted in an estimate of over 160 billion tons of identified coal resources. There is little doubt that if more exploration were done, more of the hypothetical resources would be identified and the identified resources would be better defined.

No matter what the basis of comparison, however, Alaska has huge undeveloped coal resources. If the average energy content of coal is 10,000 btus per pound, a ton of coal has the same energy content at three barrels of oil. Looked at that way, Alaska's estimated 160 billion tons of identified coal resources represents the energy equivalent, in btus, of 240 billion barrels of oil. The coal is also attractive because of its very low sulfur (generally less than 0.5 percent) and nitrogen content, which reduces sulfur dioxide and nitrogen oxide in emissions when the coal is burned.

Many of Alaska's widespread coal deposits have been mined over the years. One of Alaska's early economic activities involved coal mining. In 1855, before the U.S. purchase of Alaska, the Russian American Company developed a small mine at a coal deposit that had been discovered in 1786 by an English sea captain at Port Graham, on the lower Kenai Peninsula. The Russian American Company made an attempt to export coal to California, but the Alaska coal could not compete with less expensive coal from British Columbia. Coal was mined to support a local sawmill and a foundry, and 5,000 tons were mined until the mine closed in 1865.

Coal deposits were an important source of fuel for whaling and government ships before the turn of the century, for gold mining camps and communities during the Gold Rush and for riverboats on the Yukon River and its tributaries. Coal deposits were known along the Northwest Alaska coast on the Chukchi Sea, and these were mined on a small scale for whaling ships and shipped south to Nome, on the Seward Peninsula, then a flourishing gold mining community. A commercial coal mine was operated at Unga Island, in the Aleutians, from 1896 to 1904, to supply fuel to naval and other vessels.

In 1905 the federal government supported development of a small coal mine at Chickaloon, in the Matanuska River valley north of Anchorage, and production continued until 1922. Small coal mines were developed in the Wishbone Hill district near Palmer, in the same region, beginning in 1914 to support construction of the Alaska Railroad. Two of these, the Eska mine and the Evan Jones mine, began production in 1917. Coal production continued to 1971.

Coal was the major source of fuel for power generation at military bases in Interior and South-central Alaska during and after World War II. Natural gas is now used at Elemendorf Air Force Base and Fort Richardson near Anchorage but coal from the Usibelli coal mine near Healy still fuels military and civilian power plants in Fairbanks, and at Healy itself.

Usibelli Mine Inc. coal mine at Healy, Alaska, with 1300W Bucyrus-Erie Walking Dragline in background. Usibelli has been mining coal at Healy since 1943.

Several attempts have been made to develop coal mines in Alaska in recent years. Alaska's only producing coal mine is the Usibelli Mine at Healy, which produces coal for Fairbanks-area power plants and for export to South Korea. Usibelli has also sent shipments of coal to power plants in Latin America. There is considerable potential for expansion of coal production at the Usibelli Mine.

Considerable work has also been done by the Bass-Hunt-Wilson group and Placer Dome U.S. in developing a coal mine at the Beluga coal deposits west of Anchorage, where there is potential for 2 billion tons or more of mineable resources. High costs and low coal prices have stymied this development to date. However, international coal prices are now higher and possible new technologies to reduce the 25 percent moisture of the subbituminous coal at Beluga could raise its value, making the project possibly economic.

Idemitsu Kosan, a Japanese company, attempted to develop a mine at Wishbone Hill, a small deposit of higher-grade bituminous coal 10 miles from Palmer, north of Anchorage. Idemitsu's project was delayed by litigation over land ownership disputes and then shelved when coal prices dropped. The property has since been sold.

Arctic Slope Regional Corporation, the Alaska Native corporation for the Arctic Slope area of northern Alaska, has done considerable work in identifying coal resources in the large Deadfall Syncline area of northwest Alaska, where crews from early-day whaling fleets mined coal. The resources in this region are some of the largest in North America. The coal is also of good quality, with substantial resources of bituminous coal as well as subbituminous, and some high-grade anthracite as well. ASRC has tested Arctic mining methods and continues to work with the state of Alaska on solving transportation access problems to these large reserves.

Other, smaller coal deposits have been investigated as energy sources for local communities. The state Division of Geological and Geophysical Survey has investigated the Chicago Creek coal deposit on the Seward Peninsula. In the early 20th century Chicago Creek produced 100,000 tons for use in regional gold mining operations. The state DGGS has also carried out investigations of coal near Unalakleet on Norton Sound and Kobuk and Koyuk in northwest Alaska, deposits near Nulato on the Yukon River in Interior Alaska, on St. Lawrence Island in the Bering Sea, the Chignik and Herendeen Bay fields on the Alaska Peninsula, and on Unga Island in the Aleutians.

The City of Galena has investigated a coal deposit that outcrops on the river a few miles from the community. The Jarvis Creek deposit near Delta, in the eastern Interior, has been investigated as a possible fuel source for local power generation, to support missile defense facilities at Fort Greely and the new Pogo gold mine, also near Delta. In years past Korean companies have investigated extensive deposits in the Bering River coal field, near Cordova.

The widespread coal resources of Alaska are important in a number of respects. Coal itself can be mined and used locally or regionally for power generation or space heating. The coal is, potentially, also a source of coal-bed methane, or gas trapped in the coal seams. Gas production from coal is done on a commercial basis in the continental U.S. and it may also be possible to produce gas from coal in Alaska. The widespread coals also point to substantial undeveloped resources of conventional natural gas also, since coal is a major source of gas.

The Fischer-Tropsch process of converting coal into transportation fuels and petrochemical feedstocks is well established in South Africa and Southeast Asia. With the potential of crude oil prices remaining in the $40 per barrel range, this process could convert 1 ton of coal into 1.5 to 2 barrels of liquid synthetic fuel. As an example, the Beluga coal field near Cook Inlet has coal resources that could be converted to 6 billion barrels of synthetic fuels.

Bio-mass

Alaska has a substantial forest bio-mass resource. About 129 million acres of Alaska's 356 million acres are covered with forest. Approximately 22 million to 25 million acres of the total forest area contains forests of potential commercial value.

In Alaska, there are two distinct forest types, the coastal rain forest and the boreal forest. The coastal rainforest begins in southern Southeast Alaska, and extends through Prince William Sound, and down the Kenai Peninsula to Afognak and Kodiak Islands In South-central Alaska. The two largest national forests in the United States, the Tongass National Forest in Southeast and the Chugach National Forest in South-central, are in these coastal regions. The boreal forest covers much of interior and much of south-central Alaska.

The Tongass National Forest covers 16.8 million acres, of which 9.5 million acres are forested. About 400,000 acres of the forest lands of the Tongass have been harvested, and some of these lands are now in their second-growth stage although no second-growth harvest will be possible for some time.

The Chugach National Forest covers 5.9 million acres, but most of it consists of mountainous and glacial terrain with relatively little forest of commercial value.

Sitka spruce, hemlock and cedar are the dominant species in Southeast and South-central, while white spruce, black cottonwood, aspen, and paper birch are found in the Interior forests.

As with oil and gas and coal, the timbered lands are managed by four landholders - the federal government, 51 percent; state, university and local governments, 25 percent; Native corporations, 24 percent; and other private landowners, 0.4 percent. Most of the commercial timber harvest is in the coastal rain forest, primarily on federal and Native corporation land.

Alaska's forest products industry is very small, and the lack of a method to dispose of low-grade timber and wood waste bio-mass is a serious problem for the small sawmills which mostly operate in Southeast Alaska.

From the late 1950s until the early 1970s there were two pulp mills in Southeast which used low-value wood that was harvested along with high-value logs that were sawn or exported in the round to export markets. These pulp mills were closed, however, and at present there is no market for low-value logs. This hampers the efficiency of commercial forest harvesting.

Aside from this, a substantial volume of wood waste, mostly sawdust, has accumulated at the remaining sawmills in Southeast Alaska. The mill operators are looking for ways to economically remove or use these accumulated wastes.

Much of Southeast Alaska's coastal regions are covered with old-growth forest consisting of spruce, hemlock and some yellow cedar. The spruce and hemlock coastal forest continues northward into South-central Alaska. Most of the inland South-central and Interior regions of Alaska are covered with boreal forest consisting of certain species of spruce and birch. There is no substantial commercial forest industry in the Interior or South-central regions other than small local sawmills.

However, the resource is substantial, and one issue attracting considerable attention now is the South-central spruce forests which have been damaged or killed by a major infestation of spruce bark beetle. Spruce bark beetle infestations have killed many of the trees on the Kenai Peninsula in recent years.

The entire Chugach forest, and much of the Kenai Peninsula region, has been affected by this pest. An estimated 1.5 million acres of spruce forests in the Cook Inlet region alone are beetle-killed and constitute a considerable fire danger. The U.S. Forest Service and the Alaska State Division of Forestry are interested in ways of removing beetle-damaged timber, reducing the fire hazard and salvaging what commercial value remains in the wood.

There has also been substantial damage to spruce forests along the western shores of Cook Inlet as well as widespread areas of the Copper River valley north of Valdez.

To some extent these damaged trees retain value. If they are harvested in time they can be chipped and sold for use in paper manufacturing. But even after they have deteriorated further they can be used as feedstock in a Fischer-Tropsch process to make liquid products.

The large boreal forest of the interior creates a potential resource for bio-mass use. While much of the interior forests do not support species as valuable as the coastal forests in the Southeast part of the state, the interior birch forests have value for certain types of uses, including bio-mass to F-T fuels.

PART FOUR: Rural Alaska fuel supply

Refineries

Introduction: *We assess Alaska rural fuel distribution patterns and the capabilities of the state's refineries as well as challenges posed by new U.S. Environmental Protection Agency regulations that will take effect in 2006 and 2010. Basically, the high costs of fuels delivered to rural Alaska communities result from the inefficiencies imposed by small volumes, seasonal deliveries, lack of infrastructure and impediments to navigation in certain locations.*

Alaska has four crude oil refineries that produce a variety of products, principally jet fuel, gasoline, diesel and heating oil and other products. The major refineries include two at North Pole, east of Fairbanks; one at Nikiski, near Kenai; and one near Valdez, the terminus of the Trans-Alaska Pipeline System.

Flint Hills Resources refinery at North Pole, Alaska

Flint Hills Resources purchased the plant from Williams Alaska Petroleum Co. in March 2004. The refinery was originally built in 1977 by Earth Resources, a Dallas, Texas-based firm and subsequently sold to Mapco, which was later merged with Williams Energy.

Flint Hills refinery at North Pole, Alaska.

The refinery has traditionally relied on purchases of state-owned North Slope royalty oil for most of its crude oil supply, but from time to time has purchased oil from North Slope producing companies. The crude oil is taken from the Trans-Alaska Pipeline System and refined, with residuals returned to the TAPS pipeline. The refinery pays a fee to the TAPS owner companies to compensate for the degradation of the crude oil stream from North Pole south to Valdez, the terminus of the pipeline.

The North Pole refinery processes about 220,000 barrels per day of crude oil and produces about 70,000 barrels per day of products, which include gasoline, naphtha, and jet fuel, heating oil, diesel fuel and asphalt. About 60 percent of the refinery's production is jet fuel. Approximately 30 percent of the refinery's remaining output is gasoline, naphtha and diesel, averaging about 7,000 barrels per day of each product. Other products make up the remaining 10 percent of the product slate. Jet fuel, the most important product, is sold to commercial airlines and the U.S. military.

North Pole refinery is the principal supplier for Interior river communities

Industrial complex at Nikiski, Alaska. Tesoro Alaska Petroleum Co. refinery is at left, in rear, of photo.

Flint Hills markets its products in Interior Alaska and is the principal supplier of diesel and heating oil for small villages along the Interior river system. The company also transports considerable volumes by rail to Anchorage in Alaska Railroad tank cars. Approximately 35,000 tanks cars per year of product, mainly jet fuel, gasoline and naphtha, are moved by railroad to Anchorage. The company operates bulk storage facilities in Anchorage and Fairbanks. Flint Hills sells its products wholesale to retail gasoline outlets and to commercial air carriers at international airports in Fairbanks and Anchorage.

Flint Hills has announced that it will install desulphurization facilities at the North Pole refinery to produce ultra-low sulfur diesel as well as low-sulfur gasoline to meet new U.S. Environmental Protection Agency specifications. The company is investing approximately $200 million in plant modifications to produce the new products, and expects to have the products available in 2006 and 2007.

Tesoro Alaska Petroleum Corp. refinery at Nikiski, on the Kenai Peninsula

Tesoro Alaska Petroleum Corp. operates a 70,000 bbl/day refinery at Nikiski, near Kenai on the Kenai Peninsula south of Anchorage. The refinery was built in 1969 and purchased during its construction by Tesoro from the company that had initially developed the project. In the 1980s Tesoro upgraded its plant with a catalytic cracker to produce a wider range of fuels.

In its early years the refinery relied on state of Alaska royalty crude oil from Cook Inlet as a source of crude oil supply. Cook Inlet production has declined over the years, however, and the refinery has had to diversify its crude oil supply sources. In recent years the refinery has purchased Alaska North Slope (ANS) crude oil, both state royalty oil from the slope and oil purchased from the producers there. Because ANS crude oil has a lower API gravity and higher sulfur content than Cook Inlet crude oil the refinery continues to purchase oil from Cook Inlet oil producers as well as oil imported from foreign sources, including Sakhalin, in the Russian Far East.

Tesoro's refinery is capable of processing approximately 70,000 barrels per day but, based on product demand, now typically produces about 50,000 barrels per day of products. The company produces jet fuel, diesel and heating oil, gasoline, liquefied petroleum gas, heavy oil and bunker fuel and asphalt. About 30 percent of its production is jet fuel, about 30 percent gasoline, 10 percent diesel and the remainder is other products. During the winter months Tesoro has gasoline supplies that are surplus to local market needs, and exports the gasoline to other regions. The refinery has hydrocracking and vacuum distillation processes.

Tesoro's products are distributed locally on the Kenai Peninsula and are shipped to Anchorage through a 70-mile pipeline that carries 37,000 barrels per day to the company's bulk storage and distribution terminals in Anchorage. Tesoro is a major supplier of jet fuel to airlines at Ted Stevens International Airport in Anchorage and sells gasoline through branded retail locations across the state and to other gasoline retailers.

Tesoro supplies the majority of fuel products transported by barge from Cook Inlet to communities in southwest and northwest Alaska.

Petro Star, Inc. refineries at North Pole and near Valdez, Alaska

Petro Star Inc. operates two refineries in Alaska, one at North Pole, near Fairbanks, and the other near Valdez, at the terminus of the Trans-Alaska Pipeline System.

Petro Star's North Pole refinery processes 17,000 barrels per day of crude oil, and makes a variety of products mainly for the Interior Alaska markets. Products from the North Pole refinery are mainly trucked to market, but some diesel fuel is transported by air to rural communities. The company's Valdez refinery processes about 50,000 barrels per day of crude oil, to make a variety of products. Products are moved to market by truck and by barge from Valdez.

Present-day distribution patterns for fuel oil from Cook Inlet.

As is the case of the Flint Hill refinery, unused portions of the crude stream are returned to the TAPS pipeline from both Petro Star refineries. Petro Star makes commercial and military jet fuel, marine diesel fuel, home heating oil and a variety of lubricants and other products.

Product distribution

Western Alaska

<u>Companies in trade:</u>

Yukon Fuel Co.

Sells to rural communities in Interior, southwest and northwest Alaska. Uses contract tug and barge companies. Yutana Barge Lines, an affiliate of Yukon Fuels operates tugs and barges on the Interior river system and the Bristol Bay region, carries fuel for Yukon Fuel and serves other customers. In western Alaska Yutana and Yukon Fuel rely on Seattle-based contract tug and barge operators for “mainline” fuel shipments to regional hubs.

Crowley Maritime Inc.

Sells to coastal and inland communities in Southwest and Western Alaska. Crowley uses company-owned equipment.

Note: A merger agreement has been negotiated that could combine Yukon Fuel and Crowley operations in Alaska. The agreement is subject to litigation and is not yet in effect.

Delta Western Inc.

Owns and operates fuel terminals at Unalaska/Dutch Harbor, St. Paul and St. George, and serves Bristol Bay and Emmonak and, at times, other communities on the Lower Yukon River.

Patterns of seasonal shipments

The majority of fuel shipped to western and northern Alaska coastal communities is supplied from the Tesoro Alaska Petroleum Co. refinery at Nikiski, near Kenai. Both Yukon Fuel and Crowley Maritime deliver fuel from Cook Inlet to the regional markets. Fuel is loaded at the Tesoro dock, using contracted and, in Crowley's case, company-owned equipment.

At times, Crowley and Yukon Fuel ship fuel from the Port of Anchorage. Fuel loaded in Anchorage is purchased from both the Tesoro refinery near Kenai and the Flint Hills refinery in North Pole, near Fairbanks, which is transported to Anchorage on the Alaska Railroad.

Fuel distributors begin western Alaska seasonal service in late May with shipments to Dillingham and Naknek, which are in Bristol Bay. These communities are usually the first regions open for navigation. After delivering fuel to Bristol Bay, the tug and barges continue along the coast to Norton Sound for the first delivery of fuel of the season to Nome. Generally, the first fuel deliveries of the season follow the winter ice as it recedes.

After the first deliveries to Norton Sound, tugs and barges return to Cook Inlet for another load and make usually the next delivery to Bethel, on the Kuskokwim River. The first delivery to Bethel is typically made in the last week of May. Tugs and barges return to Cook Inlet for another load and then sail for Kotzebue north of the Bering Strait. The first fuel of the season is normally delivered to Kotzebue in the first two weeks of July.

Crowley deliveries to western Alaska

Crowley Marine Services also makes large-scale fuel deliveries to Southwest and Northwest Alaska. The company maintains a bulk fuel storage tank farm in Kotzebue and makes deliveries from Kotzebue to inland communities on the Kobuk River using smaller barges and tugs.

Crowley also makes fuel deliveries to communities on the northwest and northern coasts of Alaska, including Kivalina, Point Hope and Kaktovik, in northeast Alaska near the Canada border.

Crowley maintains a "mainline" barge in Alaska year-around and brings other large barges north for the summer shipping season. In 2004 Crowley had four mainline barges operating in the state. Two of these barges have capacities of 5.3 million gallons each; a third has a 3.6 million gallon capacity and a fourth has 1.7 million gallons.

Crowley Maritime Corp. tug and large mainline fuel barge, of type used to serve western Alaska communities.

Smaller barges and tugs are maintained by Crowley in Alaska for use in "lightering" fuel and for river transport. A typical lightering barge has a capacity for 120,000 gallons.

At times in the past fuel for the communities along Alaska's northern coast has been delivered by the Northern Transportation Co. Ltd. from Hay River, Northwest Territories, via the Mackenzie River. The shipments are made down the Mackenzie to the Beaufort Sea and then west along the Yukon Territory and Alaska coasts.

Delta Western supplies fuel to western Alaska, and will expand its marketing in the region as a result of a consent decree agreed on between the State of Alaska, Crowley and Yukon Fuel, relating to Crowley's acquisition of Yukon Fuel and Yutana Barge Lines.

Delta Western now has access to terminal facilities in Bethel; and Kotzebue, Alaska

Through a Consent Decree agreed on by Crowley and Yukon Fuels as a part of their merger, Delta Western would acquire a terminal in Bethel formerly owned and operated by Yukon Fuel, and has been guaranteed access to Crowley's terminal facilities in Kotzebue.

Prior to acquiring new assets through the Consent Decree, Delta Western supplied about 50 million gallons of fuel per year to the western Alaska region. Much of this is to terminals the company operates in Unalaska/Dutch Harbor and St. Paul and St. George in the Pribilof Islands, which support the region's fisheries. The company also supplies fuel to the Bristol Bay region, again to support fisheries.

Delta Western relies on third party contractors to transport fuel, using barges ranging from 50,000 gallons to 120,000 gallons capacity. The company operates terminals in Unalaska/Dutch Harbor, Dillingham and Naknek, and through a joint venture with local Alaska Native corporations, in St. Paul and St. George.

Delta Western also supplies fuel to Southeast Alaska, along with Petro Marine. Delta Western operates terminals in Juneau, Wrangell and Haines, and typically sells 10 million to 20 million gallons of fuel yearly in Southeast Alaska.

MV Tanana, operated by Yutana Barge Lines, at Nenana, Alaska. Yutana carries out seasonal fuel deliveries on the Yukon River and its tributaries in Interior Alaska.

Interior Alaska river system

Yukon Fuel Co. serves Interior Alaska river communities along the Tanana and Yukon Rivers from Nenana as far upriver as Fort Yukon and downriver as far as Emmonak. The transportation of the fuel is by Yutana Barge Lines, an affiliate company to Yukon Fuel.

Fuel is trucked from the Flint Hills or Petro Star refineries at North Pole to Nenana, a distance of approximately 60 miles by highway. At times, fuel is trucked to Nenana from Anchorage, a distance by highway of about 350 miles. During the summer navigation season there are typically 3 to 5 trucks a day delivering fuel from North Pole to Nenana and typically 1 truck a day from Anchorage carrying unleaded and aviation gasoline.

The river navigation season is typically late May to September, with the first deliveries of the year made to Galena from Nenana in late May. Through the season, Yukon Fuel and Yutana typically make 3 trips to lower Yukon River communities via the Tanana River from Nenana and 3 trips to upper Yukon communities, as far as Fort Yukon. At times fuel is trucked to the Dalton Highway bridge on the upper Yukon and moved by barge to communities on the upper river.

Using a smaller tug and barge, fuel deliveries are also made from Nenana to Huslia, on the Koyukuk River, a tributary of the Yukon. There are several additional trips made on the Yukon to Galena during the summer to supply fuel to government installations in that community.

In a typical year Yukon Fuels and Yutana deliver about 9 million gallons of liquid fuels along the Yukon River system, including 4 million gallons of diesel, 1.5 million gallons of gasoline, and 1.1 million gallons of aviation gasoline to communities along the Interior rivers. Additional volumes of jet fuel are supplied to an Air Force station at Galena.

Navigation issues

Navigation problems, particularly problems posed by very shallow coastal waters in approaches to coastal communities, are a major contributor to the high cost of delivering fuel to rural communities in western Alaska.

A typical arrangement is to use deeper-draft mainline barges for service to regional hubs with ports. Fuel is then transferred to onshore storage tanks or directly to shallow-draft barges for service to other communities in the region. In many communities the deeper-draft ocean barges anchor offshore in deeper water, and fuel is transferred at sea to smaller shallow-draft "lightering" barges.

In some communities it is possible that the cost of lightering fuel from deeper water a mile or so offshore is equal to the cost of transporting the fuel from its point of origin via a larger ocean-going barge to the transfer point offshore. In addition to the costs of transferring and lightering fuel, transportation companies must bear the costs of mobilizing the shuttle barges and tugs to remote locations.

Kuskokwim River access

The Kuskokwim River opens into the Bering Sea north of the entrance to Bristol Bay, and is illustrative of the navigation challenges faced in southwest Alaska. It is an area with frequent shoals and channels through the bay that are not always apparent. A 40-mile approach to the Kuskokwim has many shifting sandbars, some visible and some submerged. The channels undergo changes from year to year because of sea action, currents and ice.

The deepest draft vessel that can reach Bethel, 65 miles upriver from the Kuskokwim's mouth, is about 12 feet. Barge operators with shallower draft equipment operate further up the Kuskokwim from Bethel. Drafts are limited to 4.5 to 5 feet and sometimes 4 feet and shallower during dry summers. McGrath, 400 miles up the Kuskokwim, is the head of navigation for the river. At times barges can serve Nikolai, located above McGrath on the river. Because the Kuskokwim is narrow and has a faster ice "breakup" in the spring the navigation season on the Kuskokwim is typically about three weeks longer than on the Yukon River. Typically, navigation is possible for 120 open-water days on the Kuskokwim compared with about 100 days for the Yukon.

Interior river navigation issues

One of the major issues affecting fuel deliveries to the Interior river communities are navigation restrictions along the Tanana River from Nenana to its confluence with the Yukon River. Yutana Barge Lines operates barges up to 240,000-gallon capacity. On the Tanana River, however, these can only be loaded to about two-thirds of their capacity due to depth limitations on the river. Typically Yutana would move the barges partly-full to the Yukon, and then transfer fuel to load the barges to capacity. Once on the Yukon River the barges can carry their full load.

Navigation issues on the lower Yukon River and the Yukon Delta

Distance and navigation, as well as lack of infrastructure, are major impediments to efficient fuel supply on the lower Yukon River. Shallow approaches to the Yukon River at its mouth are major restrictions. The Yukon is typically approached by vessels traveling through the Gulf of Alaska and around the Alaska Peninsula, a journey of 1,250 nautical miles from Anchorage. Because of this, fuel is more efficiently supplied to lower Yukon communities from Nenana rather than via ocean-going barge through the mouth of the Yukon River. Approaches to the Yukon River at its mouth are shallow, and the channels through the shallow approaches are narrow, crooked and bordered by shoals exposed at low water. The shoals are also subject to constant change. Barge operators recommend transshipment of fuel from oceangoing barges to barges with a draft of no more than 11 feet.

If conditions require it, barges are "light-loaded to a depth less than 10 feet for the trip through the Yukon mouth to St. Mary's. Light-loading is a shipping practice where a vessel is loaded to

less than its capacity to lessen its depth. A typical 175,000-gallon barge draws about 2 feet when empty and 7 feet when loaded to capacity.

Lightering barges are often used that draw no more than 4 feet. Lightering vessels are more economical than larger ocean-going barges for making deliveries at many lower Yukon River communities due to lack of dock and fuel storage facilities.

Crowley Maritime and Yutana maintain tugs and barges in Alaska designed for shallow-water uses. Some are capable of operating in water between 3 and 4 feet in depth.

Infrastructure issues

Lack of infrastructure and shallow coastal waters are key factors in the high cost of delivering fuel to rural communities. Where communities have approaches with deeper water and docks or harbors, large fuel barges can be unloaded efficiently.

A fully-loaded sea-going “mainline” barge used by Crowley Maritime to serve Western Alaska is typically 430 feet long by 78 feet wide and carries 5.3 million gallons of fuel. It typically draws 17 feet to 19 feet fully loaded. Unless a dock is available with deep enough water, the transportation cost advantage of the larger barge is lost.

Dillingham, Naknek, Bethel and Nome have docks and water depths sufficient for these barges. Many coastal communities have no docks, however. For service to these communities fuel must be transferred to smaller barges that draw less water, as described earlier.

Landing sites typically unimproved

Landing sites in many communities are typically unimproved river banks or beaches. Landing sites in many river communities vary from year to year and even within a season depending on the levels of water and movement of sandbars.

Alaska is unusual in that a barge must typically be grounded to unload fuel, a procedure not permitted in other states that have more infrastructure. Typically the barge operator will do a site inspection before the barge is brought to shore, to insure safety. Landing locations in many coastal communities are challenging, and one area has been nicknamed “the mud coast” by barge operators. On Saint Lawrence Island, in the northern Bering Sea, fuel is unloaded via hoses through the surf line and across a gravel beach from a barge anchored offshore.

Location issues

The location of a community also makes a great deal of differences as to how efficiently it can be served. If a community is on the coast near a route with periodic mainline barge service, fuel supply is easier than with a community that is far from the coastal transportation routes.

Communities that are at the far end of the fuel distribution system include Hooper Bay on the Yukon Delta, which is served from Nenana via the Tanana River (as well as from the Bering Sea); Fort Yukon, on the upper Yukon, which must be served from Nenana via the Tanana River; McGrath, on the upper Kuskokwim River, which must be served from Bethel, on the lower river, which in turn is supplied from Cook Inlet, and White Mountain, a Seward Peninsula community which is inland from the coast.

Some communities, such as Nightmute and Chefornak, are in locations that are tide-sensitive; others, like White Mountain, are in locations where winds and low water levels in rivers, as well as tides, influence water depths. Many communities are supplied just once a year when local navigation conditions are optimal. White Mountain is challenging because it is accessible only when tides, winds and river water levels are all favorable. White Mountain is usually served only once a year, in fact. Typically a barge operator would land the barge at high tide, conduct fuel unloading during the low tide cycle, and then refloat the barge on the next high tide.

Costs of lightering, regional distribution

The cost penalty imposed on rural communities because of their small size, remoteness, navigation challenges and lack of infrastructure is considerable. When fuel destined for outlying communities must be stored and transferred through a regional bulk fuel distribution hub, such as in Bethel, Nome or Kotzebue, the facility, storage and extra handling costs can add 7 cents to 10 cents per gallon to the final price of the fuel.

The cost of “lightering,” or transferring fuel to smaller, lighter-draft vessels is in addition to the terminal costs. These incremental costs vary by location and season, and are estimated for different specific locations at 10 cents to 20 cents per gallon.

The range of additional costs is also illustrated by these estimates: Costs for moving fuel to coastal regional hubs with large mainline barges is typically 20 to 30 cents per gallon, although it can be as low as 15 cents per gallon with a large-volume, multi-year customer where the customer assumes the risks. These costs can be 30 cents per gallon if the location is difficult, however. When the costs of lightering to small communities are added, average costs for a rural fuel transportation operator, across the entire distribution system, can average 30 cents per gallon to $1.20 /gallon depending on location.

Small scale is a problem

The principal problem Alaska faces, particularly in supplying small, outlying communities, is the very small scale of regional fuel markets which prevents refineries and fuel distributors from achieving large economies of scale with a full range of products. For example, airlines operating through Ted Stevens International Airport in Anchorage are major customers for jet fuel, with annual fuel demand averaging almost a billion gallons a year.

In contrast, total fuel sales to western Alaska communities supplied mostly from Cook Inlet typically do not exceed 150 million gallons a year, and fuel sales to Interior river communities supplied through Nenana are typically about 9 million gallons a year.

The large demand for jet fuel creates issues and seasonal imbalances in the product mix for refiners. For example, refiners often are unable to supply the total jet fuel requirements for airlines at Ted Stevens International Airport in Anchorage, resulting in the need to import some jet fuel. Also, gasoline production exceeds the regional market demand at certain times of the year, resulting in some gasoline being sold out of state.

There are also seasonal issues. There is more demand for jet fuel in the winter, when kerosene is used as Arctic-grade fuel in diesel engines and oil-fired heaters, and more demand for No. 2 diesel fuel during summer.

Naphtha is also produced at the Flint Hills refinery near Fairbanks, and is transported to Anchorage by rail tank-car and sold in export markets as a feedstock for petrochemical industries.

The location of a particular rural community affects local fuel prices. If a community is fortunate in being close to navigation routes of large “mainline” barges, access via lightering barges is easier and less expensive. As previously mentioned, local navigation problems such as shallow coastal waters which require lightering, or shallow rivers and seasonal low water and lack of infrastructure like docks can add substantially to costs.

Economies of scale

One of the principal reasons for high fuel costs in rural Alaska is the very small size of the market being served, and the resulting high incremental costs. In a regional hub community such as Galena, which supports more local economic activity, costs will be lower because larger quantities of fuel are stored in larger tanks and more fuel is sold. Conversely, costs will be higher in communities that use less fuel, either because of small size or lower levels of economic activity.

Local distribution costs

The high costs of operating a terminal and distribution system in a small community contribute to the inefficiencies of the rural fuel delivery system. These costs are directly proportional to the amount of fuel sales because costs must be spread across the amount of fuel sold.

Two examples illustrate this: Galena, on the middle Yukon River, and Hooper Bay, on the lower Yukon. Galena actually has a smaller population (750) than Hooper Bay (1,100) but more fuel is stored and sold there because there is more local economic activity.

Galena is a regional hub, supporting a certain level of economic activity, with a local Air Force installation, a regional boarding school, a city government active in administering local projects, developed local infrastructure such as roads and water service. The local fuel distributor sells about 1 million gallons a year. The cost of the local distribution system must be added to the cost of delivered fuel.

In Hooper Bay, a community with approximately 1,100 people, there is less local and regional economic activity. About 200,000 gallons of fuel are sold annually, one fifth of the volume typically sold in Galena. Hooper Bay fuel sales must support the operation and maintenance of the local bulk fuel storage facility. Hooper Bay’s facility operates 40 hours per week and employs 2.5 full-time equivalent employees. In addition to its operating costs, the facility must pay a return on approximately $1 million in capital investment in the terminal.

The operational costs of the terminal, the salaries of the employees, the repayment of capital investment and a profit margin must be part of the per-gallon price of the 200,000 gallons of fuel sold annually.

Operating costs must also include facility maintenance and inspections, insurance, spill prevention and containment capability, and inventory carrying costs. The “fixed” costs are typically about $1 per gallon in Hooper Bay. In total, the costs of operating the local distribution system add about $1.18 per gallon to the wholesale cost of delivering the fuel to Hooper Bay.

Small fuel purchases are common

A striking aspect of terminal and fuel distribution systems in communities like Hooper Bay is the small size of the typical fuel purchase. For many reasons, including limited local cash resources, the average sale of fuel in Hooper Bay is 5 gallons. A typical residential customer buys fuel in small increments over several days of the week.

If customers could change their purchasing practices and buy larger quantities in fewer purchases, it would allow operating costs for the local distributor to be reduced, in the opinion of the terminal operator. If fuel sales could be made in larger increments so that the terminal is open for business one day a week rather than five days, the savings in labor alone might lower local costs by as much as 20 cents a gallon. The local fuel operator has installed facilities to allow 24-hour purchases, however, such as dispensing equipment where payment is made by credit or debit card, or a fuel purchase card.

There is a local economic tradeoff for this. Since any gain in efficiency would be mostly in lower labor costs, through fewer hours of employment per week, in lower fuel prices come at the cost of lost wages to the terminal employees.

Pricing

The wholesale price for fuel in Alaska is determined by U.S. west coast fuel prices and influenced directly by crude oil prices, which are determined by international markets. Alaska refineries and fuel distributors base their wholesale product prices mostly on the west coast Oil Price Indexing Service (OPIS), a national price indexing service, with transportation costs added.

Rural Alaska communities served by waterborne transport receive the benefit of a discount on wholesale fuel prices, which can amount to 10 cents to 15 cents per gallon. The discount, which applies to fuel moving by barge from Nikiski to western Alaska and through Nenana to Interior river communities, is given because these fuel volumes are taken out of the main railbelt regional markets so as to not affect competition among refiners and distributors in the larger markets of South-central and Interior Alaska. Also, the additional volume of fuel sales allows refiners to spread fixed costs over more volume, which has the effect of lowering costs for all fuel sales.

Environmental compliance

Environmental compliance costs are paid by fuel suppliers and must be part of the final price paid by the consumer. The burden is felt particularly in rural Alaska, however, because these costs are spread across the small volumes of fuel that are sold there. Private fuel distributors have estimated that compliance costs, which include installation of spill containment and cleanup equipment, training, insurance and inspections adds an average of 45 cents per gallon to the price of fuel in rural Alaska. These costs range from 20 cents to 60 cents per gallon depending on location.

One of the advantages of having access to Fischer-Tropsch fuels is the non-toxic, biodegradable character of some F-T fuels. This has advantages in small rural communities where storage and transportation of conventional diesel fuels create environmental hazards.

Ultra-low sulfur fuel requirements

U.S. Environmental Protection Agency rules will require that ultra-low sulfur diesel fuel, with a sulfur content of 15 parts per million or less, be used for on-road vehicles in 2006 and off-road vehicles and construction equipment in 2010. It is assumed that the EPA rule for ultra-low sulfur fuel will eventually be extended to include fuel used in stationary diesel engines, such as in power plants, and in marine engines, such as those typically used in Alaska fishing vessels. These requirements pose significant problems for rural Alaska.

The problems occur mainly because of the transportation and storage problems in the supply of different types of diesel, ultra-low sulfur and standard diesel. Ultra-low sulfur diesel must be moved and stored in dedicated tanks, or tanks must be thoroughly cleaned prior to transporting or storing ultra-low sulfur diesel. Either ways, costs are added. If dedicated tanks are used the costs are paid by the small quantities of ultra-low sulfur diesel moved and stored. If tanks are cleaned, the costs of cleaning must be paid. In the opinion of state officials and many community leaders in rural Alaska, the most practical arrangement for a rural community is to use ultra-low sulfur diesel for all engines used locally, or in the region if the community is a regional hub, which is likely. By doing this, larger tanks for transportation and storage can be used and the extra-handling costs would be eliminated or reduced.

There are only very general estimates for the cost of supplying ultra-low sulfur diesel to rural communities. Estimates by refineries in the Pacific Northwest are that the ultra-low sulfur fuel will cost 5 cents to 10 cents above the price of conventional summer-grade diesel. Arctic grade ultra-low sulfur diesel will be another issue. Alaska Village Electric Cooperative, a rural Alaska electric utility, has estimated costs for the fuel delivered to its rural utilities at 25 cents a gallon above current costs of purchasing conventional diesel. Another estimate is 50 cents a gallon above conventional diesel for Fairbanks delivery by highway from Edmonton, Alberta, where refineries will produce the ultra-low sulfur diesel.

Source for ultra-low sulfur diesel

There are also questions about where ultra-low sulfur diesel can be purchased. Refineries in the Pacific Northwest will be making ultra-low sulfur diesel but will probably not be making the Arctic grades of diesel needed in much of Alaska during the winter. Flint Hills Resources has announced that it will make ultra-low sulfur Arctic-grade diesel in the company’s refinery at North Pole and will have it available in 2007. However, Flint Hills’ price of the fuel is unknown at this time. Flint Hills is able to make the investment, it says, because it will also be investing in desulfurization equipment to make low-sulfur gasoline to meet EPA deadlines for this fuel.

Tesoro Alaska Petroleum Co. is considering making the fuel at its Kenai Peninsula refinery, but may also supply Alaska from its refineries in Washington state or Hawaii.

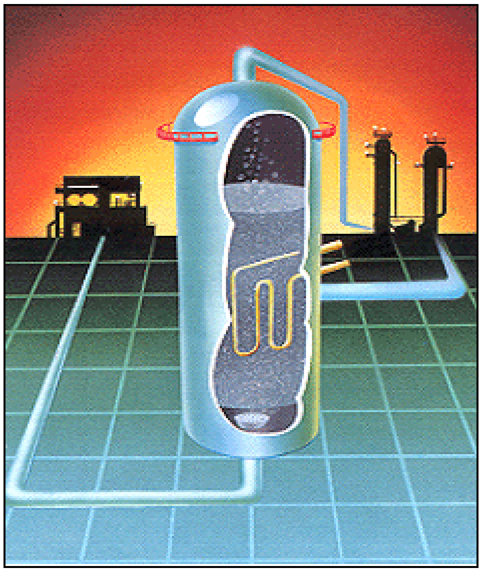
Other alternatives include a refinery in the Pacific Northwest making a special “batch run” of Arctic-grade ultra-low sulfur diesel. Making the fuel would involve a relatively low volume given the scale at which these refineries typically operate, and the low quantity would add to expense. It could, however, be made at one time of year, stored locally and loaded on barges for transport to western Alaska.

Alternatively, Arctic grade ultra-low sulfur diesel could be purchased from refineries in Alberta which will make the product for use in northern regions of Canada. From Alberta it could be shipped by rail to the Pacific Northwest for transshipment by barge to Alaska, or trucked to Fairbanks and Nenana for transshipment. An Alaska trucking company estimated the costs of moving the fuel from a refinery in Edmonton, Alberta to Fairbanks at 50 cents per gallon.

There are other transportation issues. Ultra-low sulfur diesel will require special handling and perhaps special tankage to keep it from being contaminated with higher-sulfur diesel. It cannot be stored in tanks or shipped in pipelines that previously stored or shipped fuel with higher levels of sulfur without the ultra-low sulfur fuel becoming contaminated. The tanks and pipelines will have to be thoroughly cleaned, or the ultra-low sulfur fuel will have to have dedicated tankage. These special handling requirements will add costs.

The fuel could be shipped to Yukon River communities through the existing truck and barge system that operates through Nenana. If Tesoro makes the fuel at its Kenai refinery, the existing barge distribution system from Cook Inlet can be used. If the new fuel must be supplied from the Lower 48, special shipments will be required to Cook Inlet or directly to Western Alaska communities.

A final alternative is that if a Fischer-Tropsch plant were built in an Alaska location which could serve western Alaska, the “clean” diesel that could be produced would meet the EPA requirement.



Appendix

Fischer-Tropsch Fuels

History

World Drivers

Developments in Technology

Gas-to-Liquids Transportation Fuels

Economic Support for a U.S. F-T Program

Fischer-Tropsch Technology Development
Gas To Liquids Transportation Fuels

ABSTRACT

Fischer-Tropsch (F-T) is the conversion of natural gas to liquids (GTL), coal to liquids (CTL) or bio-mass to liquids (BTL), all three processes commonly referred to as Gas-to-Liquids. (GTL) is the process for the chemical conversion of carbon into liquid products. It has been a developing technology for over 75 years. The first 50 years saw coal as the primary feed stock. In the late 1980s natural gas started a trend that today has over 500,000 barrels per day (bbl/d) of GTL plants announced or under construction in Qatar alone. Chiefly responsible for this trend has been the desire to reduce the annual 3.8 tcf of natural gas flaring and venting and to commercialize the estimated 4,200 tcf of proven gas reserves in FSU, Middle East and Africa. In the late 1990's bio-mass or bio-renewable feed stocks such as trees and dedicated crops were added to the picture in Germany.

In general the trend in the industry has been towards larger GTL plants to improve plant economics and reduce operating costs. As plant size increases, gas reserves required to support the GTL plants increase with overall costs of the GTL complex running into the $2 million to $ 5 billion dollar range, eliminating all but the largest oil companies and State-run oil companies (Parastatals) from developing new projects. To date almost all technology advances are geared towards the "mega" GTL plant projects. Development of small GTL projects, under 1,000 bbl/d, will have to be driven for specific applications such as military, space or national defense needs.

F-T fuels, an option to LNG for stranded gas development are prized for their ultra clean properties and their ability to fit into the existing transportation motor fuels system with no change to the infrastructure. Many countries around the world are providing incentives for this environmentally friendly but expensive fuel, creating incentives that draw these fuels and technology to their region of the world. If the U.S. is to participate in an F-T revolution, it will have to provide incentives to F-T as it does to many other alternative fuel and energy technologies.

This paper will briefly outline the historic development of F-T technologies and address the following points:

- **F-T Drivers**
- **F-T Economics**
- **New F-T Technologies**
- **Support for F-T fuels In The U.S.**

Gas-to-Liquids Fischer-Tropsch Technology

Development in the World

INTRODUCTION – HISTORY OF GAS-TO-LIQUIDS

In the early 1900's Germany led the world in the development of Fischer-Tropsch (F-T) transport fuels from coal. By the mid 1930's Adolph Hitler backed the development of the early F-T process to provide aviation fuel for his war efforts, resulting in numerous large scale plants built during the 1938 to 1943 era. At the conclusion of the war both the U.S. and Russia took this revolutionary F-T technology back to their respective countries. The U.S. was still an exporter of domestic crude oil and awash with cheap natural gas and while it looked at this new technology the US oil industry was not interested as it was too costly to make F-T transport fuels from coal.

South Africa, blessed with abundant coal resources but no domestic oil and natural gas resources, asked the U.S. for the rights to this technology in 1948. The South African Government formed the South African Coal, Oil and Gas Corporation (SASOL) and began development of a coal-based slurry bed F-T plant in Sasolburg in 1951.

By the late 1970s Sasol had advanced F-T technology that reduced capital costs, increased conversion efficiency and reduced operating costs. As a result of the Arab oil embargo and Sasol's advances, many other oil companies began or renewed their interests in the F-T process. By the early 1980s, the Arab oil embargo ended, a world wide recession developed and oil prices dropped. All but Sasol put their F-T work back on the shelf or relegated it to R&D.

Following work begun in Germany during the late 1950s, Sasol began looking at a new F-T reactor design called "slurry bubble column" or slurry phase. This new design had the promise of reducing operating costs and increasing both carbon and energy conversion efficiencies. In addition, work with new cobalt catalysts held promise of longer life and higher product selectivity – making more of one product and less of another while reducing the production of CO_2, a troublesome by-product when iron catalysts are used.

In the mid 1980s South Africa discovered natural gas off its southern coast. Since the F-T process is all about carbon conversion through a chemical process, Sasol was asked to design a plant to convert this new resource into F-T transport fuels. This first gas-to-liquids (GTL) plant located in Mossel Bay, South Africa rekindled the F-T efforts of many of the oil majors as a way to monetize the vast stranded natural gas reserves across the world. ***Total world gas reserves of 6,205 TCF, equivalent to approximately 1,105 billion BOE, are on a par with estimated world oil reserves of 1,147 billion barrels.***

As demand for crude oil based transportation fuels continues to increase resulting in higher crude oil prices, more oil companies are looking at natural gas based GTLs to help meet these growing demands. However, with over 70% of these gas reserves located in the Former Soviet Union (FSU) and the Middle East and little undedicated reserves in the U.S., F-T programs in the U.S. will have to focus on coal and bio-mass for their feed stocks.

Throughout the late 1990s there was a resurgence of industry interest in GTL's, driven by the need to reduce gas flaring and the prospect of turning the world's vast reserves of natural gas into clean fuels to meet increasingly stringent air quality regulations.

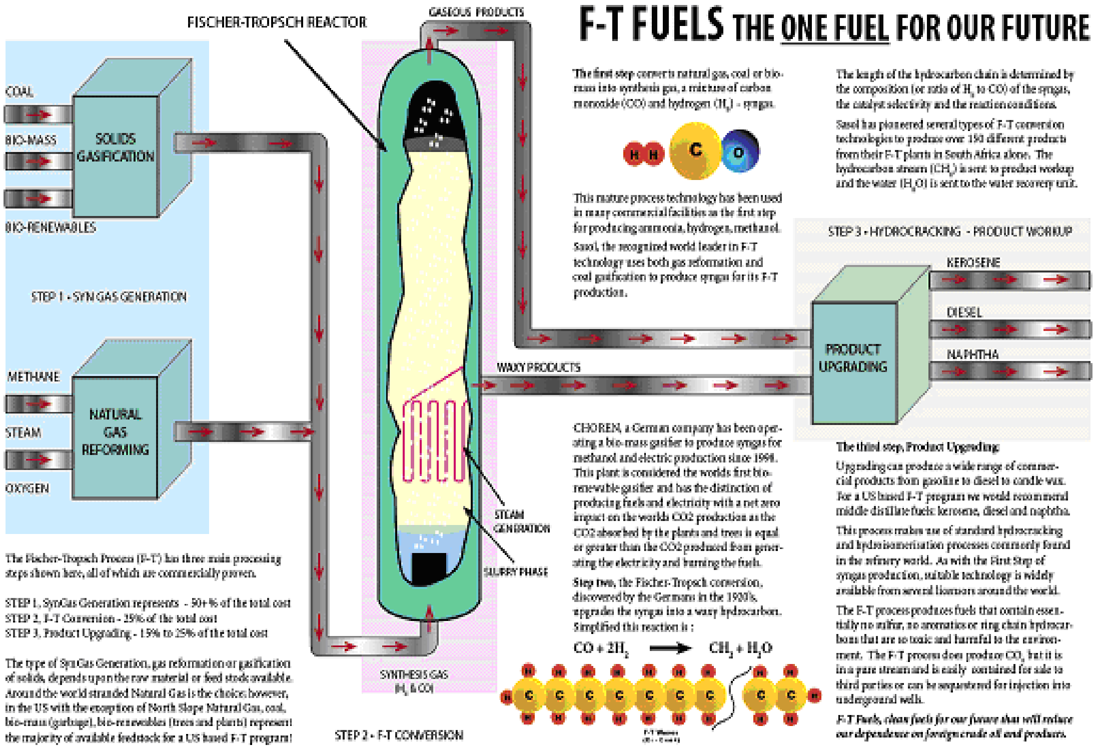
According to a World Bank study, 3.8 trillion cubic feet per year (tcf/yr) of natural gas, equivalent to approximately 700 million barrels of oil equivalent (BOE) is flared or vented as associated gas with oil production. Ten countries account for over 75% of global flaring and venting. The photo to the right is a gas flare in Nigeria flowing nonstop since 1972 from an Agip oil field. Flaring and venting in Nigeria amounts to 16% of the world total and if used in electric power generation would represent half of Africa's electric demand. U.S. flaring represents about 3% or 312 mmcf/d of the world's total.

WHAT IS THE F-T PROCESS?

The F-T process has three individual steps. In the first step carbon in natural gas (methane) or carbon in coal and bio-mass is reacted with oxygen and steam to form a mixture of hydrogen and carbon monoxide ($H_2 + CO$) called syn-gas. In the Second Step, the syn-gas is reacted under pressure in the presence of a catalyst to form long chain carbon-hydrogen molecules, termed F-T wax or paraffin. The third Step "cracks" these long chain molecules to form individual products like diesel, gasoline and petrochemical feed stocks.

Early F-T programs in Germany in the 1930s and South Africa in the early 1950s used fixed bed or fluidized bed F-T reactors with iron (Fe) catalysts with coal as the feed stock to supply syn-gas. Modern F-T plants, post 1990, are using both fluidized bed and slurry bubble column, almost all with cobalt catalysts and focusing on natural gas as the feed stock to supply the syn-gas. In the mid 1990s, Germany again began experimenting with bio-mass – bio-renewable feed stocks to provide the syn-gas. Bio-renewable feed stocks hold the promise of producing F-T transport fuels that are CO_2 neutral when evaluated on a full life cycle basis. This is a very attractive point as reducing green-house-gas (GHG) emissions gains more prominence across the world.

Figure 1, below, illustrates a typical process flow diagram for the generic F-T reaction.



F-T FUELS THE ONE FUEL FOR OUR FUTURE

The first step converts natural gas, coal or bio-mass into synthesis gas, a mixture of carbon monoxide (CO) and hydrogen (H_2) - syngas.

This mature process technology has been used in many commercial facilities as the first step for producing ammonia, hydrogen, methanol.

Sasol, the recognized world leader in F-T technology uses both gas reformation and coal gasification to produce syngas for its F-T production.

The length of the hydrocarbon chain is determined by the composition (or ratio of H_2 to CO) of the syngas, the catalyst selectivity and the reaction conditions.

Sasol has pioneered several types of F-T conversion technologies to produce over 150 different products from their F-T plants in South Africa alone. The hydrocarbon stream (CH_2) is sent to product workup and the water (H_2O) is sent to the water recovery unit.

The Fischer-Tropsch Process (F-T) has three main processing steps shown here, all of which are commercially proven.

STEP 1, SynGas Generation represents - 50+% of the total cost
STEP 2, F-T Conversion - 25% of the total cost
STEP 3, Product Upgrading - 15% to 25% of the total cost

The type of SynGas Generation, gas reformation or gasification of solids, depends upon the raw material or feed stock available. Around the world stranded Natural Gas is the choice; however, in the US with the exception of North Slope Natural Gas, coal, bio-mass (garbage), bio-renewables (trees and plants) represent the majority of available feedstock for a US based F-T program!

CHOREN, a German company has been operating a bio-mass gasifier to produce syngas for methanol and electric production since 1998. This plant is considered the worlds first bio-renewable gasifier and has the distinction of producing fuels and electricity with a net zero impact on the worlds CO2 production as the CO2 absorbed by the plants and trees is equal or greater than the CO2 produced from generating the electricity and burning the fuels.

Step two, the Fischer-Tropsch conversion, discovered by the Germans in the 1920's, upgrades the syngas into a waxy hydrocarbon. Simplified this reaction is :

$$CO + 2H_2 \longrightarrow CH_2 + H_2O$$

The third step, Product Upgrading

Upgrading can produce a wide range of commercial products from gasoline to diesel to candle wax. For a US based F-T program we would recommend middle distillate fuels: kerosene, diesel and naphtha.

This process makes use of standard hydrocracking and hydroisomerisation processes commonly found in the refinery world. As with the First Step of syngas production, suitable technology is widely available from several licensors around the world.

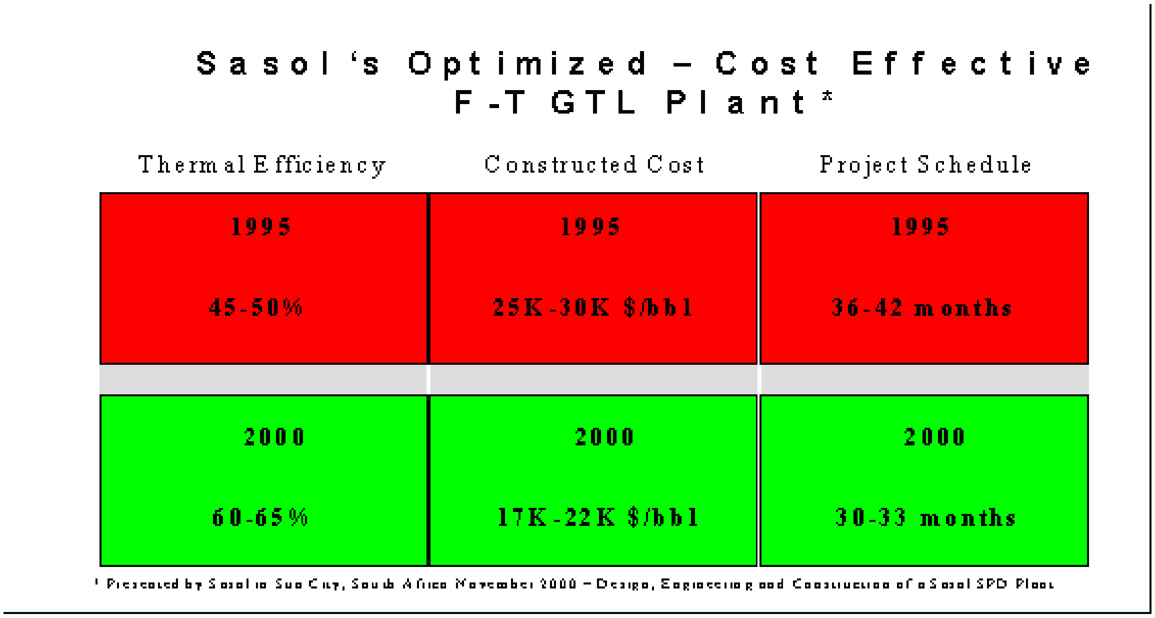
The F-T process produces fuels that contain essentially no sulfur, no aromatics or ring chain hydrocarbons that are so toxic and harmful to the environment. The F-T process does produce CO_2 but it is in a pure stream and is easily contained for sale to third parties or can be sequestered for injection into underground wells.

F-T Fuels, clean fuels for our future that will reduce our dependence on foreign crude oil and products.

Figure 1

The F-T process offers the potential to produce a range of products: middle distillates (jet, diesel, kerosene) and gasoline, as well as lubricants and specialty waxes. Because F-T products are made from natural gas, coal or bio-mass via a chemical process, they have none of the impurities associated with crude oil derived products such as sulfur, heavy metals and carcinogenic compounds such as benzene. These environmental benefits associated with F-T products add to their value in the market place. Higher product values attract new companies with innovative carbon conversion technologies to the game. In addition, well established F-T companies continue to optimize catalysts, F-T reactor designs and work with engineering contractors to reduce the costs of new F-T plant construction.

There are six factors that control the economics of modern F-T plants. The cost of capital; construction costs; the cost of the inlet feed (natural gas, coal or bio-mass); the conversion/thermal efficiency; plant operating costs; and the value of the finished products. We assume that the cost of capital, cost of feed stock and the value of the finished products are the same for any technology. Sasol, one of the recognized leaders in GTL, has been working hard to reduce the costs of traditional GTL F-T technology. The cost trends are down but the size of F-T plants is increasing; leaving behind smaller gas fields that can't support bigger F-T plants. Figure 2 below illustrates the advances Sasol has made by investing over $100 million in 5 years on process improvements and EPC optimizations.



Sasol 's Optimized – Cost Effective F-T GTL Plant*

Thermal Efficiency	Constructed Cost	Project Schedule
1995 45-50%	1995 25K-30K $/bbl	1995 36-42 months
2000 60-65%	2000 17K-22K $/bbl	2000 30-33 months

* Presented by Sasol in Sun City, South Africa November 2000 – Design, Engineering and Construction of a Sasol SPD Plant

Figure 2

Using numbers quoted by Sasol for its 33,000 bbl/d F-T plant currently under construction in Qatar, the cost per installed barrel of daily capacity is less than $20,000 per installed barrel. All the leading F-T technology providers have targets ranging from $14,000 to $18,000 per installed barrel of daily capacity; but all are working with design capacities in the 30,000 to 75,000 bbl/d or larger size F-T plants utilizing natural gas as the feed stock.

The target of $14K / installed barrel is to make future GTL plants competitive with crude oil refineries. Since the operating cost of these big GTL plants is approximately the same as a modern crude oil refinery - $4 to $5/bbl future GTL plants can go head to head with new crude oil refineries based on the price of the feed stock compared to the price of crude oil, as process efficiency is improved.

From the Sasol/Foster Wheel Engineering work on GTL plants:

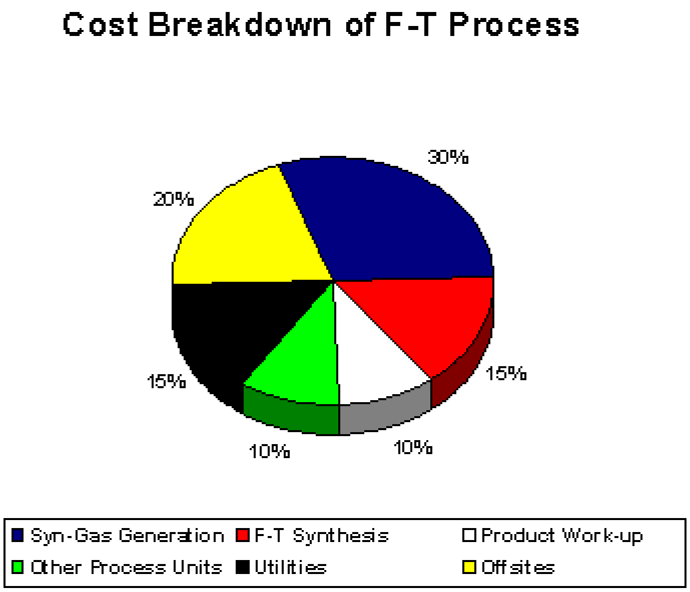


Figure 3

Typically F-T fuel plants require big investments in utility and offsite support systems which can account for 40%–50% of the total cost of a plant, (Figure 3). These costs are usually included in each of three basic F-T steps, synthetic gas generation; F-T wax conversion and product workup; with the typical cost allocation of 50% to 55% of the total cost allocated to syn-gas generation; 25% to 30% to the F-T conversion with the remaining 15% to 25% to product upgrading. However, when developing an F-T project in areas were some or all of support systems are present, there may be significant cost savings available in each of these three steps. Conversely, building an F-T plant in an area with no support systems available the actual installed cost can almost double.

Virtually all the technologies for a large scale F-T plant have a common infrastructure requirement. This includes: the need for large quantities of energy to drive the air separation processes – oxygen plant; the preheat needs for the syn-gas generation step; waste heat recovery from syn-gas and its effective utilization; medium/low grade heat generation by the FT process; hydrogen provision for the hydrocracker; and optimum product recovery to maximize yield. And finally, as F-T projects are around 60% thermal efficient, resulting in around 40% heat rejection to the surroundings, ways to economically capture this ~ 40% of the heat contained in the feed stock have to be found. In addition to heat recovery, offsite systems can be significant, especially when dealing with "Greenfield" remote locations in Alaska. Such offsite systems may include water treatment to support large steam systems and effluent treatment of hydrocarbon-contaminated water and system blow downs. Gas flare systems to deal with high flows from the hydrocarbon units and high volume flows from the gas processing units; plus firefighting systems to deal with the large volumes of volatile hydrocarbons at their vapor points and process streams containing hydrogen, are very important. Isolated synthetic product tankage and dedicated F-T product loading facilities are significant factors; compared to a crude oil refinery as a F-T plant may require similar volumes in storage, but its utilization will be low until a robust market is established for these ultra clean products. F-T plants are similar to chemical plants where upsets due to contamination from small amounts of sulfur, as well as large-scale reliable electrical systems, that must supply power during startup and market power to the grid during normal operation can adversely affect plant economics. The usual support infrastructure of administration buildings, workshops, warehouses, cafeterias and medical facilities are required, plus temporary construction facilities will be needed for remote locations. While ultra clean F-T diesel fuels have generated the most interest, we must not forget that there are many challenges in the support systems when considering engineering, construction and cost that can be improved.

The element of market risk is particularly significant due to the massive scale at which the plants are planned. With expected cash flows of over $1 billion per year from the sale of products, unexpected down time can doom a project. On a smaller scale, installation costs of GTL/CTL/BTL F-T plants rise rapidly, soon exceeding $80,000 per daily barrel of capacity. Below 10,000 bbl/d, these plants scale down poorly, not so much in the design of the gas reformer, the F-T reactor or the product workup but in the ancillary equipment such as pumps, coolers, heat exchangers and treating facilities.

Most major F-T technology companies are seeking large gas fields to support major F-T projects. Unfortunately for the U.S., with the exception of the North Slope, we have no stranded gas fields to attract natural gas based F-T projects. We are fortunate to have large coal reserves and an exceptional growing environment to supply bio-mass. CTL and BTL programs require larger syn-gas generation facilities because the available carbon is typically lower in woods and low rank coals than natural gas. Additionally, tons of waste (ash) and other impurities in coal and bio-mass that must be removed from the syn-gas before it is sent to the F-T reactor. These extra operations drive up the cost of a CTL/BTL program. Low cost mine mouth coal reserves can help offset the larger Capex costs but bio-mass will always struggle to be competitive, especially in the U.S. We will discuss later in this paper ways that the U.S. can support F-T to close this economic gap between crude based diesel and F-T diesel.

DRIVERS FOR GAS TO LIQUIDS

In the beginning of the 1980s many of the major oil companies began to invest considerable efforts and expenditure in the development of technologies for the conversion of natural gas into F-T liquid transportation fuels. The rapid rise in the price of oil following the mid 1970s Arab oil boycott and the belief that oil supplies had peaked at 50 million barrels per day of production provided strong incentives. There have been many ups and downs in the energy market in the 25 years since that time, stalling the development of GTL technology. Today world production of crude oil is just below 80 million barrels per day but enthusiasm for GTL processes has never been higher, driven by the need to reduce flaring, because of climate change fears and the prospect of turning the world’s vast reserves of natural gas into clean fuels that could meet increasingly stringent air quality regulations. Many oil companies again believe the world’s oil producing regions have reached their limits of sustainable production and natural gas must now be exploited to produce transportation fuels. Increased demand from China and India will quickly outstrip the world’s ability to supply crude oil-based products, raising crude oil prices and creating more uncertainty in the world. China is looking at all sorts of energy production ranging from hydro to coal and bio-mass to liquids to nuclear to meet its growing energy demands.

Environmental Driver – “free gas” with a hidden cost

Gas flaring, the amount of gas that is flared or lost as associated gas with oil production is estimated at 3.8 trillion cubic feet (tcf) per yr (10.4 bcf/d). This is equivalent to approximately 700 million barrels of oil (BOE) per year. Figure 4 breaks out these values by region of the world. (Source: World Bank report)

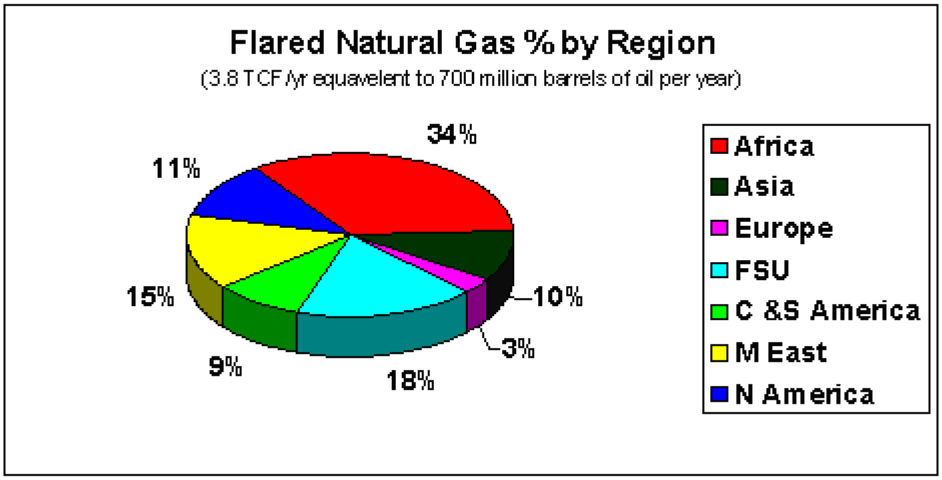


Figure 4

Gas flaring is gaining an increasingly bad name because of the severe impact on green house gas (GHG) emissions. In some countries, particularly Nigeria, flaring past a given date will bring economic penalties such that the natural gas resource will have negative values, dramatically improving the economics of most GTL programs.

Stranded Gas – Net Present Value of Zero

Total world gas reserves of 6,205 TCF, equivalent to 1,105 billion BOE, (Figure 5) are on a par with estimated world oil reserves of 1,147 billion barrels. However, the Former Soviet Union (FSU) and the Middle East account for over 70% of world reserves of natural gas (32.1% - 40.8%) and crude oil (7.6% - 63.3%) respectively. (Source 2004 BP Statistical Review) Once the development and production costs of the reserves can be covered, not producing these gas reserves can have a negative value.

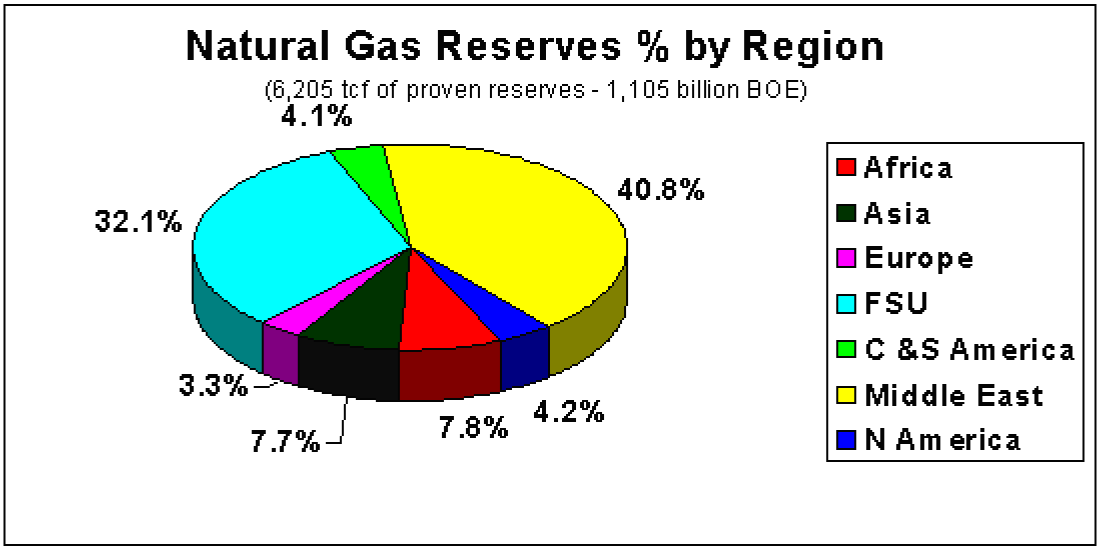


Figure 5

The GTL majors, Sasol and Shell are swamped with requests to build GTL plants adjacent to big fields in Russia, Qatar, Iran and the FSU. Engineering companies are challenged to find the necessary manpower to design and build both large and small scale projects. As more and more GTL plants come on line the available pool of engineers, process designers, plant operators will grow exponentially so that smaller EPC companies can provide expertise for smaller GTL projects across the world. The same holds true for F-T plants relying on coal and bio-mass for their feed stocks

From a GTL refining point of view, 10.4 bcf/d of flared natural gas would make approximately 1.2 million barrels per day of finished products or 420 million barrels per year. In addition, a GTL plant generates enormous quantities of waste heat and can produce large quantities of steam-derived electricity, so the conversion efficiency is improved, thermally speaking. This was pointed out in the Sasol "Optimized F-T GTL Plant" shown in Figure 2 where Sasol achieved a 20% increase in thermal efficiency in just 5 years. We need to keep in mind that early crude oil refineries were not very efficient and, with time, advances in technology improved the crude oil refinery conversion efficiency. The same will happen with GTL refineries when more are built.

Keep in mind that the first step of the GTL process, syn-gas generation, is used in many processes ranging from fertilizer, methanol and specialty chemical production to electric generation in IGCC power plants. A good example of improvements in efficiency over time is that of combined cycle electric generation. In the early 1970s the best plants were around 45%, which in itself was a major improvement over coal/steam electric generation at 30%. By early 2002, efficiencies of CCGT plants were 60% or better. We would expect similar improvements in the F-T process over the next 30 years.

There are dozens of commercial companies providing syn-gas generation technologies across the world that are looking for an edge to sell their technology. Each company is driving to develop a lower capital cost and more efficient process to market to new projects developed each year. The same goes for the hydrocracking process, as advances in design, catalyst selectivity and life can be applied in hundreds of existing refineries across the world and future GTL plants. Advances in these areas will continue each year. They will be small steps, saving a few million dollars or a percent of operating cost, or improving process efficiency.

For large-scale plants, the savings or improvements are welcome but few developers are looking at small plant designs. Still, the biggest challenge that lies ahead for GTL technology developers is process integration or the combining of all three steps to make an energy efficient process. Here is the one place smaller GTL plant technology providers may have an edge.

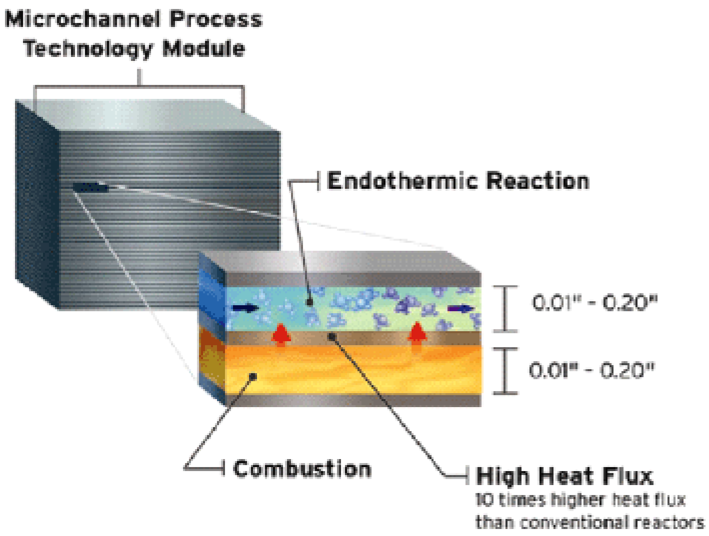
FISCHER- TROPSCH NEW TECHNOLOGY

From a technology viewpoint, the areas of maximum impact on profitability are Efficiency of Conversion (Energy and Carbon) and Capital Cost, especially as they relate to smaller GTL plant applications.

FT will always be a three-step program where a syn-gas (H_2 + CO) is generated from a carbon bearing gas or solid; the syn-gas is then reacted with a catalyst in the F-T reactor to make long-chain hydrocarbon molecules (waxes) and then is split into shorter-length hydrocarbon molecules (diesel, naphtha, kerosene to name three) in a hydrocracking or product workup stage that is almost identical to crude oil refining. The capital cost allocation of each step is generally 50% for the syn-gas generation (step one); 30% for the F-T reaction, (step two); and 20% for the product workup (step three.) Like all crude oil refineries, (step three), product workup is the most advanced, the most efficient and likely to have the least chance of major improvements in capital cost reduction, process efficiency improvements or operating cost reductions. The one advantage that F-T hydrocracking has over crude oil is that the long chain F-T molecule is very easy to crack, requiring lower temperatures and pressures. In addition, while hydrocracking, the product can be isomerised to improve cold flow properties before sending the hydrocarbon to the refinery distillation tower for fractionation. Thus F-T product workup will be a little more efficient and have a lower operating cost than its crude oil cousin. While process integration, the efficient combining of all three steps, is a major challenge for F-T technology providers, advances in the first two steps will result in step changes in costs, carbon conversion, thermal and process efficiencies.

One thing should be pointed out with respect to the F-T/GTL process; the heat required to initiate a chemical reaction; the pressure at which the reaction occurs; the heat given off by a chemical reaction; the water or steam required for a reaction or that will result from a reaction is no different for a 200 bbl/d plant or a 75,000 bbl/d plant. The only difference is the amount required, or given off. The type of catalyst required driving the reaction, and the pressure or temperature at which it occurs remains the same. Thus the ancillary equipment required to support the F-T/GTL process has the same operating requirements.

Large pumps, heat exchangers, steam generators and catalyst charges are required for many different processes across the world and are supplied by many competitors at commercial prices. One-of-a-kind or very small specialized equipment is costly. Space, military and airplane parts are examples of limited market, expensive to manufacture equipment *(we have all heard of the $600 toilet seat)*. Small GTL plants will be in this category, making it difficult to justify in a commercial economic setting.



Some new and innovative F-T technologies are looking at major reductions in the capital cost of the syn-gas generation step. One is the Air Products-led consortium looking at ceramic membranes which aim to create syn-gas for one half the current capital costs. Still others, like GTL Microsolutions and Velocys, a commercial arm of Battelle, are combining step one and two using microchannels; a very interesting and promising new technology reminiscent of the 1960s improvements-gain in the semiconductor industry. Here the F-T process is carried out in thousands of identical miniature process channels bolted together to provide a desired output.

To the left is a pictorial of a microchannel process. The more “plates” we bolt together, the more natural gas we reform to syn-gas, and the more F-T hydrocarbons are formed in the second step. This design concept may have the advantage of being able to scale up or down to meet the feed stock and/or market requirements of the area.

GTL-in-a-Can – a one stop process

Still yet another company, TIAX, is proposing to combine all three GTL steps in one process, called "GTL-in-a-Can". Some, like the TIAX process are still paper proposals; others like the Velocys program, illustrated here actually have operating pilot plants. Other innovators are working on improvements in catalyst design, catalyst reactivity and life; some are looking at heat transfer issues in the F-T reactor. One thing all have in common is a great deal of secrecy associated with their technology and for the most part, little capital to prove up the technology.

For the remainder of this paper we will look at those technologies designed to reduce the size of the natural gas-based F-T plant while not sacrificing the economics of scale. I would point out that even the so called "small" GTL technology providers are looking at 5,000 to 10,000 barrel-per-day plants (1000 bbl/d modules) with economics in the $30,000 per installed barrel range as the target. Plants ranging from 200 to 500 bbl/d are not the focus. However, developing plants for mission specific projects such as a battlefield F-T fuel module will help reduce the costs of the large-scale targets. Of the technologies looked at, only the microchannel technology lends itself to scalability, to downsize by removing "plates" from the module. However, total unit installed costs will still rise dramatically as size drops.

Abundant supplies of natural gas in remote and off-shore locations cannot be cost-effectively brought to market. Conversion of natural gas to liquids (GTL) has been a technology development goal for more than two decades as a means of capitalizing on this resource. Numerous processes have been developed and demonstrated on a relatively small scale, but Sasol's Synthol plants at Secunda, Sasolburg and Mossel Bay, South Africa and Shell's SMDS plant in Indonesia remain the only large commercial CTL and GTL plants. Widespread adoption of the various GTL processes continues to be limited by economic uncertainties, including fluctuating oil and gas prices, the cost of capital and technical risks in a fast-developing field.

Many more gas fields can be open to exploitation with a smaller plant, including gas associated with offshore platforms. Applications that can be exploited by the military for mission specific purposes can help reduce technology development costs and provide markets for smaller ancillary equipment, reducing the overall cost of new technology for civilian (commercial) applications. A GTL technology that achieves the economics of the large-scale 50,000 bbl/d plants at a 500 bbl/d scale would permit new companies to enter the GTL market. Military commercialization of small plant technology permits time for leading edge technology to advance and mature, providing operational experience, and a market for critical plant equipment manufacture, all further reducing costs for civilian projects.

Microchannel Process Technology

One of the most promising technologies is Microchannel Process Technology (MPT). Due to its modular nature, MPT scales down well and can reduce costs below those of conventional processes at all scales. While there are several ongoing MPT programs, two of the most public are the Velocys and GTL Microsystems programs. Both are pursuing programs that generate syn-gas and the F-T hydrocarbon but are initially relying on third party technology to make a finished F-T diesel fuel. However, Velocys was just awarded a DOE grant to carry the process through its final step and make a finished F-T fuel. A spokesperson for Velocys said the company hopes to validate this new program within five years.

The F-T process, upgrading natural gas to diesel fuel includes three steps: 1. Converting natural gas to synthesis gas (syngas); step 2. Upgrading the syngas to hydrocarbon liquids; and step 3. Hydrocracking the liquids to give the desired product mixture. Options for natural gas upgrading include steam reforming, partial oxidation, or a combination of the two, such as autothermal reforming. While each of the syn-gas generation processes has various advantages, the steam reforming process lends itself to significant process improvements and precludes the construction of a capital and energy intensive oxygen plant. This is similar to the Syntroleum concept of gas reforming except the MPT uses only steam and doesn't suffer the process inefficiencies and extra capital costs associated with using air, which introduces inert gases like nitrogen into the process.

In the MPT process natural gas and steam are converted in a first stage reactor heated by the combustion of fuel gas and waste heat from the F-T process - which is very exothermic. The ratio of H_2 and CO in the resulting syngas is adjusted to the desired ratio by separation in a membrane, providing some of the fuel gas for the reformer and an H_2 stream for use in the third step, hydrocracking.

The H_2/CO syngas is fed to an F-T reactor, where it reacts to form hydrocarbons and water while the heat is removed by producing steam for the first stage reformer or electric generation. The wax F-T products are then hydrocracked to produce high quality, clean diesel fuel or other specialty chemical products.

One of the biggest advantages of MPT is that unlike many hydrocarbon process technologies it does not have to be vertical and it is unaffected by motion. The MPT process can be laid out in any format allowing for horizontal modules (multiples of containers arranged end-to-end or side-by-side) and since the process is unaffected by movement it can be used for ship, spar, TLP and FPSO applications in unprotected waters. It also has a tremendous advantage when used in a hostile military environment in that if a portion of the plant is damaged, the unit can be replaced with a new module or blocked off to put the plant back in service in short order.

Both MPT providers that were willing to discuss their technology are hopeful for an installed cost in the \$24K to \$30K per barrel of capacity plus product workup costs. As far as we can determine, these costs did not include ancillary equipment costs. MPT providers will freely tell you that their goals are 10,000 bbl/d plants to take advantage of the modular design and mass production cost savings of the microchannel design. When you compare them to Sasol's total cost to engineer, design, build and place in-service target of between $16k to $22k per installed barrel, these mini-GTL plants will be expensive.

GTL-in-a-Can

TIAX's concept to put all three F-T steps in one vessel is a novel approach and if it works can revolutionize the GTL industry. However, unlike MPT which has a very large chemical industry interested in its process, GTL-in-a-Can is geared towards one industry (gas) and this industry believes "bigger is better." Without a bench scale plant to show a technology can be transferred from paper to plant, this technology appears to be off in the distance. The flow diagram of the process shows air introduced to the process in the reforming step, gas clean up prior to the "CAN" and the cracking of the $C+_5$ hydrocarbons outside of the process "CAN". In effect, this places it along-side the MPT process in that two steps will be combined in the new technology and the product workup will be accomplished via other commercial means. Given the projected costs of $25,000 to $50,000/bbl per installed barrel costs (does this exclude product workup? – No one is saying) the only advantage may be in size or foot print.

While there are references to industry and university GTL research programs plus other forms of MPT work ongoing, none has sufficient public reporting to provide comments here.

There are however, several programs that are addressing syn-gas generation that show promise of reducing the costs of natural gas based F-T.

Syn-Gas generation

Syn-gas generation represents half of the GTL complex Capex costs. The greatest step changes in the GTL process are anticipated to occur in this critical step because in addition to F-T, syn-gas is the building block for the majority of chemical and petrochemical processes across the world.

Another form of microchannel technology is the Air Products/DOE led consortium looking at ceramic membranes or Ion Transport Membranes (ITM) to reduce the cost of making syn-gas from methane and oxygen. The ITM process consists of methane (CH_4), steam (H_2O) and oxygen (O_2) chemically combined to form CO and H_2 without the expense of building an air separation (O_2) plant. *Figure 6* below provides a flow diagram of the process and a picture of a ceramic membrane. The ITM process is in the middle of a 10 year development program with commercial demonstration scheduled for the 2008-09 time period. Once commercialized, the ITM process can save up to 50% of the cost of reforming or 25% of the total capital cost of the GTL process.

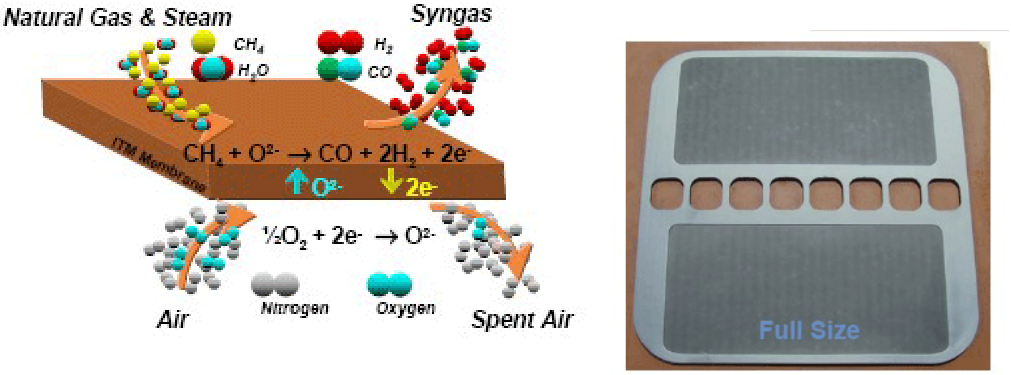


Figure 6

The ITM process will also lend itself well to the modular concept, creating reforming modules that can be mass produced in central manufacturing plants, reducing costs and will provide great flexibility in plant size for field applications.

The technology is well proven; the problem has been the manufacturing of commercial size membranes for plant sizes in the 100 million cubic foot per day range. In discussions with Air Products, the demonstration size ITM currently in the final phase of testing may be ideal for the small natural gas based F-T plants (under 10 million cubic foot per day – 1,000 bbl/d) that are the focus of this paper. There is an industry group, consisting of several of the same companies working with Air Products that is also pursuing similar ITM technology. Their findings have not been made public but we know that they are making similar progress.

Compact reformer design

Several leading companies are investigating technology that would reduce the size (foot print) and cost of traditional natural gas reforming. Each is following paths that will result in step-changes in the reforming area. Of this group, the most public has been a joint venture with BP and Davy/Kvaerner. The BP/Davy compact reformer as it has become know as was first demonstrated at the BP Nikiski, Alaska GTL test site in 2002. The radical design results in a reformer foot print of less than 30% of a normal steam gas reformer. Statements in the public domain indicate that the purpose of this design was to be used in offshore production areas to reduce or eliminate natural gas flaring/venting. No public release has been made on the reduction in cost for the compact reformer but one obvious cost savings is that it does not require an oxygen (air separation) plant which usually represents 1/3 of the gas reforming costs. Weighing in at over 3,000 tons for the 300 bbl/d test facility, it is lighter than a similar sized gas reformer by some 75%, can be manufactured in a central plant and delivered to the GTL site unlike typical steam methane reformers that usually have to be constructed on site. But it is not, nor was it ever intended to be field portable. BP/Davy's goal is a 1000 bbl/d compact reformer module that can be added in parallel to support 30,000 bbl/d + GTL plants. According to Davy, there are no plans to look at smaller applications.

Plasma Arc technology shows some promise for converting methane into syn-gas. But it requires large amounts of electrical energy making it questionable for any remote location syn-gas generation programs and certainly not suitable for field portable or mobile applications like ships.

There are numerous companies in the syn-gas generation field that are working on improvements in their current designs, catalysts and combinations of technologies that will reduce overall Capex costs and improve efficiencies. However, none of these companies to the best of our knowledge are focusing on small gas reformer technology and are not part of this paper. Advances in large scale reformer technology will find their way to smaller applications but it is our belief that microchannel, whether through the MPT or ITM route will result in the step-change in cost and efficiency that mini-GTL plants will need to compete effectively for smaller packages of stranded gas.

Catalysts

In the early days of F-T, iron-based catalysts were the most used, primarily because coal was the feed stock of choice. Early experimentation with cobalt showed improved selectivity and reduced CO_2 generation. Catalyst life was limited and early designs were expensive to produce. When Sasol first chose to commercialize its slurry phase F-T program for natural gas, catalyst life before regeneration was at most one year. Today with advances in formulation and design, life expectancy is 3 or more years with the goal of 5 years by 2006. Other GTL providers have stated similar expectations for their unique catalyst formulations and designs. This has reduced the operations and maintenance costs of the gas based GTL plants considerably. Coal or bio-mass-based F-T plants for the most part still use iron-based catalysts, but with catalyst life expectancies of 30 to 90 days they still have a long way to go.

Catalysts are involved in all three steps of the F-T process. Advances in the oxygen transfer ceramic membrane reformer (ITM) process will further reduce operating costs by eliminating catalysts in the gas reformer. The MPT program promises catalyst integration with very high selectively and conversion ratios 3 to 5 times greater than in conventional F-T reactor designs.

Figure 7

Figure 7 above illustrates the differences in catalysts for conventional reforming and F-T plants, on the left with catalyst size measuring in centimeters and for the microchannel syn-gas and F-T hydrocarbon applications on the right measuring in millimeters. The smaller catalysts associated with the microchannel technology provides much more surface area to drive the reaction of making syn-gas or the F-T hydrocarbon chains.

THE WORLD HAS STRANDED/FLARED GAS FOR F-T DEVELOPMENT

WHAT CAN BE DONE TO DEVELOP F-T IN THE U.S.?

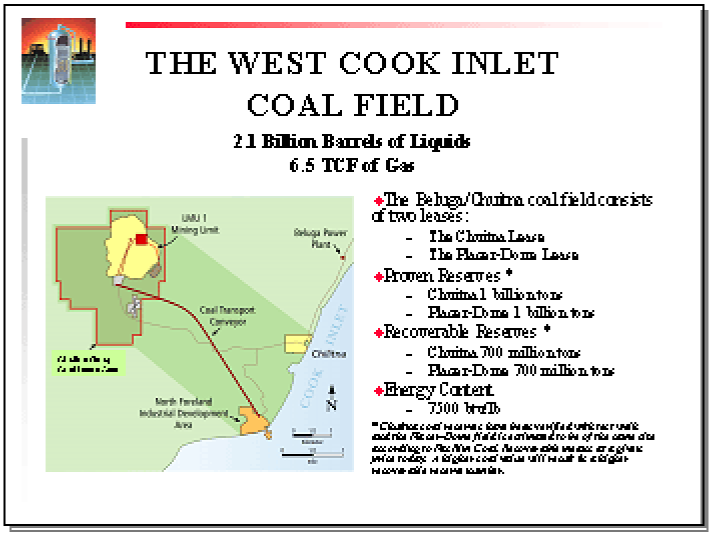
LIQUID RESERVES FROM COAL AND BIO-MASS IN THE U.S.

Beginning in the late 1990s virtually all F-T developers have focused on flared gas and large gas reservoirs across the world as feed stock for gas based F-T plants, the “G” in GTL’s. With the exception of Alaska’s stranded North Slope gas reserves, the U.S. has no giant stranded gas field waiting for a GTL program to develop it. Until someone develops a technology to extract the vast reserves of hydrates locked in our frozen north or in deep offshore pools, coal and bio-mass are the only carbon based materials available to supply large scale U.S. based, domestic F-T plants. Having the resources is one thing; being able to convert them into an economic transportation fuel is another.

COAL – THE U.S. SAUDI-SIZED NATURAL RESOURCE

It is estimated that the U.S. has over 250 billion tons of recoverable coal reserves. Using a typical conversion ratio of two barrels of F-T from one ton of coal, the **U.S. has approximately 500 billion barrels of F-T fuels** or almost 50% of known world’s oil reserves. CTL in the U.S. can have a significant impact on imported crude oil if we want it to.

Certainly from a military fuel supply point of view, a U.S. CTL program should be attractive.



THE WEST COOK INLET COAL FIELD

2.1 Billion Barrels of Liquids
6.5 TCF of Gas

- The Beluga/Chuitna coal field consists of two leases:
  - The Chuitna Lease
  - The Placer-Dome Lease
- Proven Reserves *
  - Chuitna 1 billion tons
  - Placer-Dome 1 billion tons
- Recoverable Reserves *
  - Chuitna 700 million tons
  - Placer-Dome 700 million tons
- Energy Content
  - 7500 btu/lb

As an example, Alaska has a "small" coal field in the Cook Inlet 40 miles south west of Anchorage called Beluga, see Figure 8. This west Cook Inlet Beluga area coal field has approximately 1.4 billion tons of proven recoverable subbituminous coal or the equivalent of 2.1 billion barrels of liquids. Using the Sasol F-T thermal conversion efficiency of 65% shown in Figure 2, that means that 35% of the thermal energy in the coal, if captured, can be converted into the same btu energy content as 6.5 tcf of natural gas. A 2.1 billion barrel oil field is the second largest oil field in the U.S. behind Prudhoe Bay and 6.5 TCF is the largest gas field ever found in the Cook Inlet and 20% of the proven gas reserves on the North Slope. ***The Beluga coal field is a significant Alaskan energy resource that should not be over looked.*** Multiply this across the U.S. and you can quickly see how coal can fill the gap between U.S. oil production and product demand. We will touch on ways the federal government can help make CTL and BTL economically attractive in the U.S. later in this paper.

F-T Fuels Economics for the World and the U.S.

There is no question that F-T technology works with over 250,000 barrels per day of F-T plants operating in the world today and another 500,000 barrels per day under construction or in the final design phase. It is a **PROVEN** concept.

There is no question that F-T transport fuels are compatible with the existing motor fuels market and infrastructure with over 40 billion gallons sold to date throughout the world. It's **COMMERCIALY** proven.

No new refinery (crude oil or alternative fuel) built in the U.S. can recover its capital cost (CAPEX) if it has to sell its "new cleaner fuels" at the same price as "conventional fuels".

NEW REFINERIES, whether or not they are crude oil or GTL based, will need an economic boost or incentive to compete in the U.S. This is not the case in Europe or Asia where F-T diesel sells for a premium over even low sulfur diesel.

The question is then, "CAN F-T FUELS BE ECONOMIC"? If the measure of economics is price at a U.S. fuel pump, the answer is generally no. However, as the price of crude oil continues to rise at some point the cost of manufacture of F-T fuels will equal that of crude-based transportation fuels. Environmental issues, reducing a nation's dependence on imported crude oil are two factors that will favorably affect the economics of F-T fuels across the world.

There are generally three economic drivers that impact the real cost of U.S. transportation fuels outside of the basic cost of crude oil feed stock. They are:

- Strategic, the need to maintain a military presence in the Middle East to insure the free flow of oil to the world. We refer to this as a *Security Premium*.
- Shortfall in U.S. Refining Capacity (fuel availability). We refer to this as a *Refining Capacity Penalty*.
- Environmental - Lower Emissions + CAFÉ Levels (Clean Cities Programs - lower GHG emissions & better fuel mileage). We refer to this as the *Engine Emission and Efficiency Costs*.

The problem in the US is that many factors are at play that affect overall economics of fuel at the pump. There are the hidden costs of our national energy policy that are not apparent at the fuel pump but do cost us as tax paying citizens – the *Security Premium*. There are costs we see at the fuel pump each driving season that as individuals we have no control over – the *Refining Capacity Penalty*. New alternative fuel refineries (F-T) plants cost tremendous amounts to build as they are more like chemical plants instead of crude oil refineries. If new environmental laws require crude oil refineries to make fuels as clean as F-T, then F-T plants could be competitive. If the U.S. charged a premium for importing oil or gave credits for refineries that reduced U.S. dependence on imported crude, F-T plants could be competitive. If the U.S. charged a tax for importing gasoline and diesel, refineries would be built in the U.S. making new F-T refineries competitive.

As individuals there is little we can do to control our fuel costs except buy more fuel efficient vehicles - *Engine Emission and Efficiency Costs*. However, there are two areas where the Federal Government can help promote new alternative fuel refineries in the U.S.

Strategic

The National Defense Council Foundation has performed a very detailed study of the "Cost of Imported Oil" including other factors such as loss of jobs showing that as consumers we pay a *Security Premium* approaching $2.00/gallon. Years ago the government estimated this number to be 50¢/gallon. We currently use approximately 12 million barrels per day of gasoline and diesel in the U.S., using the lower figure of 50¢/gallon this *Security Premium* cost is approaching $92 billion per year - *$368 billion at $2/gallon.*

Shortfall in US Refining Capacity

The U.S. currently has a 3 million barrel per day refining capacity shortfall. This means that each driving season U.S. refineries cannot make enough gasoline and diesel to supply motor fuels demand. They raise the price at the fuel pump to cause "economic conservation." It is estimated that the lack of U.S. refining capacity, costs the US consumer ~ 25¢/gallon for 3 months or about $11 billion per year - *Refining Capacity Penalty*.

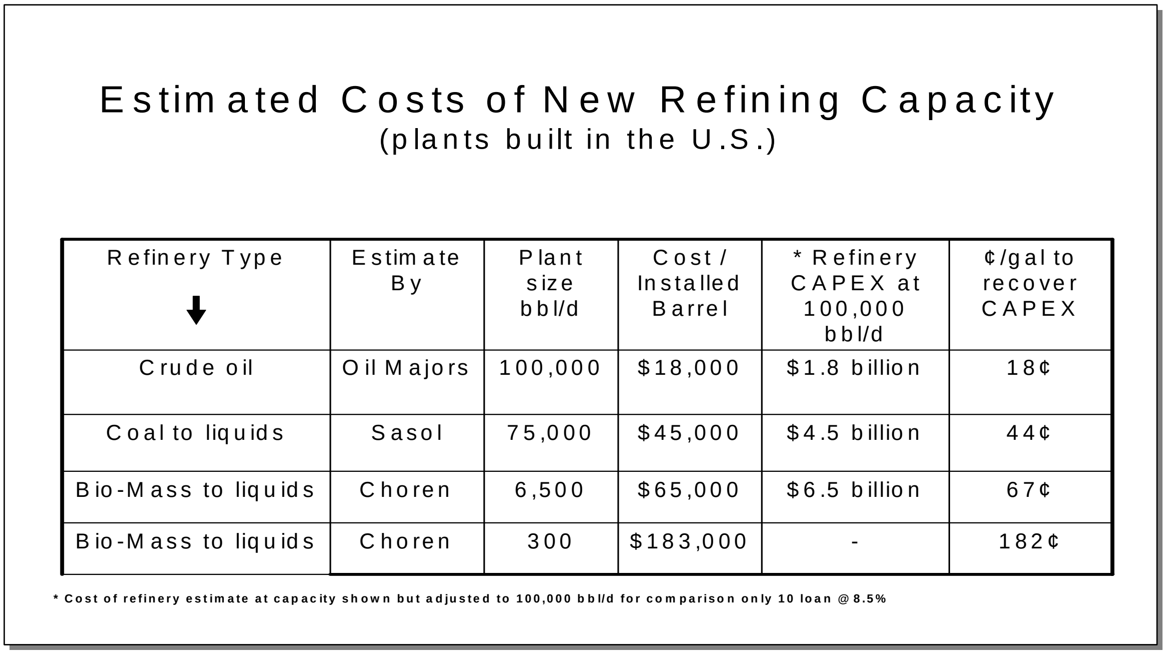
Crude oil refiners have no incentive to eliminate this refining capacity short fall as they would lose this annual windfall, plus they will claim there is no way to recover the capital cost of the new refinery if they are selling motor fuels at the same price as other refiners. Most refiners will say it is cheaper to import gasoline than to build new refineries in the U.S. In addition because Europe has a higher CAFÉ standard and cleaner diesel, most European refiners are struggling to meet diesel demands but are awash in gasoline, which they export to the U.S. A refining shortfall in the U.S. provides a home for their excess gasoline supplies in Europe.

It is estimated that if the U.S. was to institute CAFÉ standards similar to Europe, the American consumer through better mileage would save over 1.4 million barrels per day of gasoline; resulting in a fuel savings of over $35 billion dollars each year. Like in Europe, diesel would become the preferred transport fuel because diesel engines are more efficient and generally diesel vehicles get 25% to 30% better mileage than similar gasoline powered vehicles.

By instituting a tax credit or energy credit to build new refineries the federal government can reduce the refining capacity shortfall, eventually reducing the annual price fly-up seen at the pump each driving season. Who benefits? The American consumer, with lower fuel pump prices and more efficient, higher-mileage vehicles. Who loses? The traditional crude oil refiner.

Table 1 below illustrates the price needed for products from a new refinery above today's fuel prices to recover the capital cost of the refinery. As we can see even a crude oil refinery will need a higher price for its gasoline and diesel if it is to recover its capital investment. Smaller-size coal and bio-mass F-T plants will need an even higher price. However, their gasoline and diesel F-T fuel is of much better quality. Environmental rules affecting crude-based fuels can add more costs to a crude oil refinery closing the gap. As the price of crude oil continues to rise and the price of coal and bio-mass (F-T plant feed stocks) remains stable, BTL and CTL plants will become more competitive.

Conversely, crude oil prices can drop, making BTL and CTL less competitive. This has been the traditional way oil producing nations have stopped alternative fuel programs in the past. Whether world demand for crude has outstripped the ability of oil producers to produce excess crude is the big question today.



Estimated Costs of New Refining Capacity

(plants built in the U.S.)

Refinery Type ↓	Estimate By	Plant size bbl/d	Cost / Installed Barrel	* Refinery CAPEX at 100,000 bbl/d	¢/gal to recover CAPEX
Crude oil	Oil Majors	100,000	$18,000	$1.8 billion	18¢
Coal to liquids	Sasol	75,000	$45,000	$4.5 billion	44¢
Bio-Mass to liquids	Choren	6,500	$65,000	$6.5 billion	67¢
Bio-Mass to liquids	Choren	300	$183,000	-	182¢

* Cost of refinery estimate at capacity shown but adjusted to 100,000 bbl/d for comparison only 10 loan @8.5%

A recent quote regarding the Sasol CTL plants built in South Africa said "*Sasol's Secunda CTL Plant: Costly To Build, But Now It's A Cash Cow*". Once the capital costs of U.S. built F-T plant are recovered, American BTL and CTL plants can be competitive well below today's price of crude oil.

DIFFERENT WAYS FOR THE U.S. TO SUPPORT ALTERNATIVE FUELS

Support for alternative fuels in the U.S. is really about reducing the cost of the "new" fuel to be competitive with existing fuels. It's not about the technology even though we expect improvements in process and conversion efficiency. Unlike European consumers, the typical American consumer will not pay a higher price for a cleaner fuel unless he is legislated to do so. As a result programs that reduce the cost of new fuels or tax the new fuel at a much lower rate so the pump price appears the same will create the largest demand for the new fuel and the greatest interest from the industry.

Europe is years ahead of America when it comes to support for cleaner fuels, alternative energy and non-petroleum fuels. As a consequence, many alternative fuel developers are focusing on non-U.S. projects. With a limited amount of qualified engineering, construction and manufacturing facilities capable of developing new alternative fuel programs across the world, the U.S. needs to develop programs to attract them to projects in America.

There are several options available to the federal government that can cause an alternative fuel program to grow in the U.S. It makes sense to provide these incentives on a federal level as each "new" refinery built in the U.S. reduces the amount of crude oil imported to the U.S. – a Security Benefit - and reduces the refining capacity short fall and corresponding annual price fly-up at the fuel pump - *Refining Capacity Penalty*. These benefits will be seen across the country. Even if an alternative fuel plant is built in Wyoming, Kansas Iowa, Alaska or Mississippi, it is best dealt with on a federal level. Examples of support are:

- Legislation
- Government Grants
- Government Loan Guarantees
- Low Interest Loans
- Fuels Purchase Agreement
- Tax Credits
- Motor Fuels Excise Tax Reductions
- Energy Credits

Legislation

Historically, Congress has passed legislation to reduce engine emissions creating an economic pathway for alternative fuels. As an example, the 1992, EPACT established emission reduction levels for certain size fleets and cities. Individual companies and municipalities were forced to invest in new technologies or special fuels on a case by case basis. While creating a demand for alternative fuel programs the volumes were generally too small and the cost too high to cause major changes in demand. In general, legislation that focuses on a small segment of the motor fuels market doesn't serve the entire country. In contrast, legislation that requires changes across the industry can stimulate the alternative fuel programs and have a positive impact in reducing emissions, increasing fuel economy and reducing U.S. dependence on imported crude oil.

Government Grants

A second generally accepted form of government support is a grant, generally small in size, applied to a specific company or for a unique process. Typically the grant is upfront but in general it advances the alternative fuels market one small step at a time because the industry at large does not benefit. If it takes approval of the DOE/DOE or Congress, those not in the lead for the grant will lobby against it. Also there is no guarantee that a successful process will result from the grant. One advantage of grants is that in general they are small, one-time and easier to get approved than a multi-year, multi-billion dollars subsidy. Another advantage is that once given a grant can't be taken away or reduced by future government action.

Government Loan Guarantees

Government loan guarantees are not that common as they usually involve large sums of money which means Congressional approval is required. Loan guarantees also means the government is taking the risk that the technology will work and that the project developer can actually build a successful project. Like a grant, a loan guarantee applies to one project, one developer, one technology and in general does not advance the industry at large. In addition to technology risk, the government also takes a risk that the market projections of the developer are correct. A classic example of this is the Great Plains Coal Gasification plant built in the late 1970's in North Dakota. While the technology worked and the project was successfully built and operated, the economics of the project depended upon natural gas prices being $6/mmbtu or higher. The developers were wrong, the market price collapsed shortly after the plant was built and the government was forced to take over the project. Today, some 25 years later the plant is a successful venture for its new owners but the government lost more than a billion dollars. One advantage, like a grant, is that once given a government loan guarantee can't be taken away or reduced by future government action.

Low Interest Loans

Low interest loans are attractive when the cost of money is 12%, 15% or greater, as in the 1980s. But with today's commercial rates in the 7% range, a lower rate in the 4% range isn't going to save a project much money. An advantage is that once given it can't be taken away or reduced by future government action. Like a grant or loan guarantee, a low interest loan generally applies to one project, one technology, one developer and will in general not advance alternative fuels programs across-the-board.

Fuels Purchase Agreement

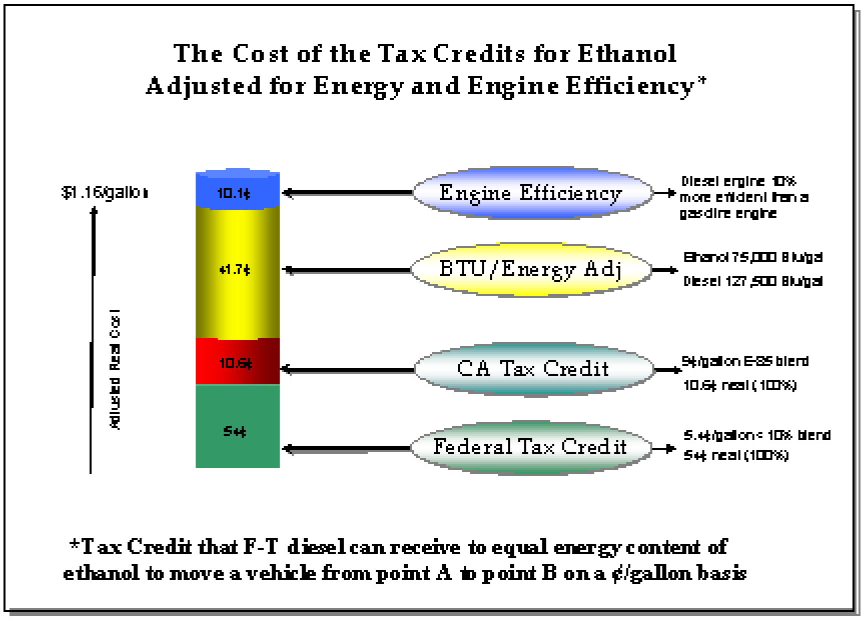
When developing a project the lender will always assign risk to the market price and the market's willingness to purchase the full plant output at the market price. Having a long-term fuels purchase agreement from a qualified buyer will reduce this risk. It also puts the risk of project development and technology on the developer. If the plant can't deliver the finished product to specifications, the fuels purchaser has to find a new supplier but is not out millions of dollars guaranteeing a project. A fuels purchase agreement is, however, similar to a grant, low interest loan and government loan guarantee in that it applies to one project, one technology and one developer. Again it will not advance the industry in general. One advantage again is that once given a fuels purchase agreement can't be taken away or reduced by future government action during the contract term.

Tax Credits

Tax credits are not that common or sought after by industry because it requires one to be very profitable, earn large amounts of pre-tax income to take advantage of a tax credit. In general the larger the plant the greater potential for income and the lower the unit cost of the "alternative" fuel. The smaller the project the higher the unit cost, the more support needed and generally the lower pre-tax income available to offset a credit. Smaller plants bring greater industry participation in terms of numbers of firms; larger plants limit development to all but the largest developers. A disadvantage is that once given, a tax credit can be taken away or reduced by future government action.

Motor Fuels Excise Tax Reductions

Probably the most common form of economic support for alternative fuels is the motor fuels excise tax reduction. Virtually all motor fuels are taxed at the fuel pump by federal, state and local governments. This tax can be as high as 50¢/gallon at the point of sale. By reducing the tax on a particular fuel the fuel manufacturer gets to sell the new fuel at the pump at the same price so the consumer is indifferent; and the fuel manufacturer keeps the difference. This works especially well when the new fuel is actually a blend. As an example:



The Cost of the Tax Credits for Ethanol Adjusted for Energy and Engine Efficiency*

*Tax Credit that F-T diesel can receive to equal energy content of ethanol to move a vehicle from point A to point B on a ¢/gallon basis

Gasohol is actually a blend of 1 gallon of ethanol and 9 gallons of gasoline. The excise tax reduction for gasohol is 5.4¢/gallon. While the apparent 5.4¢/gallon is insufficient to offset the higher manufacturing, transport, storage and delivery costs of this new fuel, the real value of the tax reduction is 54¢/gallon for the ethanol, which is sufficient. The American consumer sees the same price at the pump and is happy. Congress sees a 5.4¢/gallon tax reduction and believes it is small while the industry receives a refund of 54¢/gallon of ethanol and is happy.

Figure 9 to the left provides a good illustration of this apparent and true cost of an alternative fuel.

Another example is the reduced motor fuels tax for compressed natural gas (CNG) when used in a diesel engine. Currently the federal and state tax on crude oil based diesel in California is 43¢/gallon. The motor fuels tax for CNG is 11¢/gallon equivalent or 32¢/gallon - $13.40/bbl less. If this same tax rate were applied to natural gas based F-T diesel, this clean burning, zero sulfur F-T diesel would be attracted to this market. It is not, so the F-T diesel goes to Thailand where it enjoys a 7.5¢/gallon support.

One big advantage of the motor fuels excise tax program for the U.S. is that the government takes no risk in the technology or the development and operation of the fuels plant. If the manufacturer doesn't deliver the fuels to the consumer, he doesn't receive the credit. It places the development and technology risk where it should be, with the industry.

One disadvantage is that a motor fuel excise tax reduction applies only to markets that pay the tax. If you are trying to market your "new" fuel to a municipality or federal agency that does not pay the tax or only a portion of it, the tax reduction may not apply. Another disadvantage is that once given an excise tax reduction can be taken away or reduced by future government action. It is difficult to invest hundreds of millions or billions of dollars in an alternative fuels project if you are unsure the tax credit will be available three years down the road. Still another disadvantage is that each individual fuel group lobbies for support, placing the government in the position of trying to determine which fuel is best or which segment of the voting public has the strongest lobbying group.

Energy Credits

Energy credits are similar to a motor fuels excise tax reduction, have similar benefits and disadvantages except one. An energy credit provided to the fuel manufacturer doesn't care whether the market is a tax payer or not. Thus the fuel can be sold to any consumer and the government refunds the value of the energy credit to the manufacturer. Again a big advantage of the energy credit program like a motor fuels excise tax reduction is that the government takes no risk in the technology, the development and operation of the fuels plant. If the manufacturer doesn't deliver the fuels to the consumer, he doesn't receive the credit. It places the risk where it should be, with the industry. ***The big advantage is that an energy credit applies to all markets regardless if they pay tax on their fuels or not.***

A disadvantage again is that once given an energy credit can be taken away or reduced by future government action. *It is difficult to invest hundreds of millions or billions of dollars in an alternative fuels project if you are unsure the energy credit will be available years down the road.* Still again, another disadvantage is that each individual fuel group lobbies for support with the government.

There are numerous forms of legislation that support alternative fuel programs in the U.S. They all compete for funding and many are hidden in special legislation by special interest groups.

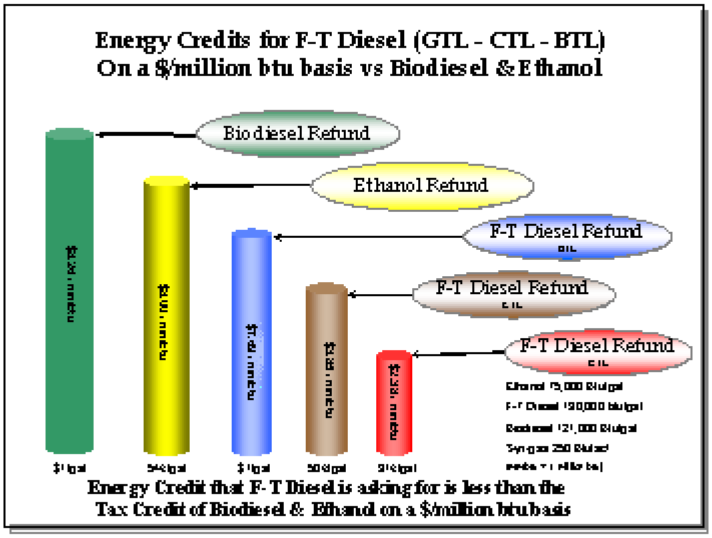


Figure 10

We believe there is a better way for the government to deal with all of these different and competing fuels programs.

F-T Fuels

By establishing an energy credit for F-T diesel produced in the U.S. from domestic resources the Federal Government could improve the economics of F-T plants throughout the Western U.S. F-T is one of the better alternative fuels for the U.S. because it can be integrated into the existing motor fuels infrastructure with minimal to no change required. F-T fuels can be used in blends from 1% to 100% with no adverse impact on the existing motor fuels infrastructure. F-T fuels appear to be the fuel of choice for the U.S. Military. Energy credits for F-T will attract the biggest and best F-T technology providers to the U.S., creating a big pool of domestic F-T for the military. Each gallon of F-T diesel produced and sold in America would reduce a gallon of imported fuel.

(See Figure 10) Virtually all alternative transport fuels in the U.S. except for F-T receive some form of federal / state economic support. F-T diesel is the one “alternative” fuel that will work in Alaska’s harsh winter environment, the desert southwest or New England and still meet EPA fuel specifications. By giving F-T fuels a similar level of economic support that biodiesel and ethanol based gasohol receive; F-T plants can be economic throughout the U.S.

A Syn-Fuels Energy Credit for F-T diesel similar to ethanol, CNG, LPG, LNG & recently approved Biodiesel Tax Credit Program:

- BTL (bio-renewable to F-T diesel) “trees/crops”
    - 1 ¢/gal per % of blending – maximum of $1/gallon for 100%
- CTL (bio-mass to F-T diesel) “coal”
    - 1/2 ¢/gal per % of blending – maximum of 50¢/gallon for 100%
- GTL (natural gas to F-T diesel) “gas”
    - 32¢/gallon the same tax rate as CNG
- SYN-GAS (bio-renewable) “trees/crops”
    - $1/mscf (thousand standard cubic feet)

An Energy Credit Allows <u>Anyone</u> To Build New F-T Refining Capacity.

An energy credit established for F-T that provides a clear time-frame to develop and build an F-T plant but, more importantly a clear time period under which the fuel manufacturer can collect the energy credit will go a long way in attracting the most interest from both big and small F-T technology providers to the U.S.

An energy credit established for <u>all</u> alternative fuels, regardless of the type of process used to manufacture the fuel, will result in the greatest amount of interest from the industry to build new alternative fuels plants in the U.S. The market will decide which fuel is the best for the particular application, weeding out the worst technology from the best and attracting more efficient technology from F-T and other alternative fuel entrepreneurs.

Domestic Security Tax

Today alternative fuels are funded through a variety of tax (credit) measures, historically from the Federal Highway Trust Fund, but now from the General Fund. We believe the best way to fund an energy credit is to place a 5¢/gallon tax (*Domestic Security Tax*) on all motor fuels, on-road, off-road, marine and rail and place this money in an “alternative fuel pool” from which ALL alternative transportation fuels draw from. Based upon today’s diesel and gasoline sales, this account would receive approximately $15 billion dollars each year, considerably more money that the current credits provided for ethanol, methanol, biodiesel, CNG, LNG, LPG, propane and butane to name several now receive. Government can limit the size of the alternative fuel programs by limiting the amount of money that can be drawn out of the pool each year or dropping different alternative fuels from the support pool.

We do not believe alternative energy programs should be funded forever. Once the capital costs of the “refinery” are paid off the level of support should drop or be eliminated all together. For all of you readers who rolled your eyes in the back of your head and said” read my lips – no new taxes” it is important to note that you are not creating a “new” tax when you place a “Domestic Security” tax on gasoline and diesel. All you are doing is consolidating all the different alternative fuel funding mechanisms into one place and placing all alternative fuels under one program. In addition the 20¢ to 30¢/gallon price fly-up of spring 2005 has not reduced consumption so one could conclude that a 5¢/gallon tax that reduced the importation of crude and crude oil products would be acceptable to the American consumer.

Let government establish the level and duration of support each particular fuel should receive based upon its benefit for the economy, the environment and national security. Once determined, let the fuels industry decide the best way to produce these alternative fuels. When the alternative fuels are delivered to a consumer, then and only then, the alternative fuel manufacturer is paid from the “alternative fuel pool”.

As more and more alternative fuel plants are built in the U.S., the *Refining Capacity Penalty* will decrease and could actually create intense competition for market share in non peak driving times, further driving down the price at the fuel pump. As more alternative fuel refining capacity is added to the U.S., oil producing nations will see that the U.S. has the resolve to reduce its dependence on imported crude opening the door for negotiations and possible reductions in the U.S. military presence in the Middle East reducing the U.S. *Security Premium.* Each dollar saved is a dollar that offsets the *Domestic Security Tax.*

We believe an energy credit program such as this will provide a clear path forward for the industry. It is important that we begin as soon as possible as there is not an unlimited supply of qualified companies in the world today that can design, build and operate large sophisticated alternative fuel plants. Countries that provide economic support first will attract the best and most talented leaving countries who delay to choose from second and third tier companies.

MILITARY NEEDS

The military has a dual role in the future of fuels in the U.S. Foremost, it has to be concerned that the fuel to power its vast array of machines and aircraft is available in time of national need. Almost as important is the need to insure that the military's fuel of the future is environmentally friendly and can power the advanced high performance engines of the future.

As the refining capacity of the U.S. continues to decline, the amount and quality of the world's crude supply falls short of meeting world demand the U.S. military needs to attract domestic alternative fuel programs to the U.S. You can park your car in time of national crisis; you can't park your tank or ground your aircraft. In addition to supporting an energy credit, the military may want to create a program similar to its sea lift and air transport programs for U.S. built alternative fuel plants – a *U.S. Military Refining Assistance Program (MRAP)*.

By investing in alternative fuel plants that will produce fuels specific for the needs of the military, the military could reserve the right to call on the output of an alternative fuel refinery in time of national need. The co-funding (grant) or annual subsidy paid to the alternative fuel plant may be just the economic boost the new plant needs to be able to compete with existing refineries at a market price, while producing ultra clean fuels the military needs for its advanced fighting machines.

We believe combining both the energy credit and the U.S. Military Refining Assistance program will address the needs of both the military and the U.S. transport fuels consumer.

SUMMARY

Fischer-Tropsch fuels, many believe the “fuels of the future”, have been around for over 75 years but are just now beginning to gain prominence world wide. As the world deals with increased demand for crude oil, dwindling crude oil and natural gas reserves, almost equivalent to proven world oil reserves are being exploited to fill the gap. F-T technology, long the purview of major oil companies and Parastatals is attracting new companies in hopes of developing more efficient processes to convert the world’s stranded gas reserves into valuable transportation fuels and petrochemical feed stocks. Some of these new technologies are the result of hundreds of millions spent on R&D, others are innovative ways to modify existing processes and still others are the result of advances in other industries, applied to one or more of the F-T processes.

The general trend in the industry is for the conversion of natural gas into valuable liquids, (GTL) while a select few companies are looking into bio-mass feed stocks in an effort to produce bio-renewable fuels (BTL) and electric power. Both industries have the attitude that bigger is better, taking advantage of scale up lowering the cost of the large ancillary requirement for process water and gas treating, electric generation and power supply, products storage and loading facilities. Second generation GTL plants are under construction in Qatar with next-generation GTL facilities expected to show marked improvement in economies of scale and syn-gas generation beyond the general creep of improvements in machinery and catalyst design.

Syn-gas generation, the first step of the F-T process holds the biggest promise of cost reduction. Programs like the Air Products led consortium are a few years away from commercializing an exciting new technology called ceramic membranes that will reduce the CAPEX costs of an F-T plant by as much as 25%. Other companies are pursuing micro-channel technologies where the F-T process is carried out in thousands of identical process blocks. Similar to the advances in the semi conductor industry in the 1960s, micro-channel holds the promise of both large and small scale F-T plants based upon how many “blocks” you bolt together. While these new technologies will improve the economics of future F-T applications, they still suffer from the same issues as today’s GTL plant, the high capital cost of the supporting equipment and utilities. As a result the drive is towards “bigger is better” even for these new technologies.

Many under funded F-T technology entrepreneurs are trying to attract investment capital to prove up their “new” concept. We believe that once many GTL or F-T plants are built around the world and the public recognizes the value of F-T fuels, funding for different technologies will become common. We do not think spending limited resources on 20 different F-T technology or process improvements makes sense at this time. Spending dollars on proven F-T technology and building commercial scale F-T plants today will generate more interest from the public and create economic support for future F-T technologies.

Unfortunately for the U.S., it is not blessed with large volumes of stranded natural gas reserves. F-T programs based in the U.S. will have to use coal and bio-mass for its feed stock. Coal to liquids, CTL, the grand daddy of F-T, began the process in Germany in the 1930s and today helps South Africa supply 50% of its gasoline and diesel needs from domestic resources. The U.S. can do the same with its extensive coal reserves and its world leading farm producing regions.

The economics of producing new ultra clean environmentally sensitive fuels and selling them at the same price as crude based fuels will have to be addressed before F-T plants can be economically built in the U.S. The American consumer pays a hidden cost from 50¢/gallon to $2.00/gallon ($90 billion to $360 billion dollars per year) to maintain a military presence in the Middle East and each driving season an additional $10 billion to $12 billion dollars at the pump because we lack enough domestic refining capacity to meet U.S. demand.

Establishing a U.S. alternative fuels F-T program could go a long way in reducing these costs, both hidden and at the pump. Adding F-T fuels to existing economic support programs established for other alternative transportation fuels can reduce U.S. dependence on imported crude oil. F-T fuels can provide the U.S. military with a domestic source of fuel while meeting the mission specific fuel requirements of the next generation military combat vehicles, vessels and aircraft.

We believe F-T fuels are the future of a U.S. transport fuel system. They represent the cleanest transport fuels man has made and are totally compatible with the existing motor fuels transportation infrastructure. Once introduced to the American public, demand for F-T fuels will outstrip production creating, economic incentives for new F-T technologies and process improvements.

Comparison of Diesel-Engine Cold-Starting on Syntroleum S-2 and Conventional Diesel Fuels in a Refrigerated Test Cell

Final Report

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ABSTRACT

Under the Department of Energy's Ultra-Clean Transportation Fuels Program, Integrated Concepts and Research Corporation (ICRC) carried out the project titled, "Ultra-Clean Fischer-Tropsch (F-T) Fuels Production and Demonstration Project." As part of this project ICRC conducted a cold-starting evaluation utilizing a Detroit Diesel 50 Series engine inside a refrigerated test cell. The evaluation was conducted in a controlled environment to determine the engine's unassisted cold-start capabilities with Syntroleum F-T diesel fuel, which could be produced in a remote Alaskan small-footprint plant (SFP) for local use, and with conventional petroleum-derived fuels.

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EXECUTIVE SUMMARY

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) is the sponsor of an Ultra-Clean Fuels Production and Demonstration Program with Integrated Concepts and Research Corporation (ICRC) as the prime contractor and AVL Powertrain Engineering, Inc. as a principal subcontractor. Under this demonstration program Syntroleum Corporation has built a small footprint plant (SFP) to demonstrate Fischer-Tropsch (F-T) technology and produce ultra-clean diesel fuel from natural gas. The F-T fuel was evaluated for its unassisted cold starting characteristics alongside No. 1 and No. 2 diesel fuels in a Detroit Diesel Series 50 four-cylinder heavy-duty diesel bus engine in a refrigerated test cell at AVL Powertrain's test facility in Ann Arbor, MI.

The test engine was installed in a refrigerated test cell capable of cold soaking the engine to -36°C (-33°F). The engine was allowed to cold soak overnight at the test temperature. The stabilized temperature of the engine was tracked using the engine coolant temperature. The starting test consisted of the engine being cranked until start, or until 10 seconds had elapsed. If the engine failed to start the cranking procedure was repeated, after a 5 second interval, no more than two additional times. Since experience has shown that cold-starting behavior from one attempt to another of an engine/fuel combination at a particular low temperature cannot be predicted (or repeated) with absolute certainty, the test was designed to characterize the temperature range where the fuel and engine would begin to experience difficulty in starting and finally fail to start.

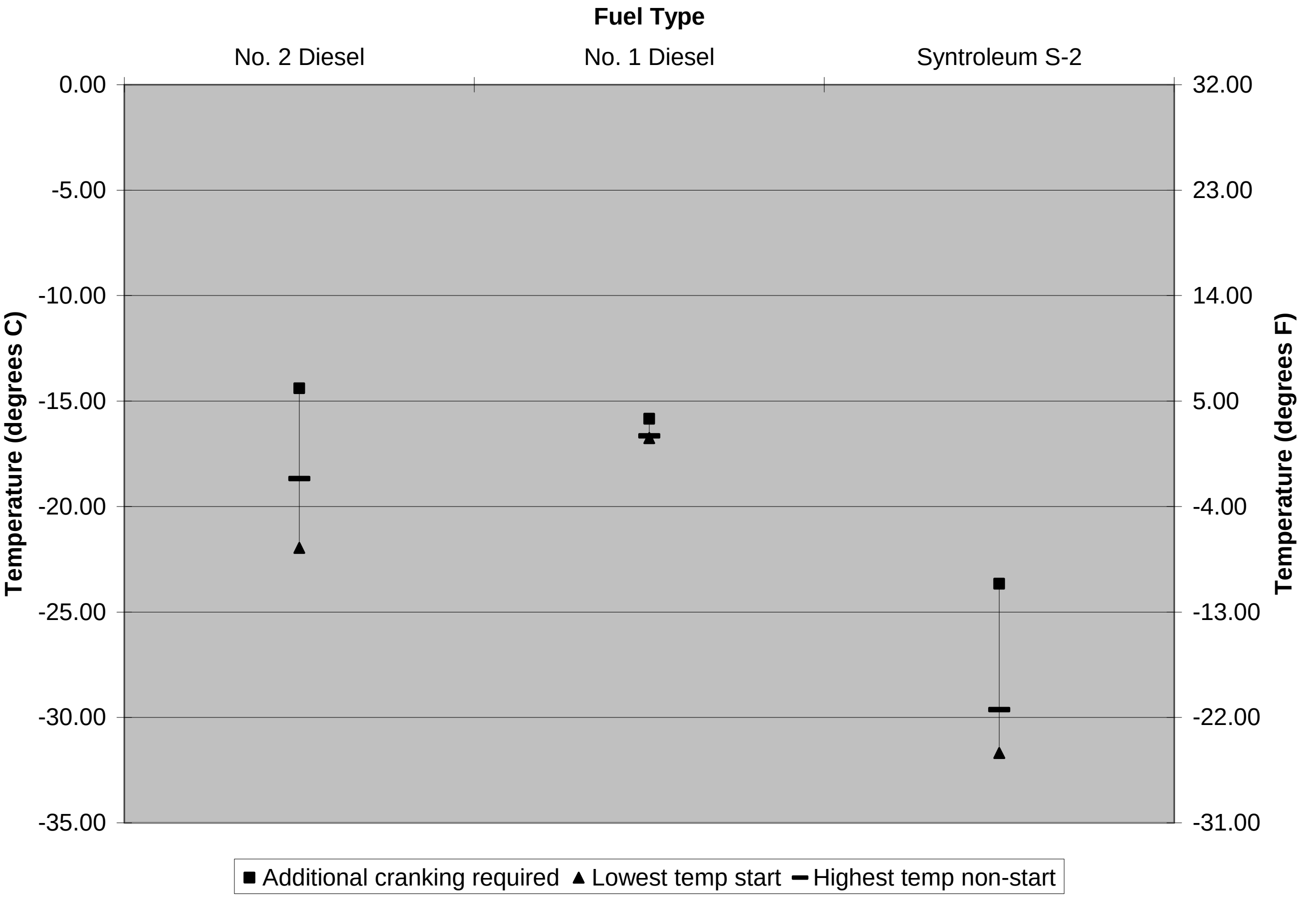
Three temperatures were considered to be important for characterizing the region with difficult or unreliable cold-starting. The highest temperature of interest is where additional cranking events were required to have the engine start. The next highest temperature of interest is the highest temperature at which a non-start was recorded. The final or lowest temperature of interest is the coldest temperature at which a start was recorded. Relatively quick, reliable starting can be expected above this region and no starting can be expected below this region.

The results of this study are summarized in Table 5 and Figure 6 of the report and they are reproduced here in the executive summary. Table 5 presents the temperatures for the three fuels that define the area of difficult or unreliable starting in tabular format. Figure 6 shows graphically the regions of difficult or unreliable cold-starting for the No. 2 diesel, No. 1 diesel, and the Syntroleum S-2 fuels.

Table 5: Temperatures of Interest °C (°F)

	Diesel No. 2	Diesel No. 1	Syntroleum S-2
Additional cranking required	-14.39°C (6.10°F)	-15.84°C (3.49°F)	-23.66°C (-10.59°F)
Highest temperature non-start	-18.68°C (-1.63°F)	-16.65°C (2.03°F)	-29.63°C (-21.33°F)
Lowest temperature start	-21.96°C (-7.52°F)	-16.75°C (1.85°F)	-31.68°C (-25.03°F)

Figure 6: Regions of Difficult or Unreliable Cold-Starting



When compared with No. 2 diesel fuel, the Syntroleum S-2 fuel exhibited the following results:

- The S-2 fuel did not require additional cranking events until the temperature was 9.27°C (16.69°F) lower.
- The S-2 fuel did not experience its highest temperature non-start until the temperature was 10.95°C (19.7°F) lower.
- The S-2 fuel started at a 9.72°C (17.5°F) lower temperature.

When compared with No. 1 diesel fuel, the Syntroleum S-2 fuel exhibited the following results:

- The S-2 fuel did not require additional cranking events until the temperature was 7.82°C (14.08°F) lower.
- The S-2 fuel did not experience its highest temperature non-start until the temperature was 12.98°C (23.36°F) lower.
- The S-2 fuel started at a 14.93°C (26.88°F) lower temperature.

It is of note that No. 1 diesel fuel does not exhibit a lower minimum starting temperature than No. 2 diesel fuel. This is despite No. 1's improved cold-flow properties and increased volatility. Future testing could investigate the capability of the fuel–engine-vehicle system to continue running at extremely low temperatures ICRC speculates that No. 1 diesel fuel would allow the engine to continue running at lower temperatures than No. 2 diesel fuel. The No. 2 diesel fuel used in this program exhibited gelling at temperatures below -27°C (-18°F), while No. 1 diesel and Syntroleum S-2 showed no gelling down to -36°C (-33°F), the lowest test temperature.

This testing program was designed to characterize the cold-starting behavior of the fuels in question to allow an evaluation of whether or not ultra-clean F-T diesel fuels can allow diesel engines to start at lower temperatures. The characterized improvement over No. 2 and No. 1 Diesel successfully demonstrates that this ultra-clean F-T diesel fuel does exhibit better cold-starting characteristics.

INTRODUCTION

Under the Department of Energy's Ultra-Clean Transportation Fuels Program, Integrated Concepts and Research Corporation (ICRC) carried out the project titled, "Ultra-Clean Fischer-Tropsch (F-T) Fuels Production and Demonstration Project." As part of this project ICRC conducted a cold-starting evaluation utilizing a Detroit Diesel 50 Series engine inside a refrigerated test cell. The evaluation was conducted to determine in a controlled environment the engine's unassisted cold-start capabilities with Syntroleum F-T diesel fuel, which could be produced in a remote Alaskan small-footprint plant (SFP) for local use, and with conventional petroleum-derived fuels.

Diesel engines are often required to operate in cold climates, and the startup of a diesel engine in the cold can be problematic. For combustion to take place in the engine, air must be compressed, raising its temperature past the temperature needed to ignite the injected fuel. Cold engine starts can be hampered by a loss of compression efficiency and the colder air temperatures, resulting in lower in-cylinder temperatures.

A fuel with a high Cetane Number ignites more readily and requires a lower compressed air temperature to ignite. The Cetane Number of a fuel can be raised by fuel additives such as 2-ethylhexyl nitrate. The national minimum requirement for Cetane Number in highway diesel fuel is 40; Syntroleum F-T fuel has a Cetane Number greater than 70. This fuel also has superior low-temperature flow properties because isomerization processing is used to convert some of the fuel's normal paraffins (i.e. wax) to iso-paraffins. Therefore, it is expected that the Syntroleum F-T fuel will have a minimum start temperature that is lower than conventional No. 2 and No. 1 diesel fuels.

The purpose of the testing was to characterize the relative cold-starting performance of ultra-clean F-T diesel fuel in comparison to conventional fuels in a typical diesel engine without assistance. ICRC performed a series of cold-start tests on a diesel engine that was cold soaked at different temperatures utilizing three separate fuels. Data was gathered including soak temperature, number of ten-second cranking events (up to 3 maximum), and success or failure of the overall cold-start attempt. The objective of this test program was to locate three temperatures of interest for each fuel. These three temperatures are used to characterize the temperature region where difficult to unreliable starting can be expected for the three fuels. The temperatures are:

- The highest temperature at which additional engine cranking (i.e. more than a single ten-second crank) is required to start the engine, the onset of "difficult" starting.
- The highest temperature at which the engine failed to start after three (3) ten-second cranking events.
- The lowest temperature at which the engine started within three (3) ten-second cranking events.

As will be shown, it is common for some "overlap" to occur between the last two temperatures listed above. This means that for a particular fuel-engine combination there is usually a cold-soak temperature range where cold-starting is sometimes possible, but starting is not always reliable, even with extended cranking.

BACKGROUND INFORMATION AND LITERATURE SURVEY

As an absolute minimum requirement, diesel engines need a fuel that is capable of autoignition after it is injected into the cylinder near Top Dead Center (TDC). A wide range of hydrocarbon blends can meet this autoignition requirement when the engine is operating and fully warmed-up. To achieve acceptable engine performance and long life, however, a more stringent requirement must also be met. This more stringent requirement is that there must be a relatively short and predictable ignition delay[1] which requires the fuel to have an acceptable ignition quality as measured by Cetane Number[2].

The starting of a cold diesel engine places even greater requirements on the fuel's autoignition properties. This higher requirement can be reduced in some diesel engines by the utilization of glow-plugs, ether, and/or other "starting fluids" to aid ignition. It is undesirable to utilize these aids due to their cost and complexity. They have also been shown to lead to engine damage. For example, failure of a glow plug that subsequently releases debris into the engine can cause significant damage.

Recently, several studies have been completed investigating the fundamentals of diesel engine cold-starting and fuel autoignition. The cold-start performance of several fuel blends and a cetane-improver additive, isooctyl nitrate, were investigated in a fully instrumented single-cylinder research engine[3]. In another study it was discovered that starting failure can be attributed to combustion instability which resulted in some cylinders firing on some, but not all, cycles. This study was carried out in a fully instrumented four-cylinder, heavy-duty diesel engine[4]. Comparison of experimental results on a cycle-by-cycle basis was also studied through modeling of the diesel cold-starting process[5]. The foregoing studies have lead to a greater understanding of what goes on during the starting of a cold diesel engine. There is a lack of data, however, on whether or not a typical diesel engine will be more likely to start on a high-Cetane fuel at a particular low temperature than on a more conventional fuel.

The study reported here does not aim to explain the cold-starting process in detail, but rather to seek a greater understanding of the cold-starting limits of the test fuels. The first goal was to determine whether or not F-T diesel fuel with a Cetane Number above 70 and good low-temperature flow properties would provide an advantage for cold-starting a typical heavy-duty diesel engine; the advantage being whether starting would be possible at lower temperatures than would be possible with conventional petroleum-derived No. 2 and No. 1 diesel fuels.

The limited amount of information in the literature concerning the effects that very high Cetane Number (50+) fuels might have on diesel engine cold-starting is not particularly reassuring that any benefit will actually be obtained. For example, in one study[6] the influence of increasing Cetane Number of the fuel from 50 to 60 was considered negligible in terms of the ignition delay compared to the influence of the compression temperature. Another study[7] included experimental fuel blends ranging in Cetane Number from 26 to 61, and concluded, by cold-start testing them in two light-duty diesel vehicles equipped with glow-plugs, that “above 40 cetane, both vehicles were relatively insensitive to changes in cetane number.”

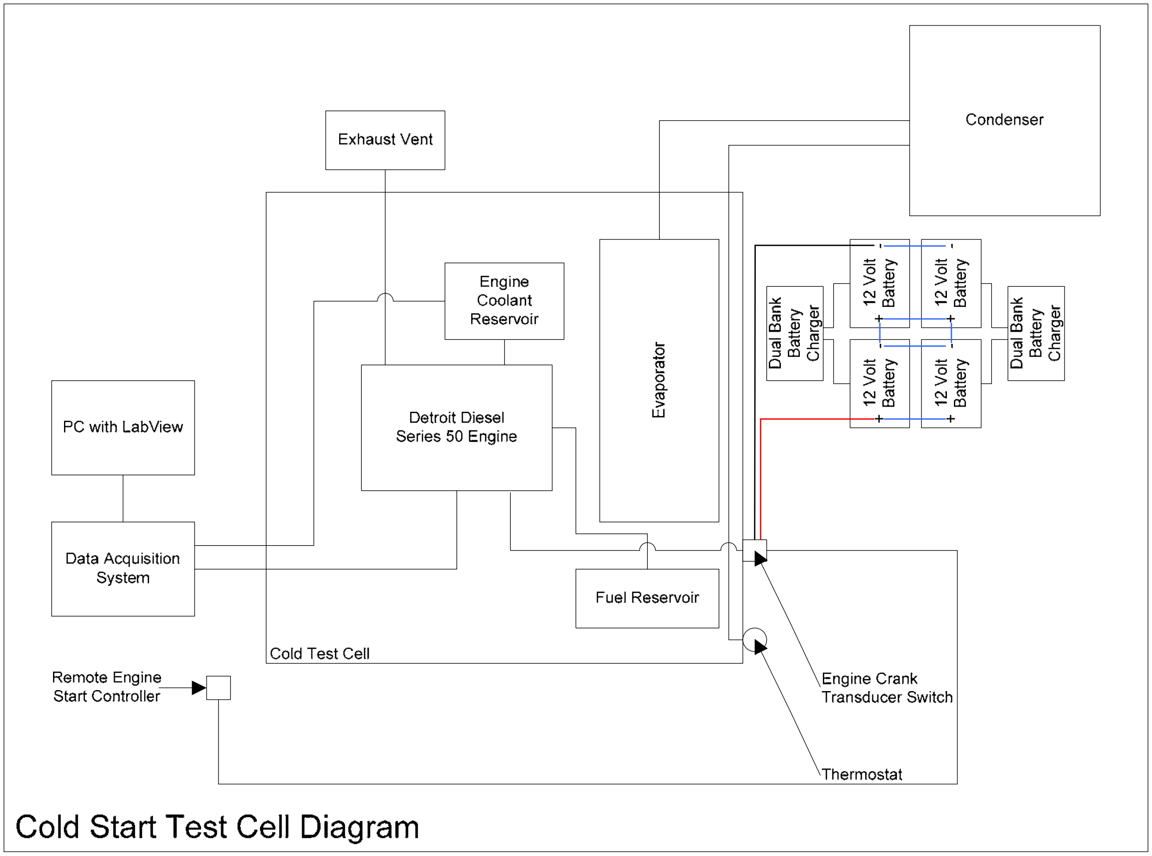
EXPERIMENTAL

The experimental section of this report will introduce the equipment, fuels and procedures that were utilized to conduct all testing.

Experimental Equipment

Cold-Start Test-Cell

Figure 1: Cold-Start Test-Cell Diagram



The cold-start test-cell was an International Cold Storage Co., Inc. refrigerated, insulated walk-in cold box. The floor of the cold-start test-cell was a slotted-iron dynamometer-type bed plate to facilitate engine mounting. Basic cold-start test-cell interior dimensions were 9’ 4” wide by 9’ 4” deep by 7’ 3” high, with reduced ceiling height directly below the evaporator coil/air-blower assembly which was mounted at the top rear of the cold cell. The cold-start test-cell was cooled by an electrically driven Bitzer HML 220 refrigeration system using R404A refrigerant.

The refrigeration system was capable of cooling the cold-start test-cell to an absolute minimum temperature of -36°C (-33°F) when the refrigeration system was allowed to run continuously (i.e. without normal cycling on and off) during the overnight cold-soak period. Bypassing the normal built-in test-cell thermostatic temperature control system prevented refrigeration system cycling and thus allowed continuous running and achievement of the minimum -36°C (-33°F) temperature. Operation in the continuous-run mode entailed some risk to the refrigeration system, and was done only after extended cold-start test-cell operation at temperatures in the -26°C (-15°F) to -32°C (-25°F) range to ensure that the moisture content of the air in the cold-cell had already been minimized, thus lessening the risk of significant ice build-up on the evaporator coil. With the normal built-in thermostatic control system operational and the refrigeration system cycling on and off normally, minimum achievable cold-start test-cell temperature with the selection dial at its minimum setting, was approximately -32°C (-25°F).

The air intake of the engine was located inside the cold-start test-cell, so that inducted air during cold-cranking would be at the cold-soak temperature. The exhaust from the engine was piped out of the cold-start test-cell through a standard dynamometer-type engine exhaust system. Infiltration of room air at several locations (door weather-stripping, seams between wall panels, etc.) around the periphery of the cold cell would allow test-cell pressure to remain at atmospheric during cranking, while not significantly increasing effective test-cell air temperature during cold-starting attempts.

The cold-start test-cell and related equipment are shown in Figures 2 to 4.

Figure 2: Cold-start test-cell

Figure 3: Data acquisition system and operator's station

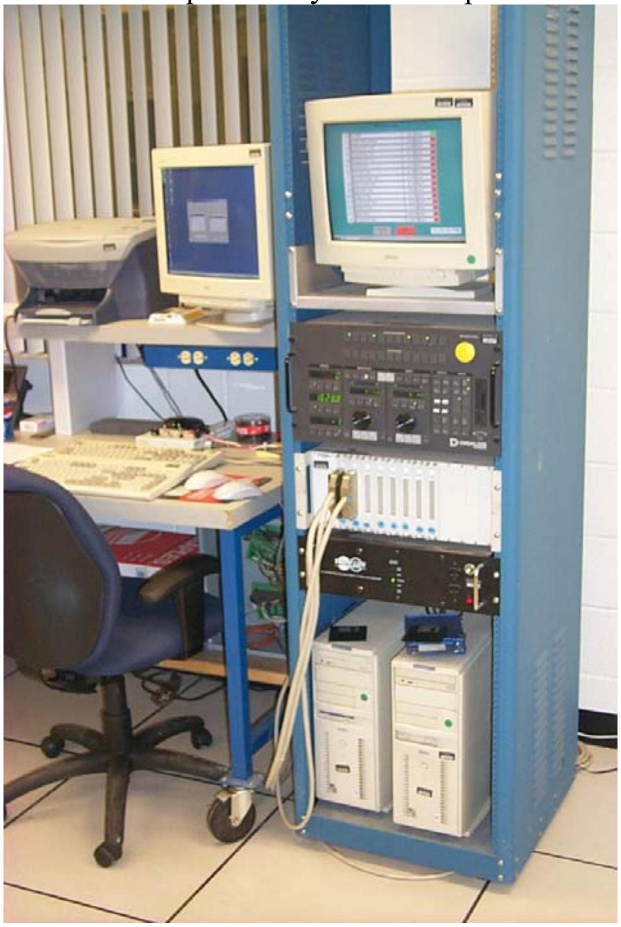


Figure 4: DDC Series 50 engine in cold-start test cell

Temperature Selection and Control

The cold-soak temperature in the cold-start test-cell was changed by resetting the set-temperature selection dial which was part of the normal built-in cold-box temperature control system. This thermostatic control system was intended to provide for temperature adjustment, then to maintain the cold-box temperature, when used as an industrial-size freezer, within a temperature range of approximately 1°C (2°F) by cycling the refrigeration system on and off. However, this temperature control system did not allow for great precision in selecting a "new" set-point temperature for the cold-start test cell. The implications of this lack of precision in the ability to set the system to a desired "new" cold-soak temperature will be discussed further under the Experimental Procedure section.

Engine

All cold-start tests were conducted on a Detroit Diesel (DDC) Series 50 inline four-cylinder 8.5-liter heavy-duty diesel engine, unit number 04R0033607. This engine was provided to ICRC for use in evaluating Syntroleum F-T clean diesel fuel by the Washington DC Metropolitan Area Transit Authority (WMATA) under this DOE-NETL sponsored program. The engine had been rebuilt by WMATA after having been run an unknown interval in normal transit bus service. The rebuilt engine was "in-stock" in WMATA's normal inventory of rebuilt engines, for use in a bus when needed, before being shipped to ICRC for this program, but its history is otherwise unknown. The engine calibration used in the cold start tests gave the engine a rating of 250 horsepower at 2,100 rpm. When the engine started during the cold-start tests, it was allowed to run approximately 30 seconds at idle without external load other than its flywheel.

Batteries

The cold-start test-cell used four marine deep-cycle batteries to start the engine using the engine's standard 24-volt starter motor. This battery array was configured for 24-volt starting voltage. The battery voltage was maintained at 24 volts with a battery charger. The charger was disconnected just before each cold-start attempt. The battery array was stored outside of the test cell at a consistent room temperature of approximately 70°F. The batteries were not the subject of the cold start test, and thus were maintained at full charge and nearly constant room temperature.

Engine Oil

Oil used in the DDC engine during all cold-start tests was Mobil Delvac 1 SAE 5W-40. This synthetic-basestock oil contains virtually zero wax, and has extremely favorable low-temperature flow properties, thus maximizing oil pumpability while minimizing viscous drag during low-temperature engine cranking.

Data Acquisition System

Lab VIEW software and a National Instruments Data Acquisition system was used to acquire all the data during the cold-start tests.

Temperatures and Other Data Collected

The following temperature readings were measured:

- Inlet Air; measured in the engine air intake housing
- Fuel Inlet; measured fuel temperature before the fuel pump
- Fuel Return; measured fuel temperature in the fuel return line
- Engine Coolant; measured temperature of coolant in the engine block

Along with the temperatures the date and time of the test was also recorded at the time of the test.

Cold-Start Test Fuels

Three fuels were utilized in testing. The fuels were reference No. 2 diesel used for EPA emissions certification, a low-temperature-capable No. 1 diesel fuel blended by Chevron Phillips, and Syntroleum S-2. The three test fuels were tested in accordance with industry standard practice with the results summarized in Table 1.

Syntroleum S-2 is a synthetic diesel fuel which can be produced from a multitude of energy resources. The S-2 fuel used in this project was made from natural gas, but it can be made from other domestic energy resources including coal and biomass. Ultra-clean Syntroleum S-2 is a paraffinic, high-cetane distillate fuel that is essentially free of sulfur, olefins, metals, aromatics or alcohols. Unlike several other alternative fuels, Syntroleum S-2 can be shipped, stored and dispensed using the same fuel distribution and handling procedures as petroleum diesel. Volatility properties are similar to those of conventionally produced No. 2 diesel. The fuel is compatible in all diesel-powered vehicles.

Table 1: Fuel Characteristics

Sample ID	**RDIL 4306**	**RDIL 4309**	**RDIL 4317**
Description	**EPA No. 2D**	**S-2**	**No. 1D**
Grade	**No. 2D**	**S-2**	**No. 1D**
D5771 Cloud Point, °C (°F)	-18 (-0.4)	-27 (-17)	-48 (-54)
D93 Flash Point, °C (°F) (closed cup)	74 (166)	63 (145)	62 (143)
D445 Viscosity, 40°C	2.906	2.154	1.47
D4052 Density, 15°C	0.843	0.769	0.805
D4052 Specific Gravity, 15°C	0.8473	0.769	0.8095
D4052 API Gravity, 15°C	35.5	52.51	43.3
Cetane Index, D976	49.7	74.0	46.7
Cetane Index, D4737	49.8	80.7	48.3
IQT Derived Cetane Number[8]	46.8	72.7	45.8
D86 IBP, °C (°F)	199.8 (391.6)	196.3 (385.4)	181.2 (358.1)
D86, 5%	213.9 (417.1)	205.6 (402)	191.3 (376.3)
D86, 10%	220.6 (429)	208.9 (408)	193.6 (380.4)
D86, 15%	226.9 (440.5)	211.8 (413.3)	195.8 (384.4)
D86, 20%	232.5 (450.5)	214.6 (418.3)	197.7 (387.8)
D86, 30%	244.4 (471.9)	219.6 (427.3)	201.8 (395.2)
D86, 40%	256.5 (493.7)	223.9 (435.1)	205.9 (402.6)
D86, 50%	267.8 (514.1)	228.6 (443.4)	210.4 (410.7)
D86, 60%	278.7 (533.6)	233.8 (452.8)	215.3 (419.5)
D86, 70%	289.4 (552.9)	239.7 (463.4)	221 (429.8)
D86, 80%	301.3 (574.3)	246.8 (476.3)	228.3 (443)
D86, 90%	315.7 (600.2)	256.6 (493.9)	239.1 (462.3)
D86, 95%	327.7 (621.9)	265.5 (509.9)	247.7 (477.8)
D86, FBP	342.2 (648)	301.7 (575)	265.9 (510.6)

Experimental Procedure

Temperature as the Only Controlling Parameter

The fundamental assumption made in the series of cold-start tests described in this report is that too low a cold-soak temperature is the only factor that would cause the test engine not to start. Therefore, to justify this assumption, the test plan included conducting a series of engine starts on conventional No. 2 EPA Certification diesel fuel at soak temperatures further and further below room temperature, but high enough that a normal heavy-duty diesel engine would be expected to start.

For this reason, the initial approach was to move the cold-soak temperature downward on successive days. Monitoring of temperature data within the cold-start test-cell and within the engine indicated that after the engine had started and run briefly, a full 24 hours was required for all temperatures to equilibrate at the new lower cold-soak temperature. Although all cold-soak temperatures were approximately equal at the end of the cold-soak period (i.e. just before attempting to start the engine), the stabilized engine coolant temperature was selected as the most representative temperature for use in plotting the results.

Cranking Schedule

The cold-cranking procedure was as follows:

1. Manually push the engine-crank button, thus cranking the engine for up to 10 seconds, releasing the button immediately if the engine starts. The engine was allowed to run for 30 seconds before shutting it down.
2. If the engine has not started after the initial 10 second crank, wait 5 seconds (to allow some battery recovery), then repeat the 10 second crank.
3. If the engine still has not started, wait 5 seconds, and then do a final crank of up to 10 seconds.

Cold-Soak Temperature Settings

The temperature selection dial on the cold-start test-cell would be changed after each test to obtain the next cold-soak temperature for the next cold-start test. The "ideal" amount of change in the cold-start test-cell temperature setting would have been 1°C (2°F), but the built-in temperature selection dial was not sensitive enough to allow much precision in selecting a new cold-soak temperature. Therefore, the new setting would be selected as close as possible (based upon experience) to a 1°C (2°F) change, and the resulting cold-soak temperature actually obtained would be used for the next cold-start attempt and the measured stabilized coolant temperature would be used in plotting the results.

The direction of the set-temperature change, up or down, would depend upon the start/no-start result just obtained. If the engine had just started, the cold-start test-cell temperature would be set lower for the next overnight soak, seeking the "transition" temperature between Start and No-Start behavior. If the engine had not just started, the cold-start test-cell temperature would be set higher, again seeking the transition temperature. For this particular case, a non-start followed by an increase in the set-temperature for the next cold-start test, equilibrium at the new (higher) cold-soak temperature would be obtained in as little as eight (8) hours allowing a second cold-start test within the same shift after an initial non-start result.

Transition between Start and No-Start

The initial assumption was that there would be a "sharp" transition temperature between Start and No-Start behavior for each fuel. As shown clearly by the data in the Test Results section below, as the cold-soak temperature is decreased, there are three temperature ranges of cold-starting behavior for a given fuel:

1. Reliable cold-starting (start quickly and easily every attempt)
2. Difficult and unreliable cold-starting

3. No-Start (cold-soak temperature so low that the engine never starts)

The difficult and unreliable cold-starting region is described in this testing through the three temperatures of interest.

Plotting the Results to Facilitate Interpretation

The combination of the following factors makes it extremely difficult to interpret the results if the Start/non-Start results for a given fuel are simply plotted vs. stabilized coolant temperature in the time-order that the results were actually obtained:

1. Imprecision in the ability to pre-select cold-soak temperatures
2. The conscious strategy to continuously "hunt" for the transition temperature (by moving the next set-temperature down or up based upon last start or non-start result respectively)
3. The nature of the transition (with a range of difficult and unreliable cold-starting) between start and non-start behavior

However, when all the Start/non-Start results for a given fuel are sorted and plotted in order of decreasing stabilized coolant temperature, the three distinct temperature ranges of cold-starting behavior are easily discernible. These ranges are illustrated in Figure 6 of the Test Results section.

Implications for "Outdoor" Cold-Start Testing

It is important to consider the relationship between real world vehicle behavior and a simulated cold-start environment. What heavy-duty vehicle operators are concerned about in regards to cold weather starting is whether or not the engine starts. Therefore it is important to identify the point at which a fuel/engine combination begins to experience difficulty in starting.

The best way to address this difficult starting on-set is by way of a laboratory environment where the temperature is the only variable and the temperature is controlled. Although laboratory testing does not directly translate into performance in the field, it does provide comparative data. Unlike laboratory testing, outdoor testing does not provide control over the soak environment as the temperature is likely to be constantly changing. This leads to an unknown condition of the engine. Therefore, the starting characteristics of different fuels cannot be compared reliably in the same engine in an outdoor environment.

TEST RESULTS

The following tables provide the cold-start testing results obtained during this test program. All test data was combined and placed onto a single graph to illustrate the temperature ranges where difficult and unreliable starting was experienced for the three fuels. Figure 5 shows test results plotted by temperature. Figure 6 shows the regions of unreliable starting as characterized by the three temperatures of interest.

No. 2 Diesel Fuel

Table 2 contains the test data from No. 2 Diesel testing. The lowest recorded temperature that the No. 2 diesel fuel started at was -21.96°C (-7.52°F). However, the engine began experiencing difficulty in starting at -18.68°C (-1.63°F), with increased cranking usually needed at -14.39°C (6.10°F).

No. 1 Diesel Fuel

Table 3 contains the test data from No. 1 Diesel testing. The lowest recorded temperature that the No. 1 diesel fuel started at was -16.75°C (1.85°F). However, the engine began experiencing unreliable starting at -16.65°C (2.03°F), with increased cranking needed at -15.84°C (3.49°F).

Syntroleum S-2 Fuel

Table 4 contains the test data from Syntroleum S-2 fuel testing. The lowest recorded temperature that the S-2 fuel started at was -31.68°C (-25.03°F). However, the engine began experiencing unreliable starting at -29.63°C (-21.33°F), with increased cranking needed at -23.66°C (-10.59°F).

Table 2: Test Data from No. 2 Diesel Fuel

Coolant Temp		Engine Start Y/N	Number of Cranks	Test Date
°C	°F			
8.78	47.80	Y	1	3/12/2003
1.23	34.21	Y	1	3/13/2003
-0.07	31.88	Y	1	3/14/2003
-6.19	20.85	Y	1	3/15/2003
-8.15	17.33	Y	1	4/16/2003
-14.39	6.10	Y	2	3/21/2003
-14.58	5.75	Y	2	4/17/2003
-16.63	2.07	Y	1	4/01/2003
-17.65	0.23	Y	2	4/13/2003
-18.68	-1.63	N	3	3/27/2003
-18.77	-1.78	Y	3	4/23/2003
-20.44	-4.80	N	3	4/15/2003
-20.60	-5.08	Y	1	3/26/2003
-20.76	-5.37	N	3	4/03/2003
-20.80	-5.44	N	3	4/04/2003
-20.91	-5.63	N	3	4/14/2003
-20.91	-5.64	Y	1	4/02/2003
-20.93	-5.68	Y	3	4/25/2003
-21.86	-7.35	N	3	4/22/2003
-21.96	-7.52	Y	3	4/26/2003
-23.24	-9.83	N	3	4/21/2003
-23.66	-10.59	N	3	4/28/2003
-25.84	-14.52	N	3	4/24/2003

Table 3: Test Data from No. 1 Diesel Fuel

Coolant Temp		Engine Start Y/N	Number of Cranks	Test Date
°C	°F			
-8.47	16.76	Y	1	7/15/2003
-12.74	9.06	Y	1	7/17/2003
-15.84	3.49	Y	2	7/18/2003
-16.11	2.99	Y	2	7/24/2003
-16.65	2.03	N	3	7/16/2003
-16.75	1.85	Y	3	7/25/2003
-17.03	1.34	N	3	7/23/2003
-19.97	-3.95	N	3	7/22/2003
-20.75	-5.35	N	3	7/21/2003

Table 4: Test Data from Syntroleum S-2 Fuel

Coolant Temp		Engine Start Y/N	Number of Cranks	Test Date
°C	°F			
-11.78	10.80	Y	1	5/2/2003
-14.20	6.44	Y	1	5/5/2003
-16.84	1.69	Y	1	5/6/2003
-19.68	-3.43	Y	1	5/7/2003
-20.63	-5.14	Y	1	5/8/2003
-23.66	-10.59	Y	2	5/9/2003
-27.54	-17.58	Y	3	5/22/2003
-27.56	-17.61	Y	3	5/15/2003
-28.12	-18.61	Y	3	5/13/2003
-28.66	-19.58	Y	3	5/16/2003
-29.63	-21.33	N	3	6/9/2003
-29.66	-21.38	N	3	5/27/2003
-29.84	-21.72	N	3	6/13/2003
-30.18	-22.32	Y	3	5/12/2003
-30.39	-22.70	Y	3	5/28/2003
-30.63	-23.13	Y	3	5/14/2003
-30.92	-23.65	Y	3	5/20/2003
-31.48	-24.67	N	3	5/21/2003
-31.68	-25.03	Y	3	6/12/2003
-35.84	-32.52	N	3	5/16/2003

Fuel Comparison

Table 5 shows the three temperatures of interest for each fuel. The first temperature is the point where two or more 10-second crank events were required to start the engine. The second temperature is the lowest temperature where a start was obtained. The final temperature is the highest temperature where a non-start was experienced.

Table 5: Temperatures of Interest °C (°F)

	Diesel No. 2	Diesel No. 1	Syntroleum S-2
Additional cranking required	-14.39°C (6.10°F)	-15.84°C (3.49°F)	-23.66°C (-10.59°F)
Highest temperature non-start	-18.68°C (-1.63°F)	-16.65°C (2.03°F)	-29.63°C (-21.33°F)
Lowest temperature start	-21.96°C (-7.52°F)	-16.75°C (1.85°F)	-31.68°C (-25.03°F)

Figure 5 shows all the starting attempts for each fuel grouped in order of decreasing overnight cold-soak temperature. In the plot, the green triangles show successful starts and the red circles show failures, with the number of crank-events indicated by the blue dot in line with the attempt temperature.

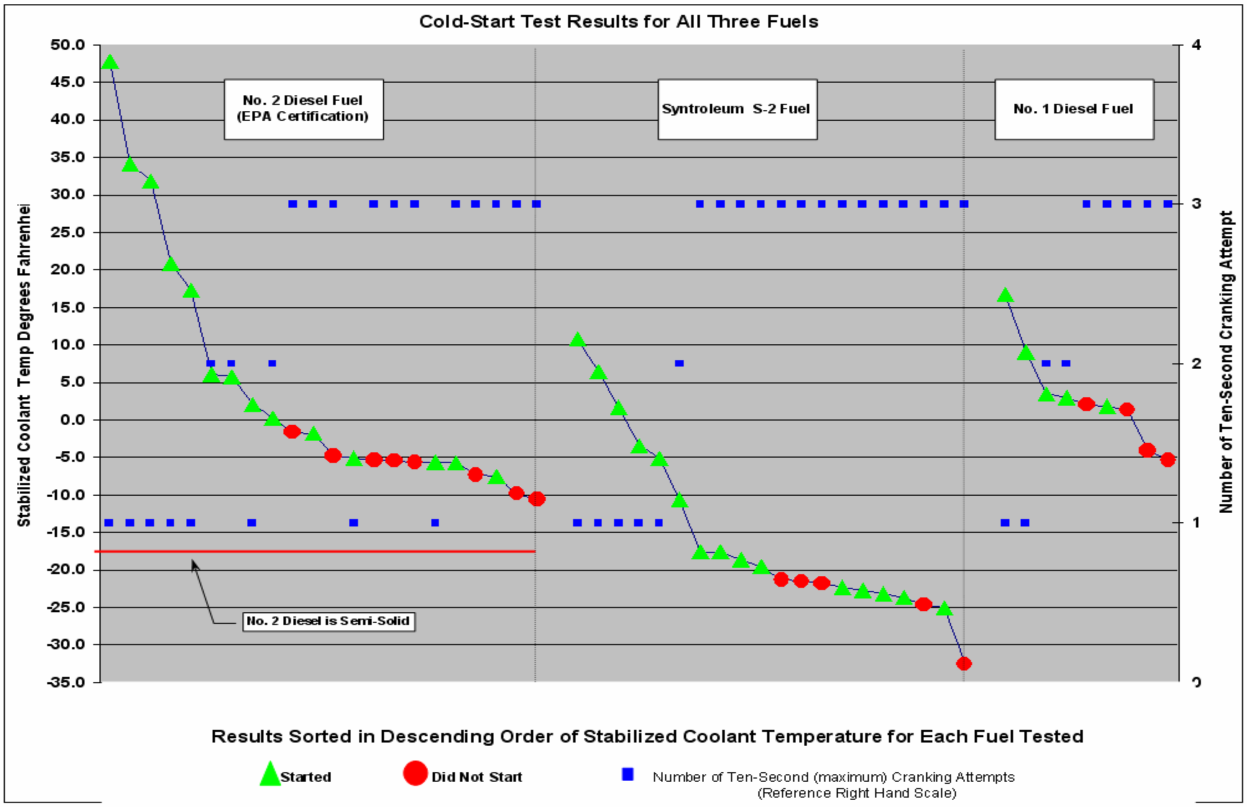
As can be seen in Figure 5, for No. 2 diesel fuel reliable engine starting was achieved down to about -19°C (-2°F), but the engine would not start below -22°C (-8°F), with unsuccessful attempts being made down to -26°C (-15°F). Note also that at temperatures below about -28°C (-18°F), the No. 2 diesel fuel was semi-solid (gelled), which was determined from "jar-tests" of the three test fuels that were kept in the cold-start test-cell and checked manually after each cold-starting test to monitor for this fuel state.

No. 1 diesel fuel would reliably start down to -17°C (2°F), but was difficult or impossible to start at temperatures below that.

Syntroleum S-2 demonstrated reliable starting down to -30°C (-21°F). This represents a reduction in minimum reliable starting temperature of 11°C (19°F) below conventional fuels. The temperature range where starting on S-2 was unreliable, but sometimes possible, was from -30°C (-21°F) to -32°C (-25°F). This range is also about 11°C (19°F) lower than the comparable "unreliable" range for No. 2 diesel fuel. This approximately 11°C (19°F) improvement in cold starting performance of S-2 is solely due to the significant improvement in the ignition quality, usually expressed as Cetane Number, of the Syntroleum fuel.

It is interesting to note that No. 1 diesel fuel, and also Jet A, do not provide easier starting in cold climates despite their improved cold-flow properties and increased volatility. These fuels are still formulated with the same conventional crude oil components as No. 2 diesel fuel, but without some of the heavier, high-Cetane components found in the higher boiling range No. 2 fuel.

Figure 5: Cold-Start Test Results for All Three Fuels



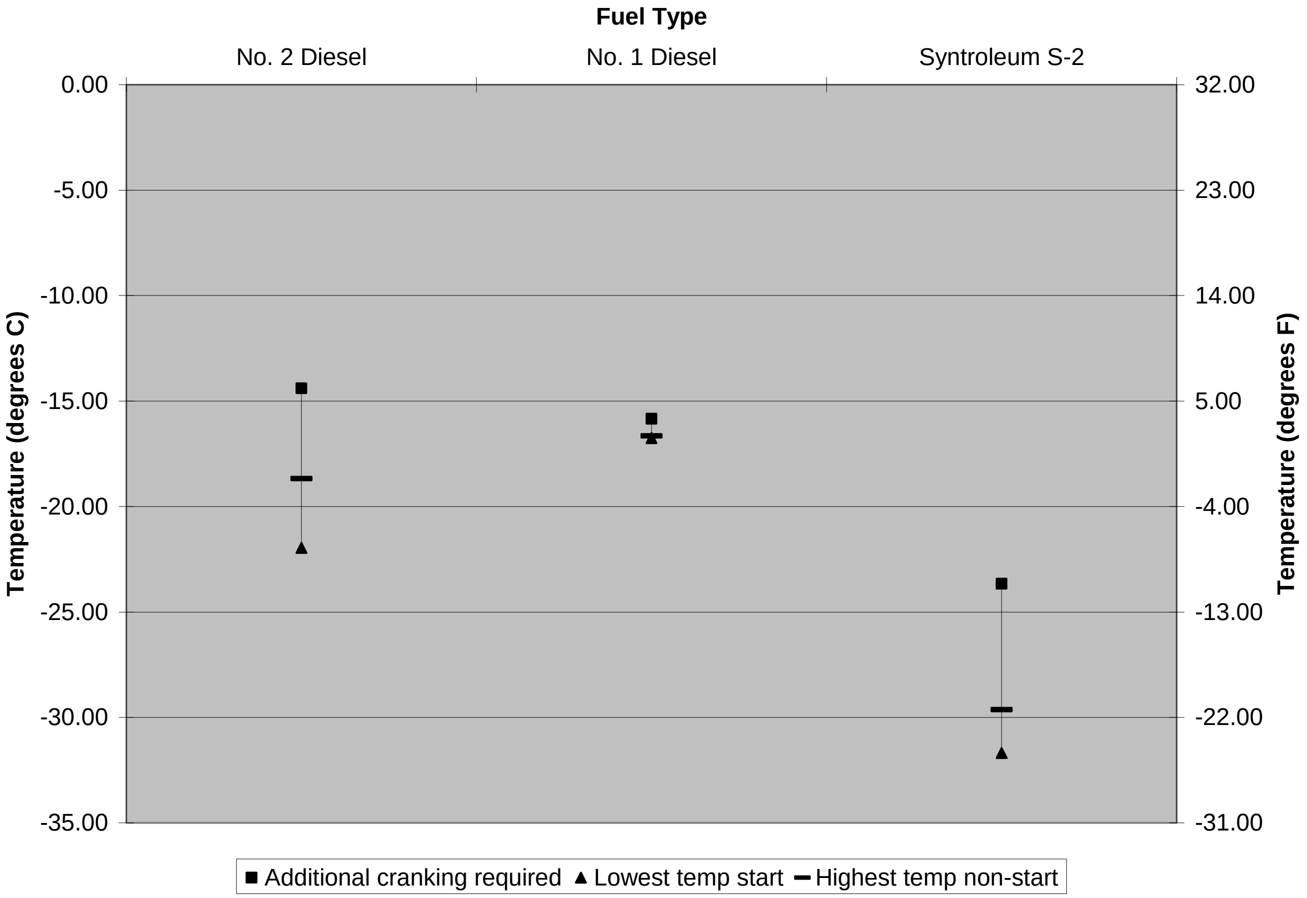
Characterization of Regions of Difficult and Unreliable Starting

Figure 6 shows the relative ranges where the three fuels experienced difficulty in starting. The chart shows for each fuel:

- the temperature where additional crank events were required to achieve a start
- the highest temperature where a non-start occurred
- the lowest temperature at which a start occurred

These three temperatures give some insight into where difficulty in starting the engine can be expected. Relatively quick and reliable starting can be expected above these regions and no starting can be expected below these regions.

Figure 6: Regions of Difficult and Unreliable Cold-Starting



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Long Term Testing
of Syntroleum Synthetic Fuels
In a Stationary Generator Set

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Final Report

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ABSTRACT:

There have been many studies concerning the use of Fischer-Tropsch fuels and their performance in combustion engines, but few have addressed the long-term effects on engine performance and reliability. To explore these issues UAF assembled a 125kW diesel generator test platform that would mimic a typical Alaskan installation and also provide accurate data on engine performance and possible degradation. This generator was run for over 2200 hours on 3 different grades of Syntroleum synthetic fuel, a winter grade No. 2 diesel fuel (S2-W), a standard No. 2 diesel fuel equivalent (S2), and an arctic-grade No. 1 diesel fuel equivalent (S1). The Syntroleum fuels exhibited lower emissions levels across the board and a lower Brake Specific Fuel Consumption when compared to conventional diesel.

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EXECUTIVE SUMMARY:

With rising concern about depleted crude oil sources, interest in synthetic diesel fuels created from natural gas or coal is increasing. The Fischer-Tropsch processes for creating these fuels were patented in Germany in 1923, and these fuels have been used in Germany during World War II, and in South Africa during the embargo. However, these fuels have not been used in most areas of the world, as production of them is significantly more expensive than conventional fuels made from crude oil.

Additional motivation for use of synthetic fuels comes from the EPA ruling requiring diesel fuels used in transportation to be converted to low sulfur fuels by 2006. Synthetic fuels have very low sulfur content, in part due to the sensitivity of the catalysts to contamination by sulfur, requiring that reactant streams be purged of sulfur before the Fischer-Tropsch process. However, since much of the natural lubricity of diesel fuels comes from the sulfur containing compounds, users have expressed concerns about the proposed low sulfur fuels.

In this study, the impact of clean fuels on the operation of diesel generators is examined. In most parts of the US, the majority of diesel fuel (90%) is used for transportation, in trucks and busses, but in Alaska, the majority (about 95%) is used in diesel generators for the production of electricity in remote areas. Diesel generators typically use the same engines as used in trucks and busses, but operate them in a different manner (constant speed at 1200 or 1800 rpm, continuous operation.) In addition, cold winters in Alaska require the use of Arctic Grade fuels, capable of flowing at temperatures of -50F.

The study plan for this project included a 2000 hour test on clean fuel, emissions measurements, and a test of a new arctic grade fuel. Fuel was supplied by Syntroleum Corporation, of Tulsa, Oklahoma, in three lots. The first batch of fuel had properties somewhere between that of conventional S2 fuel and the arctic grade S1 (delivered in June, 2004), the second batch met the specifications of S2 (delivered in August, 2004), and the third lot met the specifications for S1 fuel (delivered in October, 2004).

Highlights of the testing program included:

- 2200 hours of operation of the Detroit Diesel Series 50 generator with no issues traceable to the fuel.
- Emissions testing indicated that no change to injection timing map necessary with the Detroit Diesel engine.
- Emission measurements indicated that the synthetic fuel burned cleaner than conventional diesel fuel
- Exhaust condensate from clean fuels is less corrosive than those from conventional fuels.

Several operational issues occurred during the testing. These included

- Turbocharger failure at 962 hours, not traceable to the clean diesel fuel
- Low lubricity values as measured in the scuff ball test, but no resulting operational issues
- A leak at the bulk fuel pump in cold weather (-8 C) traceable to the lack of arctic grade seals in the pump
- High CO measured in emissions test, traceable to the high intake air temperatures inside the generator shed.

Our conclusions indicate that the clean fuel could be used in diesel generators with no significant changes in operational or maintenance procedures.

EXPERIMENTAL:

The primary goal of this project was to demonstrate the ability of the Syntroleum synthetic fuel to function reliably for over 2000 hours in a diesel generator. To accomplish this goal a diesel generator test bed was developed and a testing plan formulated. This test bed and the test plan are discussed in the paragraphs below. In addition, several experiments were devised to try to better characterize both the engine performance, and the effect of wear and degradation on the engine itself. These experiments will be discussed at the end of this section.

The following is a description of the test bed used for all experimentation. A brief description of the test equipment is provided along with a schematic of the entire test bed.

General Description:

In order to simplify installation, and have the ability to be placed outdoors, the diesel generator and related equipment were installed in a 40 foot insulated conex box. The conex houses the following equipment

1. Detroit Diesel Series 50 Diesel generator.
2. Two day tanks.
3. Inlet air after-cooler.
4. Coolant radiator.

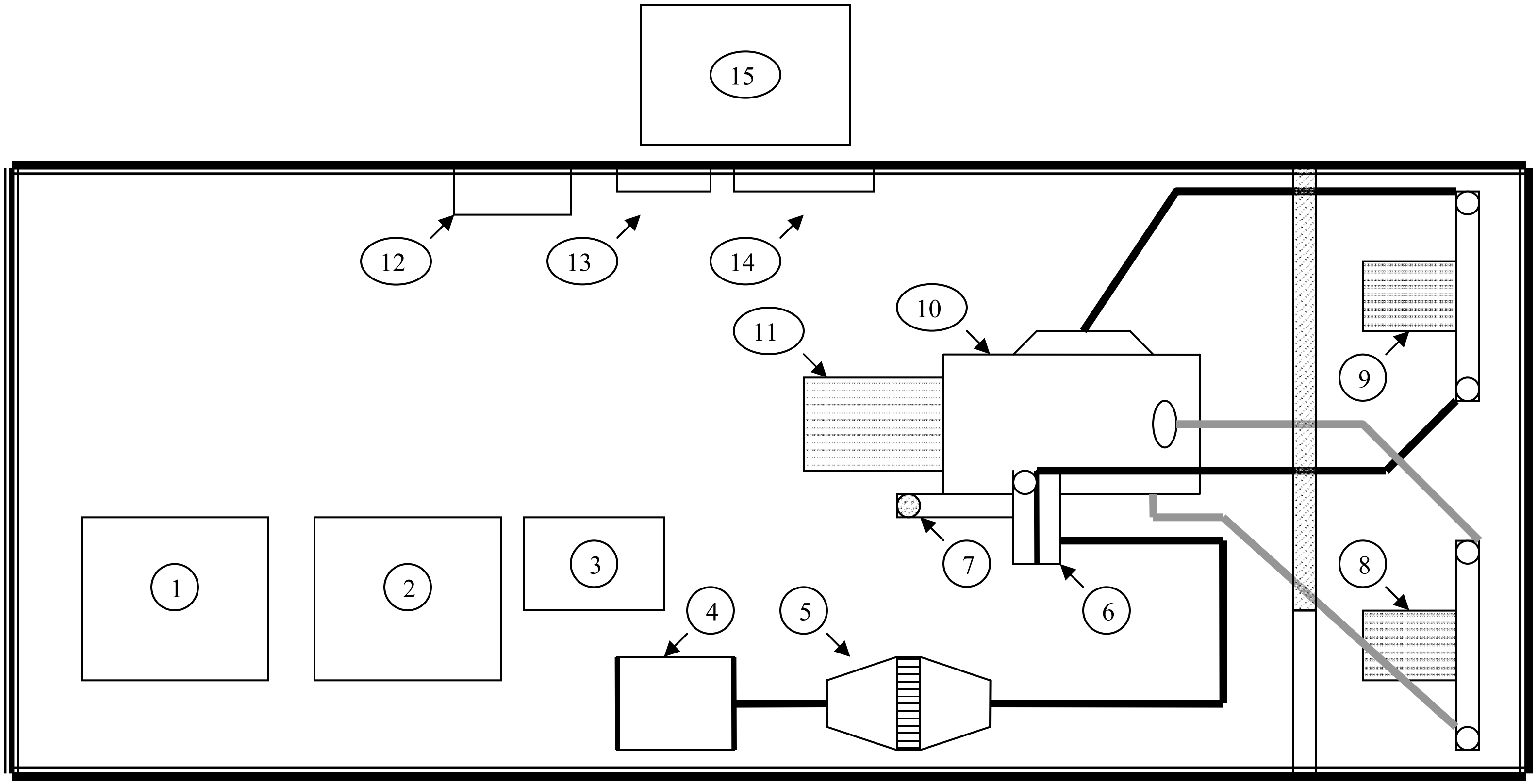
Additional equipment placed outside the conex consists of an 8000 gallon bulk fuel storage tank and a resistive/reactive load bank.

Generator:

The core of the test bed is a 4 cylinder Detroit Diesel Series 50 Heavy Duty diesel engine. The engine is rated at 180 KW and operates at a constant speed of 1200 rpm. The engine is not fitted with a reduction catalyst nor does it employ Exhaust Gas Re-circulation (EGR). The engine is coupled to a 125 KW generator operating at 1200 rpm.

Load to the generator is supplied through the resistive/reactive load bank rated at 250 KW and 0.8 P.F. The load bank employs a digital user interface, located inside the conex. The interface allows the user to input a customized load profile to the generator, and also set a desired power factor.

In order to accurately calculate the total electrical load on the generator, all load bank accessories, are connected to a separate 220 V harness supplied by the university grid. However, power for on-board electronics and load bank fans, also termed as parasitic load, is supplied by the generator.



Legend

1. Day tank
2. Day tank
3. DAQ system
4. Inlet filter
5. Laminar flow element
6. Turbo-charger
7. Engine exhaust
8. Radiator
9. After-cooler
10. Series 50 diesel engine
11. Generator
12. Load bank digital interface
13. Circuit breaker box
14. Load switch
15. Load bank

▬ Air flow lines ▬ Coolant flow lines

Fuel Storage:

(a) Bulk Fuel Storage

Synthetic diesel, to be used for testing, was stored in an 8000 gallon, bulk fuel storage tank. The storage tank is fire-guard, lightweight steel double wall aboveground storage tank conforming to the Underwriters Laboratories (UL) standards. An attached fuel pump and metering system helps document all fuel transfers from the tank. The tank is also equipped with a level indicator, to measure fuel levels at any instant of time.

(b) Day Tanks

The synthetic diesel and conventional diesel are stored in two separate day tanks located inside the conex. Both the tanks are double walled with a 300 gallon capacity and have a UL certification. Each tank is fitted with independent overflow and low level alarms and there are a series of valves that allow the operator to switch tanks on the fly. The bulk fuel storage tank is located within close proximity to the generator conex and allows for easy transfer of fuel from the bulk tank to either of the day tanks.

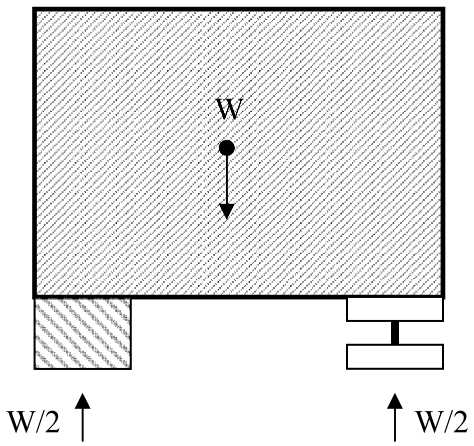
Emissions Sensors:

Exhaust emissions are measured with the help of an ECOM AC Plus portable exhaust emissions analyzer. The analyzer uses electro-chemical sensors to detect regulated gaseous emissions, namely CO, CO_2, NO, NO_2 and O_2. Un-burnt hydrocarbon emissions were measured with a separate, Flame Ionization Detector (FID) analyzer. A portable gas conditioner and a heated filter ensured a dry, particulate free, sample gas supply to either analyzer. During testing, both analyzers were placed inside the conex and were fed through 25’ of heated sample line, which maintained sample exhaust temperatures at 250°F.

Fuel Flow Measurement:

Several different methods were used to measure the fuel flow rate to the generator. The first utilized a load cell located at the base of the day tank, the second incorporated a submersible pressure transducer in the day tank itself, and the final method relied on information produced by the Engine Control Unit (ECU) and broadcast through the CAN bus system.

Fuel flow measurements were made using a single load cell located at the base of the day tank. The load cell was placed at the center of one of the edges of the tank while the other end was supported and fixed to a metal plate. The load cell was situated so that it would support approximately half the weight of the tank and the fuel combined.

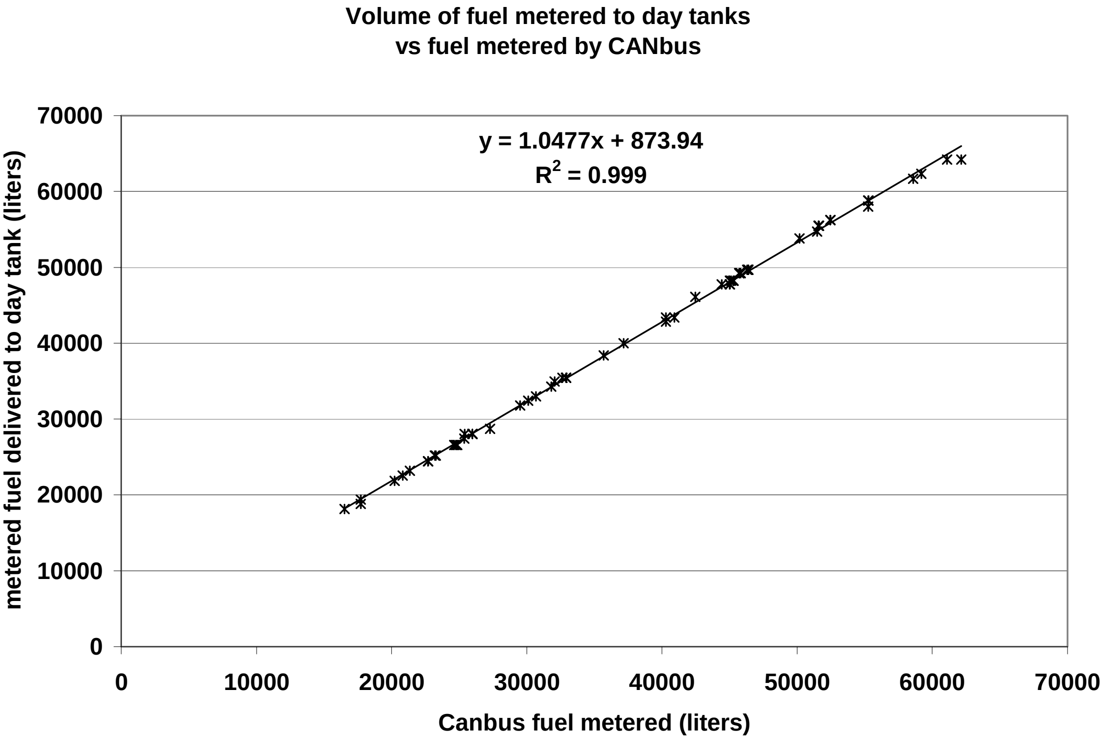


A change in fuel mass (fuel flow into the engine) would therefore show up as a change in load cell output voltage. Calibration of the load cell was done by adding a fixed mass of fuel and measuring the load cell response. This was repeated until the tank was full providing a plot of the load cell output versus fuel mass in the day tank. Unfortunately, because load cells are based on strain gauges they are very sensitive to changes in temperature. Despite considerable steps to isolate the load cell from temperature changes the response showed considerable drift and nonlinearity.

The second source for fuel flow measurements was the submersible pressure transducer. This transducer sits on the bottom of the tank and uses a diaphragm exposed to the fuel on one side and connected to an atmospheric vent line on the other to accurately measure the pressure, and therefore mass, of the fuel. The pressure transducer could be calibrated and used in much the same way as the load cell but provided a much more stable output.

The inherent resolution of both of the previously mentioned fuel measurement techniques makes them more suitable for situations were average fuel consumption is desired, but the CANbus system is capable of reporting instantaneous fuel usage quite accurately. This system uses the ECU to calculate fuel flow based on timing information and the known volume of the injectors. As a result of the Detroit Diesel Unit Injector design the injectors function like a positive displacement pump controlled by the ECU. This provides a real time fuel measurement that is estimated to be within 5% of actual fuel flow from the factory but can be further calibrated if needed.

To verify the accuracy of this measurement the CANbus data was compared to the data from the bulk tank fuel pump for overall fuel consumption. The CANbus information, in liters per minute, was recorded at ten second intervals using LABview, but the ECU also keeps a running tab of total fuel usage. The bulk storage tank mounted FillRite meter measured the Syntroleum fuel delivered to the day tank, and the vendor's tanker mounted delivery meter measured the conventional fuel delivered to the day tank. The diesel generator operated for 275 hours on conventional fuel and 376 hours on Syntroleum before CANbus fuel consumption data was first acquired on 8/27/04. The ECM fuel consumption data is in the form of total volume of fuel consumed in the diesel engine since its manufacture. The National Instruments Data Acquisition system recorded the CANbus "total fuel used" data on many of the data sets. To compare the two systems a running summation of the fuel delivered to the day tanks was plotted against the fuel volume reported by the CANbus system. In this comparison there is no adjustment for volume of fuel remaining in the day tank when the CANbus reports the fuel volume used. The capacity of each of the two day tanks is 1135 liters.



The CANbus system reported less fuel volume than the bulk tank metering systems by approximately 5%. The coefficient of determination (r^2) of the two sets of fuel use data is 0.999.

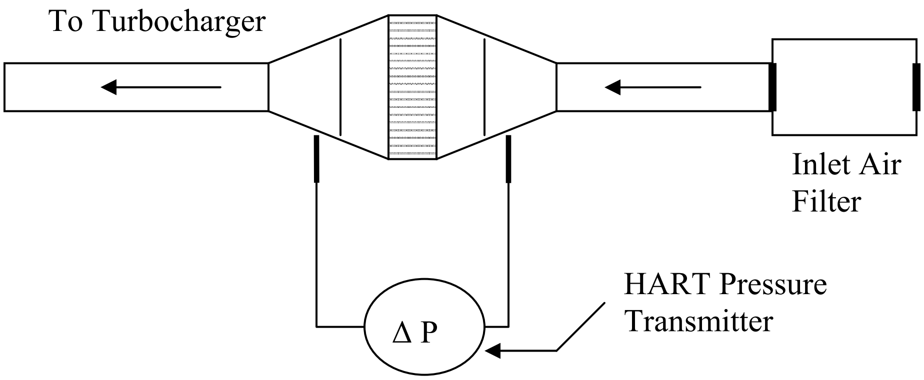
A number of factors introduce some error into the bulk tank metering data. The FillRite meter on the AETDL bulk tank has an accuracy of +/- 1%. It is assumed that the fuel vendor bulk meter would have a similar accuracy. Thermal expansion and contraction of the fuel would have an effect since the fuel was dispensed at ambient temperatures ranging from approximately 20 C to -20 C and the engine metering was done at elevated temperatures of as much as 70 C.

The CANbus fuel data appears to be as consistent as that from the logs of the fuel delivered from the bulk tanks. With calibration, a correction factor should be able to bring the data from both sources into agreement.

Air Flow Measurement:

All air flow measurements were made using a laminar flow element and a HART Pressure Transmitter manufactured by ABB. The laminar flow element was located on the air inlet line, after the inlet air filter. The HART pressure transmitter was connected to the laminar flow element and calculates the pressure drop across the element. This pressure drop is then translated into an air flow measurement in cubic feet per minute, with the help of conversions charts provided by the manufacturer.

A schematic of the apparatus is as shown below.



ΔP: Differential Pressure across the Laminar Flow Element

Volumetric flow in cubic feet was converted to a mass flow using air density. Corrections for the change in density and air humidity were applied to obtain the final air mass flow rate. Periodic checks were made to the laminar flow element to ensure that there was no resistance to air flow due to dirt or dust. Calibration of the differential pressure meter was made such that a 1 to 4 mA signal would signify a 1" to 4" WCG gauge across the laminar flow element.

Data Acquisition System:

The data acquisition system was comprised of the transducers for the various parameters of interest, excitation power supplies, and a cabinet mounted National Instruments PXI chassis with supporting modules. A list of all the data channels recorded can be found in Appendix A.

Transducers requiring external excitation were provided excitation from an auxiliary 24 volt DC power supply or an internal 10 volt DC supply on a data acquisition module. Output from devices with a 4-20 milliamp current output was passed through a precision 249 ohm resistor to generate a 1 – 5 volt DC signal. Voltage and current signal wiring with the exception of thermocouple wiring was routed through an intermediate junction box in the data acquisition cabinet to facilitate troubleshooting and calibration. Thermocouple wiring was terminated at the thermocouple amplifier.

The data acquisition system was housed in a cabinet with the junction box and auxiliary power supply. The cabinet environment was moderated with a temperature controlled ventilation fan and vent supplying outdoor air. The temperature control was employed to prevent overheating of the data acquisition system caused by elevated temperatures in the generator enclosure.

The National Instruments data acquisition system was comprised of the following:

- PXI 1042 Pentium based chassis
  - PXI 4472 dynamic signal acquisition module for vibration
  - PXI 8464 CANbus data acquisition
  - PXI 6070E input from auxiliary SCXI chassis
    - SCXI Chassis
      - SCXI 1120 (4 modules) analog input 0-10V DC
      - SCXI 1121 analog input 0-10V DC with excitation
      - SCXI 1102 thermocouple amplifier

Vibration information was acquired using one Dytran model 4120 current source for vibration transducers along with two single axis accelerometers and a triaxial accelerometer.

Emissions and Performance Standardized Testing Procedure:

The standardized testing procedure used to evaluate the emissions and performance of the generator was based on ISO 8178 D2 protocol. This testing procedure measures the engines performance at 5 operating points and then uses a weighting scheme to assign overall performance numbers. These operating points (as a function of full load) and their corresponding weightings are given below.

Power	100%	75%	50%	25%	10%
Weighting	0.05	0.25	0.30	0.30	0.10

For each fuel type tested the generator will be run for approximately 15 minutes at each power level and emissions and fuel consumption will be recorded. After all points have been measured the data will be processed and overall performance numbers calculated. This procedure is then repeated with the injection timing (beginning of injection) set to (+3), (+5), and (-3) degrees.

There were several different fuels tested throughout the course of this experiment: S-2 (a Fischer-Tropsch synthetic fuel equivalent to number 2 diesel), S-1 (a Fischer-Tropsch synthetic fuel equivalent to number 1 diesel), S-2W (a winter weight Fischer-Tropsch synthetic fuel with properties lying between number 1 and number 2 diesel), and conventional diesel (to use as a base for comparison and evaluation of the synthetic fuels). A synthetic Naptha was also considered for testing but was rejected due to the safety and code issues associated with using this type of fuel.

Vibrations Measurements:

Every type of fuel contains a different mix of hydrocarbon compounds which should result in differences in the combustion process. This goal of this test was to measure the engines vibration patterns and try and correlate this data with changes in fuel or other engine operating characteristics.

The accelerometers were placed as close to the cylinders as possible in order to detect the changes in vibrations produced due to the combustion process. Several data sets were collected for each of the operating conditions mentioned above in the emissions and performance standard testing procedure. The raw data was then filtered and plotted using MATLAB to provide a visual representation of engine vibration.

Fuel Properties:

In order to better understand how using the synthetic fuels was going to affect the engines operation, several tests were done to examine the fuels' basic physical properties. These properties included lubricity, viscosity, density, and thermal expansion.

(a) Lubricity

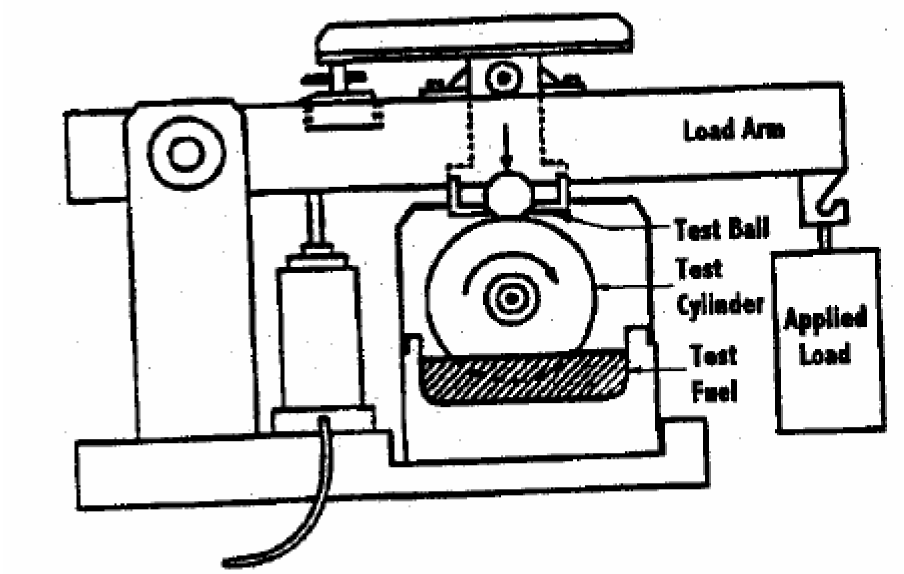
Lubricity is a complex property of a fluid that greatly depends on the technique used to measure it. A widely used definition is that offered by Appledorn and Dukek (1996).

> "For two liquids of same viscosity, if one gives lower friction, wear, or scuffing, then it is said to have better lubricity"

Lubricity of the fuel is evaluated based on ASTM (American Society of Testing Materials) standards .The two most commonly used standard ASTM methods to evaluate the lubricity of Diesel fuels are as follows

1. **Scuffing Load Ball on Cylinder Lubricity Evaluator (SLBOCLE ASTM D6078)**
   This test involves pressing a non-rotating steel ball against a polished steel ring as shown in figure 1. The ring is partially immersed in the test fuel and rotates at 525 rpm. The fuel is maintained at 25^0 C throughout the test. The traditional BOCLE test (ASTM 5001) pushed the ball into the cylinder with 1000g (9.8 N) of force for 30 minutes and then measured the diameter of the wear scar produced on the ball.

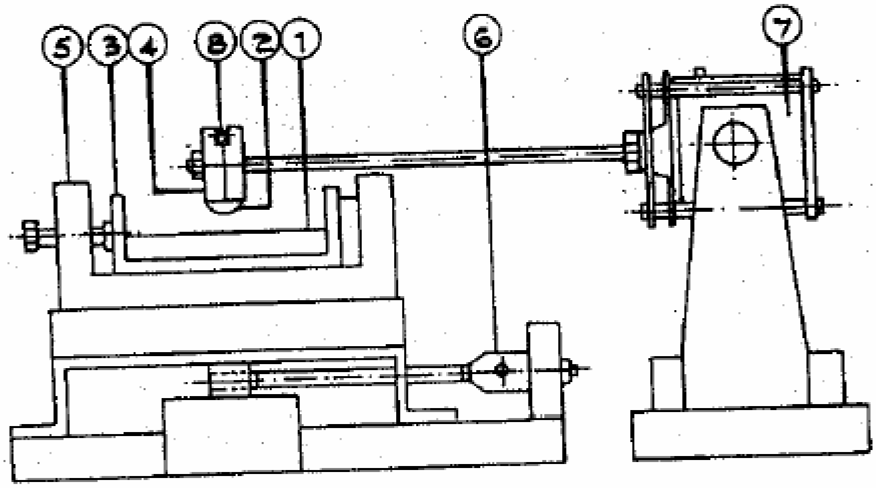
   The SLBOCLE actually measures the friction coefficient between the ball and cylinder as the load is increased. When the load is increased to the point where the friction coefficient just exceeds 0.175, that force is a measure of the fuel's lubricating properties. The test result is a weight value and the Engine Manufacturers Association (**EMA**) has recommended that diesel fuels have a SLBOCLE level greater than 3100 gm. The SLBOCLE test has been found to be more severe than ASTM D 5001 and is therefore more sensitive to differences between fuels. (Lacey and Westbrook, 1995)



Scuffing Load Ball-on-Cylinder Lubricity Evaluator

2. High Frequency Reciprocating Rig (HFRR ASTM D 6079)

The HFRR, developed at Imperial College in London (Wei and Spikes, 1986), is shown schematically in Figure2.This apparatus consists of a 6.35 mm ball that oscillates along a static flat surface. The ball is held against the surface with a calibrated load. The test result is the diameter of the wear scar formed on the ball, usually expressed in microns. The EMA recommends that the scar diameter be no greater than 450 microns.



High frequency Reciprocating Rig: 1.Test plate 2.Test ball 3.Oil bath

4. Chuck 5.Heating block 6. Piezoelectric crystal force gauge 7.Vibrator 8.loading pin (Wei and Spikes, 1986)

Among the above mentioned standard testing methods ASTM D6078 (**SLBOCLE**) was selected to evaluate the lubricity of Syntroleum synthetic Diesel fuel. At first it was decided to carry out the test in the university tribology lab but due to partial instrumentation and high cost of set up, later it was decided to send the samples to **SWRI** (South West Research Institute) to evaluate the lubricity of the fuel.

The fuel shipment was received from Syntroleum in three different batches.

- Batch 1 was S-2 Winter grade fuel.
- Batch 2 was Normal S-2 fuel.
- Batch 3 was S-1 Arctic grade fuel.

The fuel samples from different batches were sent to **SWRI** for lubricity test and evaluation.

(b) Viscosity

Viscosity is a measure of a fluid's resistance to flow. The greater the viscosity, the less readily the liquid flows. This measurement directly relates to the injection pump and injector leakage. Viscosity affects fuel spray atomization (turning the liquid fuel into as small droplets as possible before combustion) and fuel system lubrication.
(Source: http://www.rxp.com/DieselFuel.htm)

Viscosity of the Syntroleum S-2 synthetic diesel was evaluated using the Wells-Brookfield Cone /Plate Viscometer (DV-11+).

The principle of operation of DV-11+ viscometer is to drive a spindle (which is immersed in the test fluid 0.5 -2ml) through a calibrated spring .The viscous drag of the fluid against the spindle is measured by the spring deflection. Spring deflection is measured with a rotary transducer. The measurement range of a DV-11+(in Centipoises or milli Pascal seconds) is determined by the rotational speed of the spindle, size and shape of the spindle, the container the spindle is rotating in and the full-scale torque of the calibrated spring.

(c) Density

Measurements were taken to determine the density of each of the Syntroleum synthetic fuels as well as conventional diesel, but as these measurements are fairly routine there is no need to discuss them further.

(d) Coefficient of thermal expansion

The coefficient of thermal expansion for S1 Syntroleum was established in the lab using a 500 ml volumetric and an electronic balance that measured to 0.1 gram. The filled volumetric flask was heated and liquid removed until 500 ml remained then weighed. The flask and fuel were then cooled to approximately room temperature and fluid added to return the volume to 500 ml and again weighed. This was then repeated at outdoor ambient temperature (about 0°C). The weight of the empty volumetric flask was subtracted from the total weight to yield the weight of the fuel. The expansion of the volumetric flask was neglected.

Corrosion:

One of the major advantages of the Syntroleum fuel is the fact that the lack of Sulfur makes exhaust after treatment feasible. The lack of Sulfur also opens up the possibility of capturing heat from the exhaust stream and putting it into productive use. In order to support the design effort for both after treatment and heat recovery systems, corrosion tests were performed on condensed exhaust gasses.

For this experiment exhaust gasses were condensed and collected for each of the fuels used. Corrosion coupons, both stainless steel (316L) and mild steel (C1010), were then submersed in these different exhaust condensates. After 72 hours the coupons were removed and weighed allowing the differences in corrosiveness between condensates to be demonstrated.

For each condensate sample this procedure was repeated twice. The first case measured the corrosion effect with insufficient oxygen (sealed container), and the second allowed oxygen to migrate freely (open container). The Ph value of each condensate was also tested.

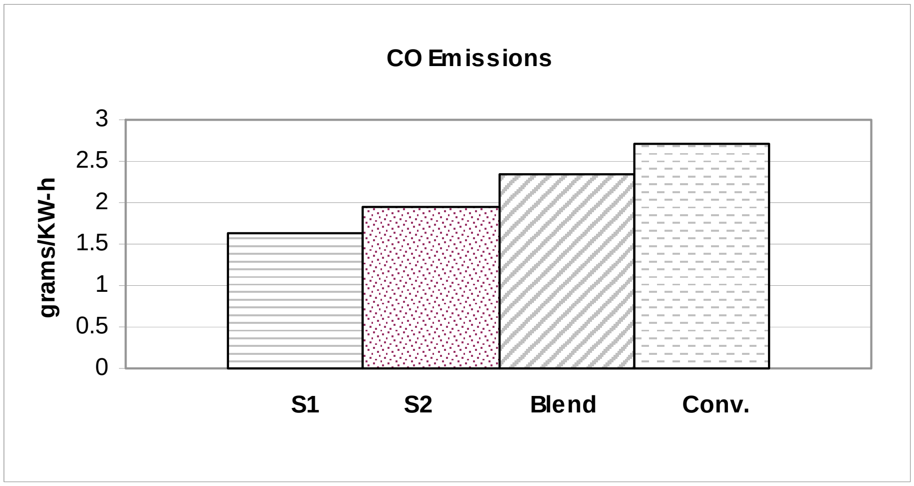
RESULTS / DISCUSSION:

The results of each of the various experiments are shown below, starting with emissions/performance, then vibrations, and finally fuel property testing. This section concludes with a discussion of several equipment problems/failures experienced during this project.

Emissions/performance:

(a) CO Emissions

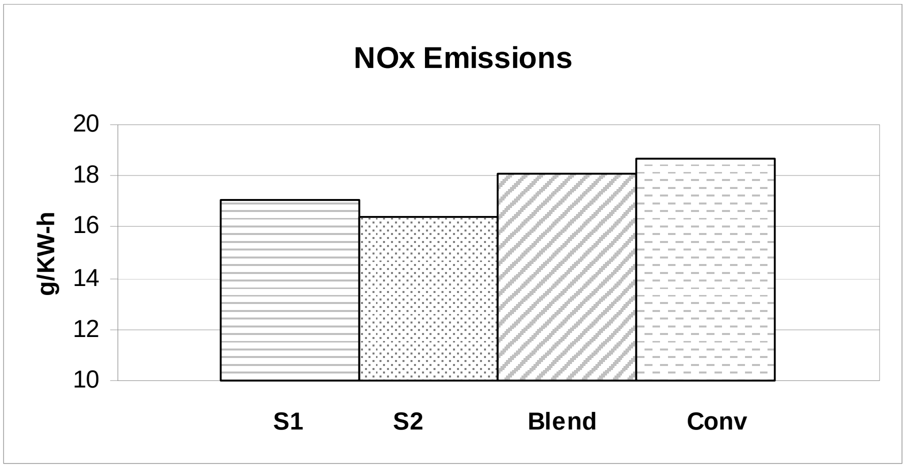
Both grades of synthetic fuel were seen to perform better than conventional diesel. Tests conducted with no change in injection timing saw a decrease of 39.88% on S1, 28% on S2 and a decrease of 11.56% on the blended fuel.



CO Emissions with no IT change

(b) NOx Emissions

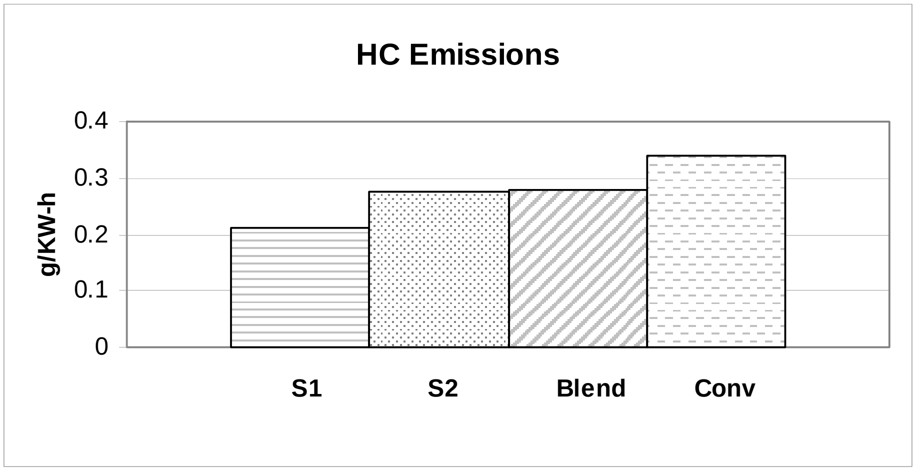
Preliminary testing conducted by Syntroleum on the S2 fuel, had indicated that the fuel might produce higher NOx emissions as compared to conventional diesel. Tests were conduced on 2.0 L Volkswagen diesel engine. However during testing, NOx emissions were actually seen to decrease when the engine was operated on synthetic diesel. A decrease of 8.69% was observed on the S1 fuel, while the S2 and the fuel blend showed a decrease of 12.17% and 3.1% respectively.



NOx Emissions with no IT change

(c) HC Emissions

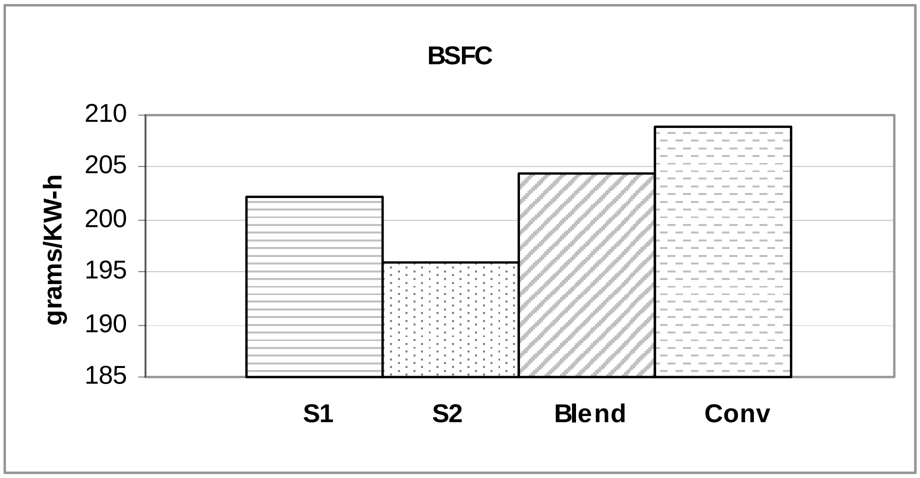
All HC emissions were calculated as propane equivalent. HC emissions on synthetic fuel were much lower as compared to conventional diesel. A decrease of 37.65%, 18.82% and 18.23% were seen on the S1, S2 and the blended fuel respectively.



HC emissions with no IT change

(d) BSFC

From the perspective of heating values, the synthetic fuel had 10 % lower heating value as compared to conventional diesel. This however translated into a 3.2 % decrease in fuel consumption at full load for the S1 fuel and a 6.3 % decrease in fuel consumption for the S2 as compared to conventional diesel. Following is a graph depicting the specific fuel consumption for the fuels tested.

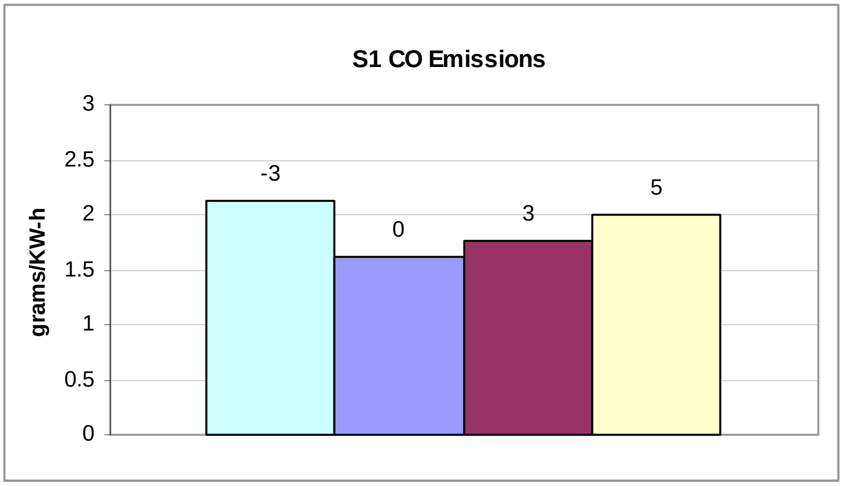


BSFC with no IT change

Effect of Injection Timing (IT) on engine emissions:

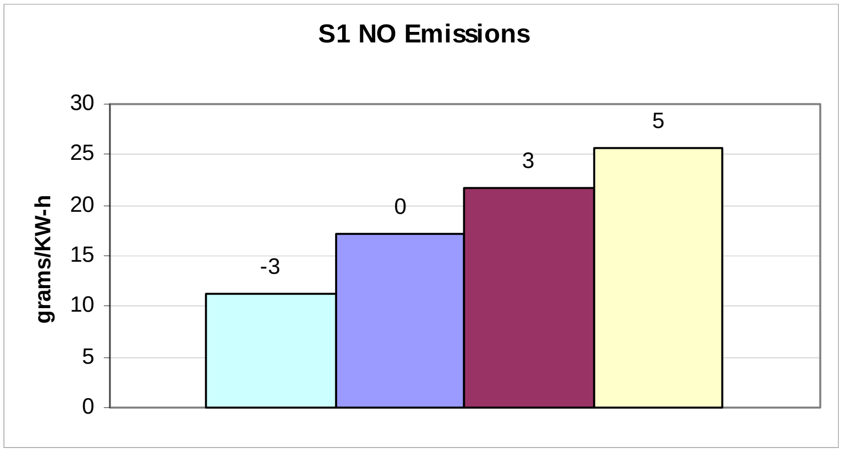
Emissions testing were conducted at three different injection timings, other than the factory setting. The three chosen injection timings were three and five degrees injection advance and a three degree injection retard.

Emissions results on the S1 synthetic fuel showed the optimum injection timing to be the factory set injection timing. CO emissions were at a minimum, when operated at the factory set injection timing. CO emissions seem to gradually increase with an injection timing advance, but a rapid increase was seen with an injection timing retard.



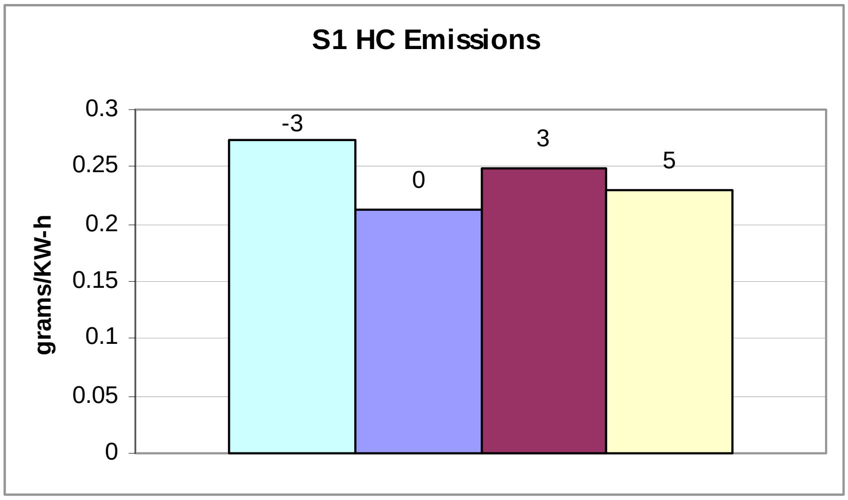
S1 fuel CO emissions at different IT

NO emissions for the S1 fuel at varying injection timing followed a predictable path. With an advance in injection timing NO emissions increased. With an advance in injection timing, higher flame temperatures and more time for combustion translates into higher NO emissions. As seen the NO emissions were seen to decrease with an injection timing retard.



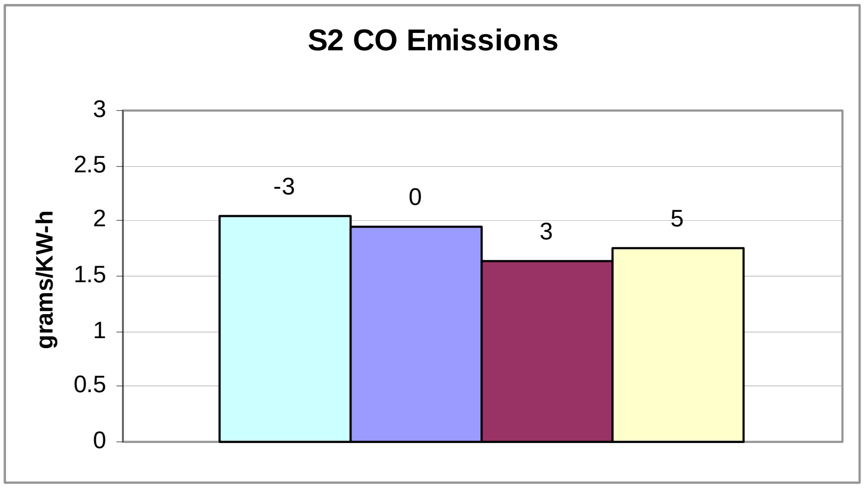
S1 fuel NO emissions at different IT

The HC emissions were seen to be lowest at the factory set injection timing. Increase in HC emissions were seen with an advance or retard of three degrees. However, the HC emissions seem to decrease when the injection timing was set to a five degree retard.

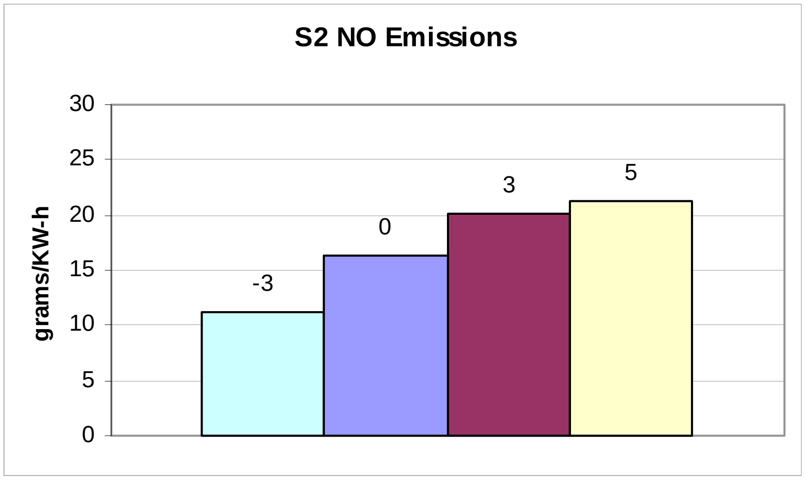


S1 fuel HC emissions at different IT

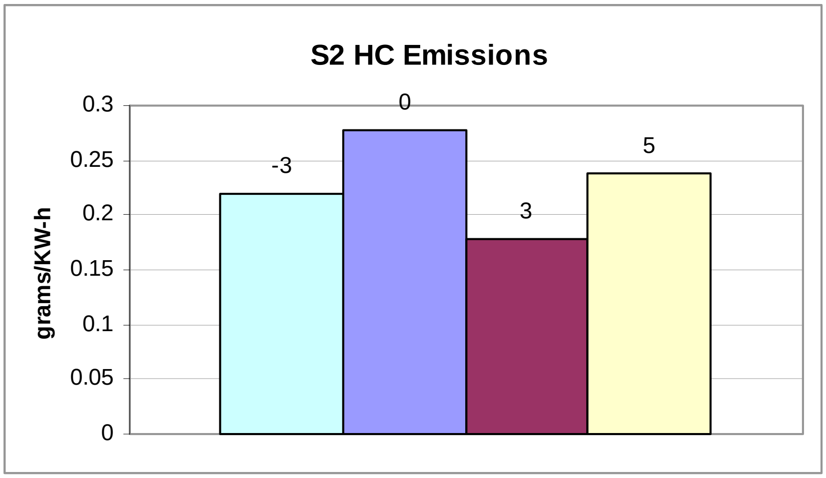
The S2 fuel displayed a similar trend in NO emissions when the injection timing was changed. However, minimum CO emissions were evident at a 3 degree advance, with a decrease of 16 % as compared to the factory set injection timing. HC emissions were seen to decrease with a three degree advance or retard.



S2 fuel CO emissions at different IT



S2 fuel NO emissions at different IT



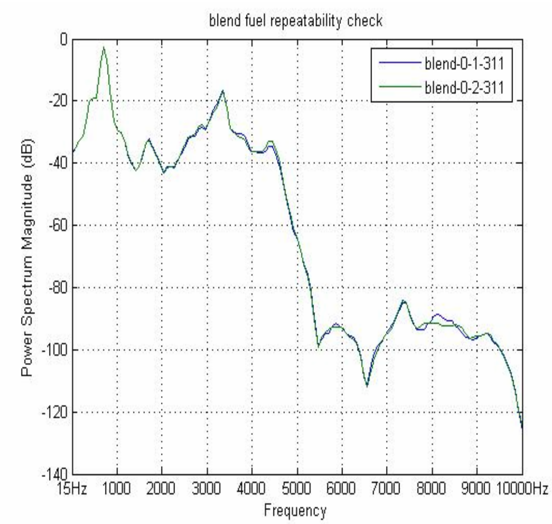
S2 HC emissions at different IT

The following table lists fuel emissions and brake specific fuel consumption (BSFC) at different injection timings.

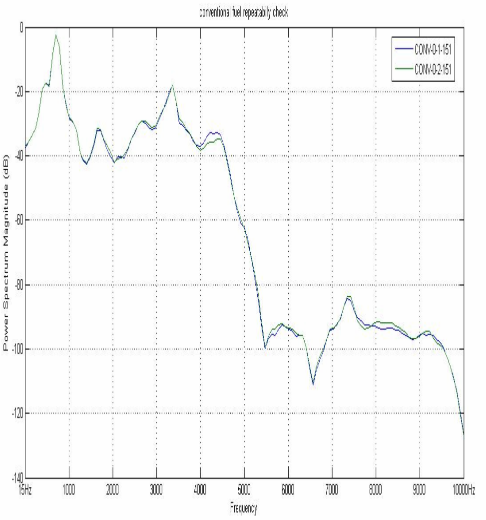
Fuel	Injection Timing	Emissions (g/KW-h)			BSFC (g/KW-h)
		CO	NO	HC	
Syntroleum S-1	+3	1.760	21.70	0.248	203.49
Syntroleum S-1	+5	1.992	25.66	0.229	203.09
Syntroleum S-1	-3	2.134	11.26	0.272	211.78
Syntroleum S-2	+3	1.635	20.04	0.177	191.41
Syntroleum S-2	+5	1.762	21.21	0.238	192.8
Syntroleum S-2	-3	2.046	11.94	0.219	203.96
Conventional (No.1)	+3	2.500	22.67	0.261	204.55
Conventional (No.1)	+5	2.534	23.9	0.393	203.69
Conventional (No.1)	-3	3.176	14.08	0.428	215.73
Blend	+3	2.346	22.54	0.239	198.01
Blend	+5	2.339	24.30	0.333	198.57
Blend	-3	2.227	13.20	0.228	209.11

Engine Vibrations:

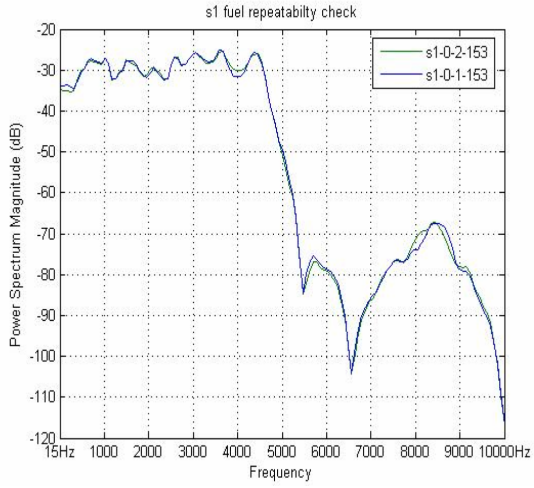
The vibration signals collected are being analyzed using MATLAB 7.0. The analysis of this data is just beginning, but the following sample graphs indicate the consistency of the vibration signals colleted.



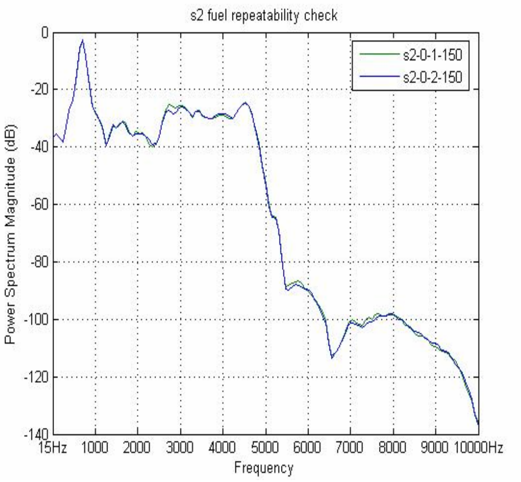
Blend fuel (50-50% conv&s-2)



Conventional diesel



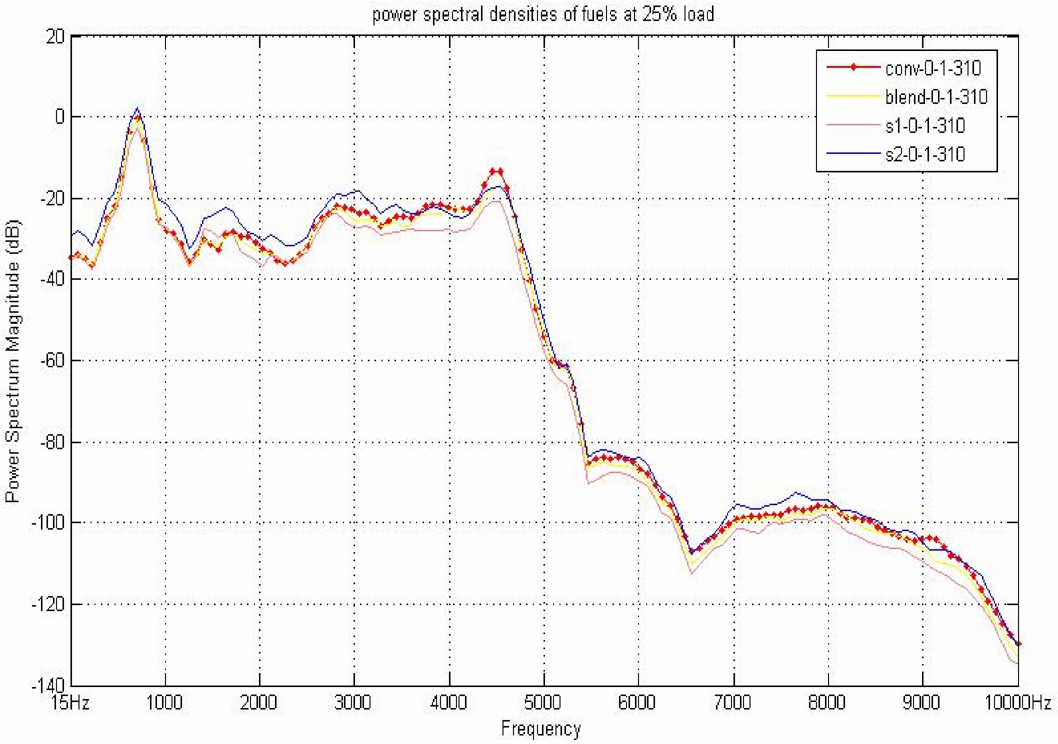
S-1 Arctic fuel



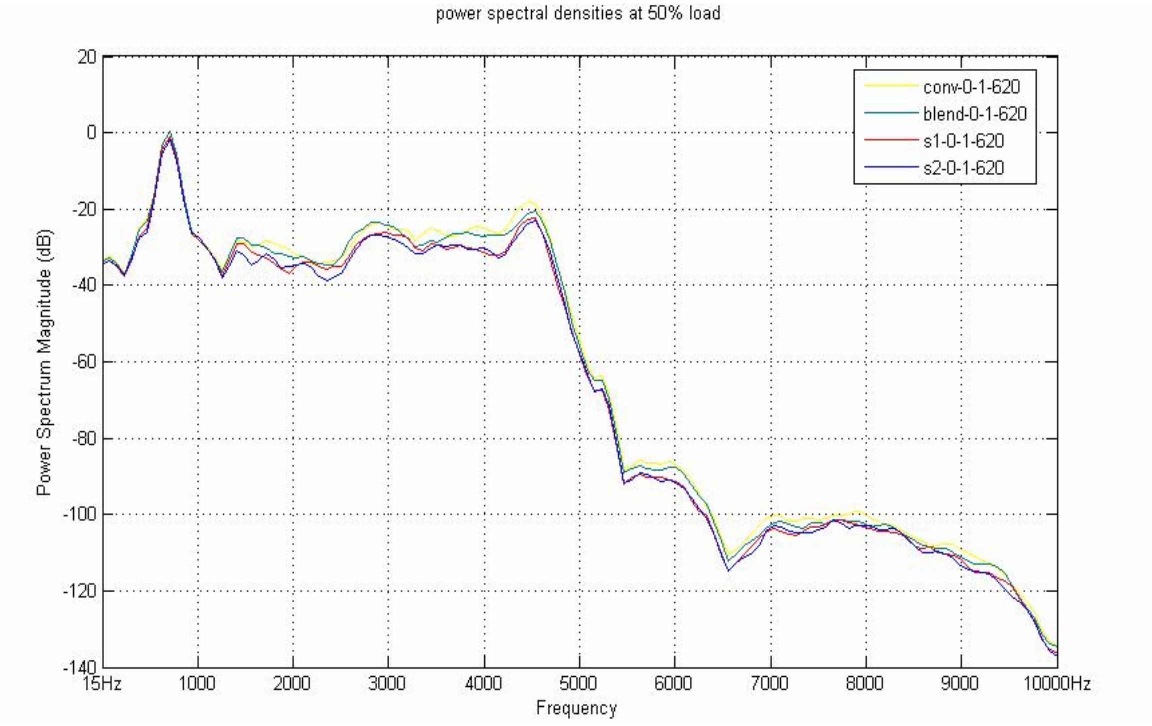
S-2 fuel (Syntroleum)

The above figures show power spectral densities of two identical signals but collected at different times. The signals contain frequencies between 15Hz to 10000Hz. The signals collected were filtered using a band-pass elliptical filter to remove noise from the raw signal. The filtered signal is processed using Fourier transformations to get the power spectral densities.

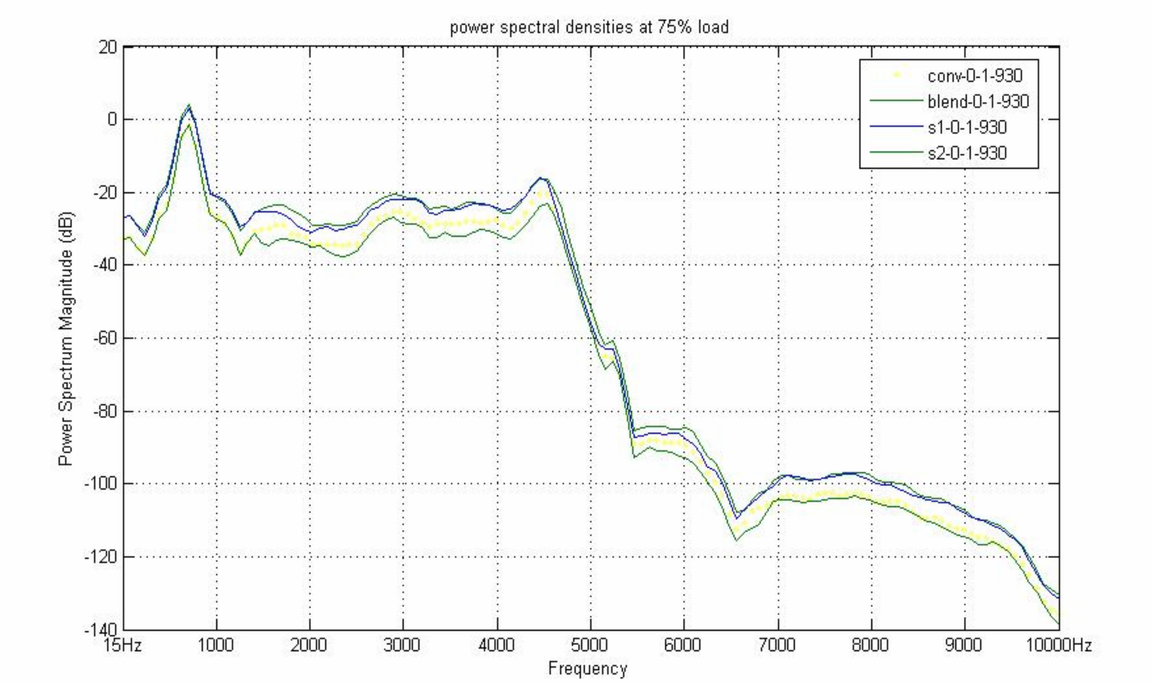
The following graphs show differences in power spectral densities of different fuels at different loads.



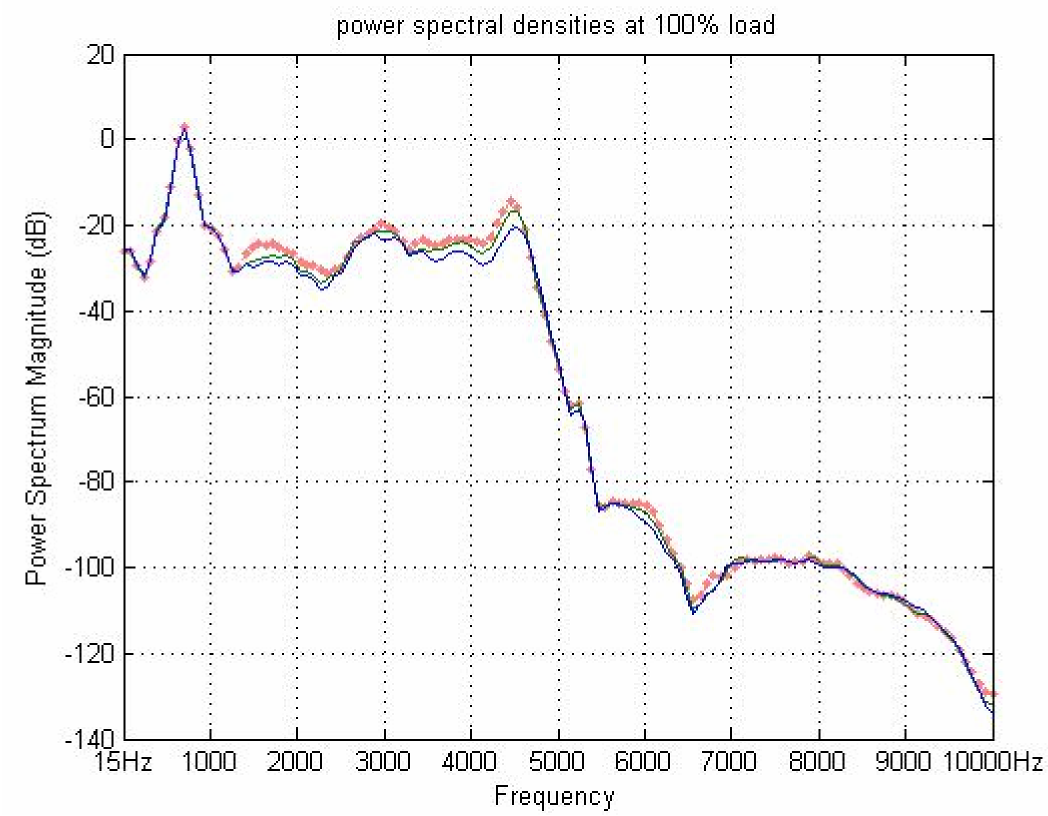
25 % Load (fuels used S-1, S2, Conventional, and Blend Fuel (50-50%))



50% Load (fuels used S-1, S2, Conventional, and Blend Fuel (50-50%))



75%Load (fuels used S-1, S2, Conventional, and Blend Fuel (50-50%))



100% Load (fuels used S-1, S2, Conventional, and Blend Fuel (50-50%))

The above graphs show variations in diesel engine vibrations caused by the various fuels used in the engine. The instantaneous and cyclic characteristics of the engine can be obtained using the vibration signals by using wavelet transformations, this provides time-frequency information for the vibration signal collected. The future work will be concentrated on analysis of the vibration signals using wavelet transformations.

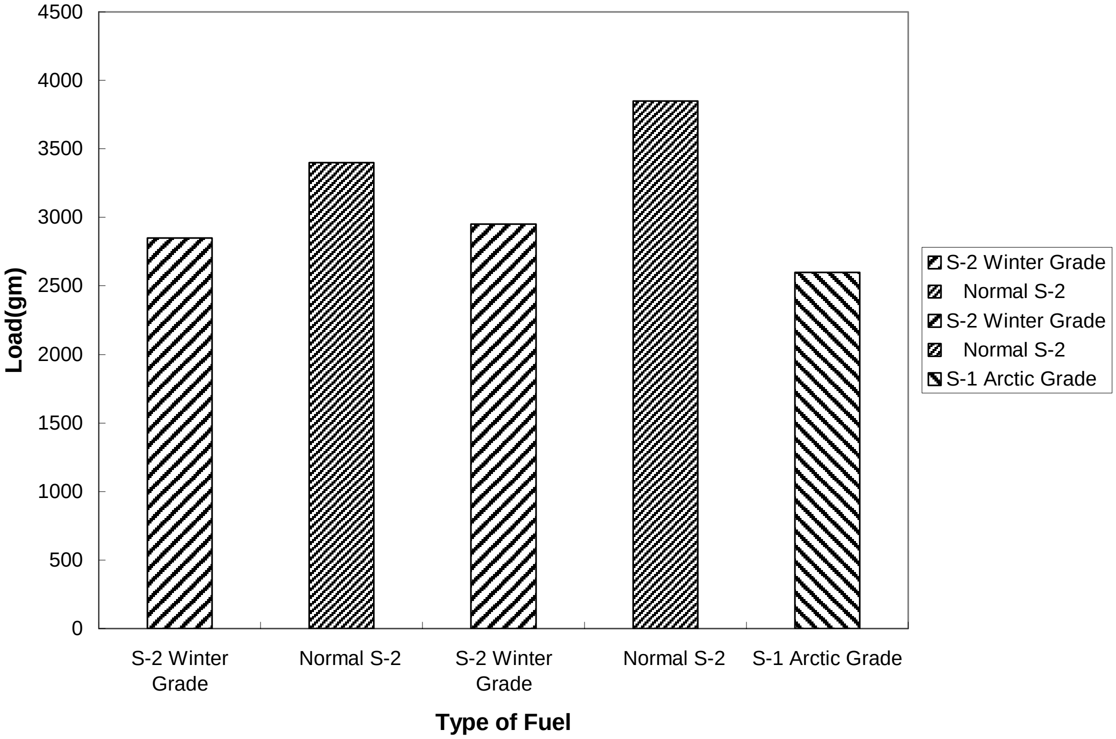
Fuel Properties:

(a) Lubricity

The lubricity results from the SLBOCLE tests conducted by SWRI are shown below.

Date of Testing	Batch No	Sample No	Type of Base Fuel	Lubricity(grams)
8/19/04	1	1	S-2 Winter Grade	2850
9/17/04	2	1	Normal S-2	3400
10/14/04	1	2	S-2 Winter Grade	2950
10/21/04	2	2	Normal S-2	3850
11/30/04	3	1	S-1 Arctic Grade	2600

Lubricity of various types of synthetic fuels.



Lubricity of various types of fuels

From the graph above it can be seen that batch 1 (S-2 Winter grade) and batch 3 (S-1 Arctic grade) both failed to meet the EMA/ASTM minimum 3100 gm load and that batch 2 (Normal S-2) passed the test. The Lubricity test on batches 1 and 2 of the fuel was performed twice in order to check the repeatability of the results.

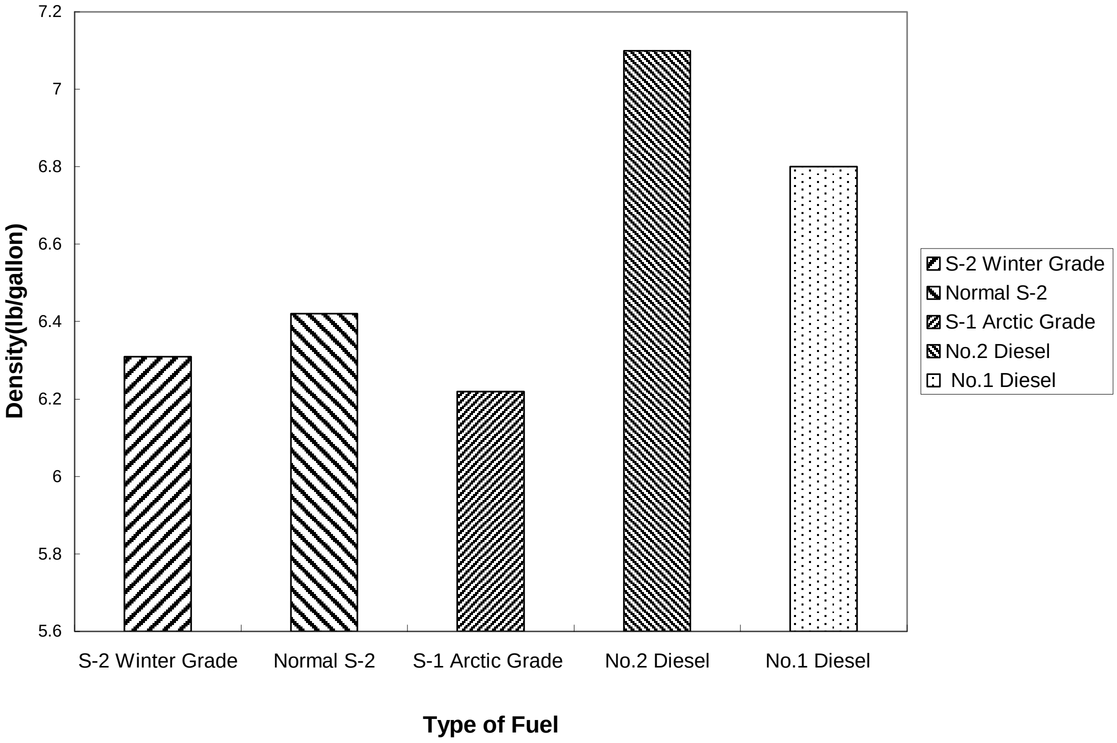
(b) Density

Increasing the fuel density increases the power output of the engine per unit volume of fuel consumed. However, reducing the fuel density often reduces the NOx and PM emissions. To correlate this trend, the density of each types of synthetic diesel fuel was measured and compared with the densities of No.1 and No.2 diesel fuel. This can be seen in the table and chart that follow.

Type of Fuel	**Density (lb/gallon)**
S-2 Winter Grade	6.31
Normal S-2	6.42
S-1 Arctic Grade	6.22
* No.2 Diesel	7.1
* No.1 Diesel	6.8

Densities of various types of fuels.

(*The data of No.1 and No.2 Diesel were provided by Flint Hill Resources, North pole Refinery, Alaska)



Density of different types of Diesel Fuel

(c) Viscosity

The viscosity results of individual batches of fuel are given in the charts that follow

R.P.M	**Torque**	**Viscosity@40Deg C(mPas)**	Shear stress **(N/sqm)**	**Shear Rate (1/sec)**
10	1.8	0.55	0.04	75.0
15	4.7	0.96	0.11	113.0
20	6.2	0.95	0.14	150.0
25	7.7	0.94	0.18	188.0
50	12.3	0.77	0.29	375.0
75	21.6	0.88	0.50	563.0
100	30.9	0.95	0.71	750.0

Viscosity results of Batch 1 S-2 winter grade fuel

R.P.M	Torque	Viscosity@40Deg C(mPas)	Shear stress (N/sqm)	Shear Rate (1/sec)
10	5.1	1.56	0.12	75.0
15	7.2	1.47	0.17	113.0
20	9.7	1.49	0.22	150.0
25	11.9	1.46	0.27	188.0
50	22.4	1.37	0.51	375.0
75	36.2	1.48	0.83	563.0
100	48.8	1.50	1.12	750.0

Viscosity results of Batch 2 normal S-2 fuel

R.P.M	Torque	Viscosity@40Deg C(mPas)	Shear stress (N/sqm)	Shear Rate (1/sec)
10	4.3	1.32	0.10	75.0
15	8.1	1.66	0.19	113.0
20	9.2	1.41	0.21	150.0
25	10.8	1.32	0.25	188.0
50	17.0	1.04	0.39	375.0
75	23.7	0.97	0.54	563.0
100	32.3	0.99	0.74	750.0

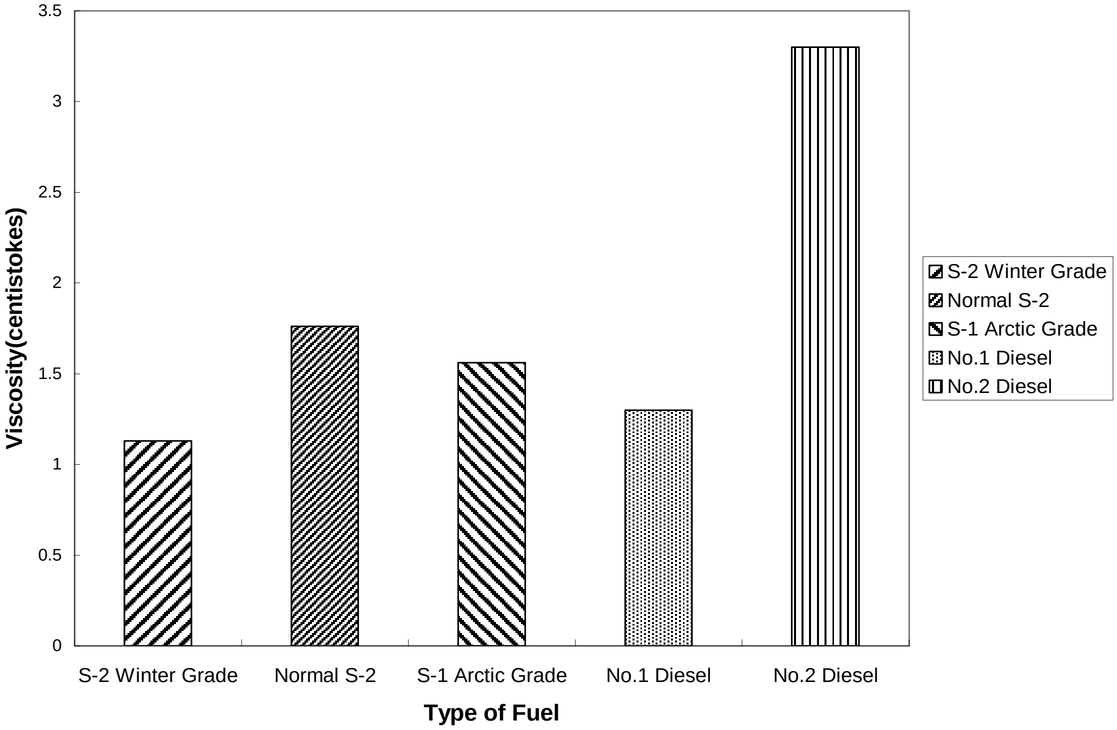
Viscosity results of Batch 3 S-1 arctic grade fuel

The Absolute viscosity value of the individual fuels is calculated by taking the average of the above readings and dividing by the density of the fuel to get the kinematic viscosity in centistokes. These results are given below.

Type of Fuel	**Dynamic Viscosity(centipoises)**	**Kinematic Viscosity(centistokes)**
S-2 Winter Grade	0.85	1.13
Normal S-2	1.32	1.76
S-1 Arctic Grade	1.1	1.56
*No.1 Diesel	1.05	1.3
*No.2 Diesel	2.8	3.3

(*The data of No.1 and No.2 diesel was provided by Flint-hills Resources, Alaska.)

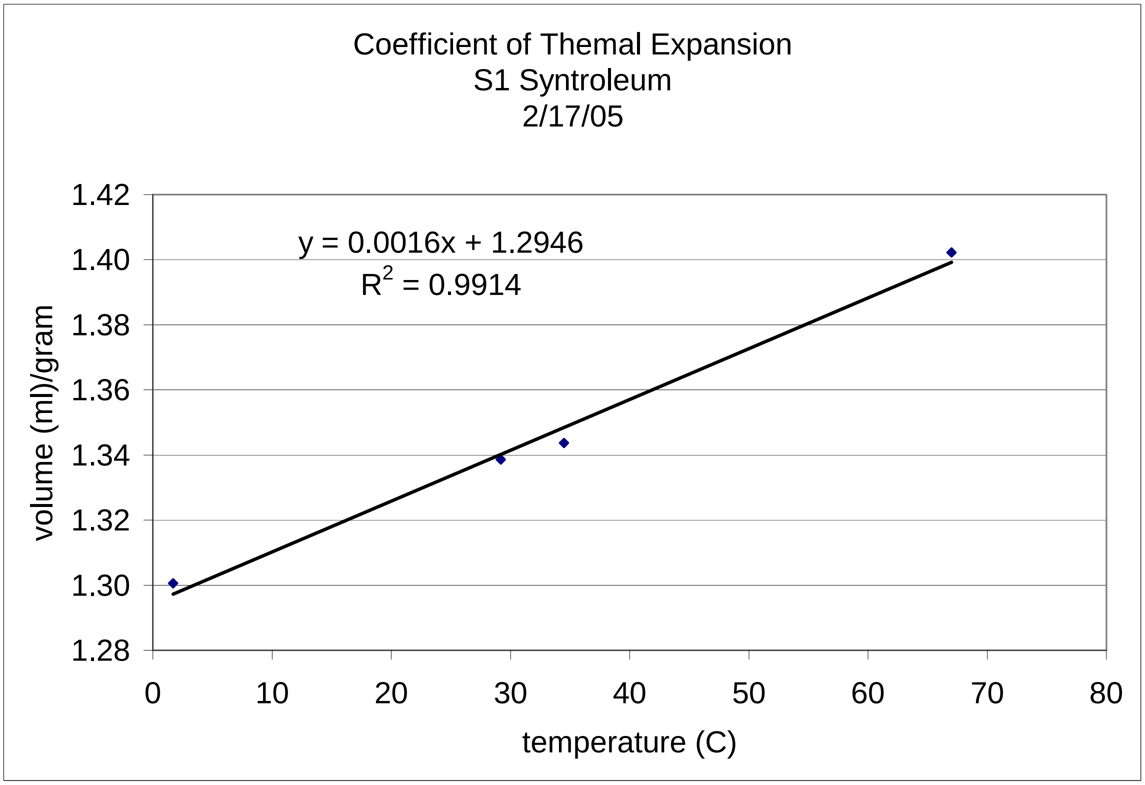
Viscosities of various types of fuel



Viscosities of various types of fuels

(d) Coefficient of Thermal Expansion

In order to correlate fuel flow measurements between the bulk fuel tank and the Detroit Diesel CANbus system, the coefficient of thermal expansion for the S1 synthetic fuel had to be determined. From the graph below it can be seen that this value was found to be 0.0016/°C.



Coefficient of Thermal Expansion (S1) Fuel

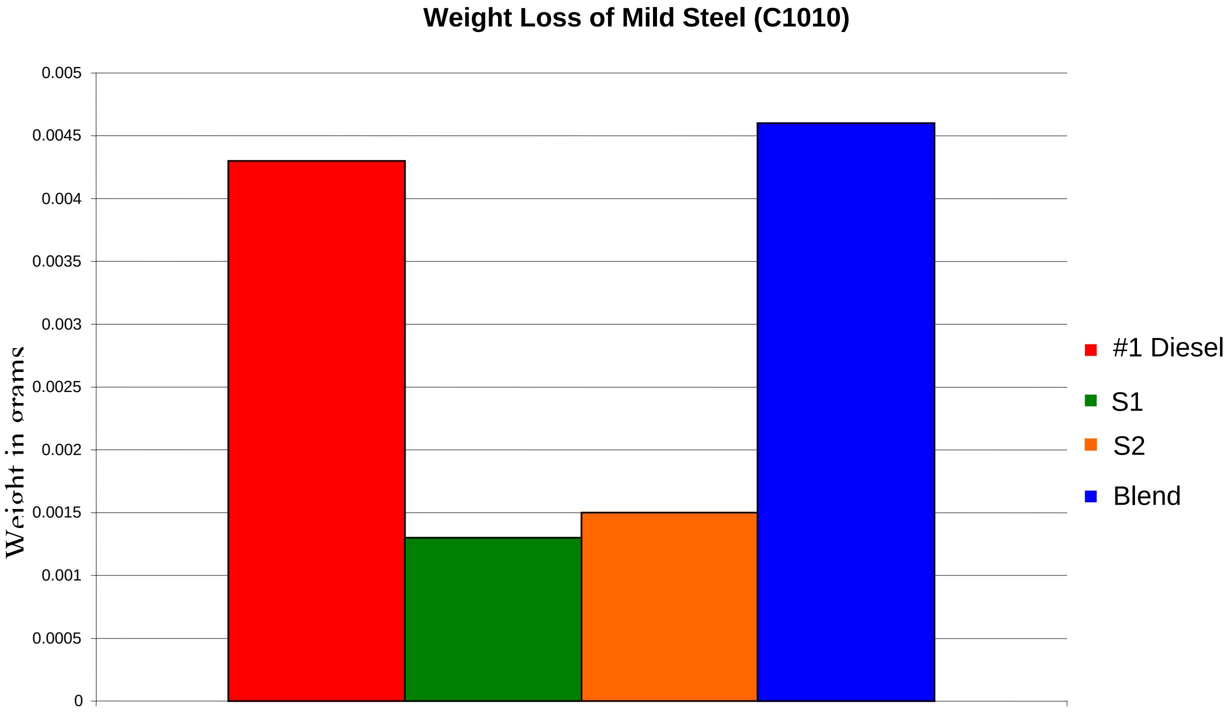
This value allowed researchers to convert the volumetric flows at different temperatures back to mass flows which could be directly compared, which in turn, allowed the actual error in fuel measurement to be determined.

Corrosion:

After being submersed for 72 hours the corrosion coupons were removed. They were then cleaned and weighed to determine the total loss of metal due to corrosion. This information is shown below with case 1 representing the sealed samples and case 2 represented the open samples.

Case 1:

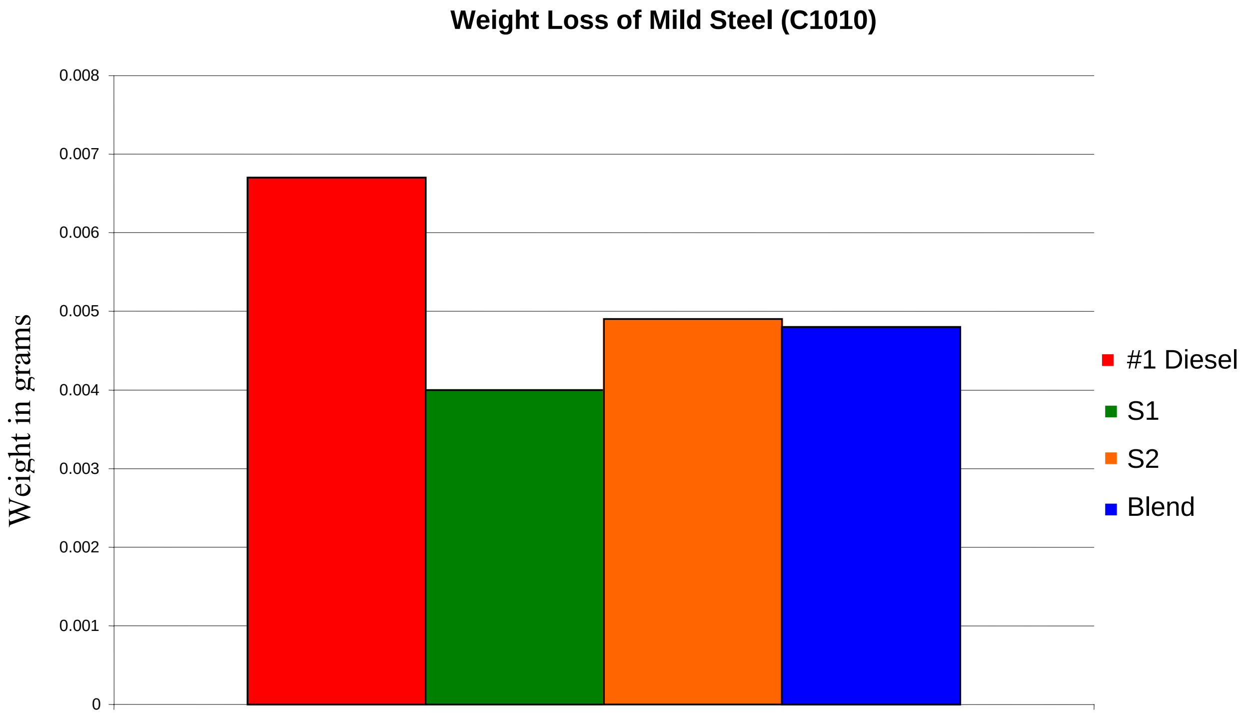
	Coupon 316L (stainless steel)			Coupon C1010 (Mild steel)			
Condensate Type	Before (Wt.in gms)	After (Wt.in gms	Difference (gms)	Before (Wt.in gms)	After (Wt.in gms)	Difference (gms)	Ph
#1 Diesel fuel	10.6801	10.6800	0.0001	11.7881	11.7838	0.0043	2
S1 fuel	10.6542	10.6542	0.00	11.7181	11.7168	0.0013	3
S2 fuel	10.5962	10.5962	0.00	11.8027	11.8012	0.0015	4
Blend(50%S2, 50% #1Diesel)	10.6276	10.6271	0.0005	11.7023	11.6977	0.0046	3



Weight Loss for the Sealed Sample

Case 2:

	Coupon 316L (stainless steel)			Coupon C1010 (Mild steel)			
Condensate Type	Before (Wt.in gms)	After (Wt.in gms	Difference (gms)	Before (Wt.in gms)	After (Wt.in gms)	Difference (gms)	Ph
#1 Diesel fuel	10.6800	10.6798	0.0002	11.7838	11.7771	0.0067	2
S1 fuel	10.6542	10.6542	0.00	11.7168	11.7128	0.004	3
S2 fuel	10.5962	10.5962	0.00	11.8012	11.7963	0.0049	4
Blend(50%S2, 50% #1Diesel)	10.6271	10.6271	0.00	11.6977	11.6929	0.0048	3



Weight Loss of the Open Sample

These results show a significant increase in corrosion for the coupons exposed to the conventional fuel. It should also be noted that no significant corrosion occurred on the stainless steel coupons regardless of the condensate they were submersed in.

Failure Analysis:

Over the course of this project there were several key components that malfunctioned or failed to perform as expected. These components included the NOVA emissions analyzer, the engine air intake system, and the fuel pump for the bulk fuel storage tank. These failures will be discussed in detail in the following paragraphs, but of primary importance is the fact that none of these problems can be attributed to the use of the Syntroleum synthetic fuel.

The first piece of equipment that we had problem with was the Nova emissions analyzer. This analyzer was purchased to measure and compare relative emissions levels while operating the engine on a variety of fuels and injection timing settings. The Nova analyzer relies on NDIR analysis to measure unburned hydrocarbons, CO, and CO2; and uses electrochemical sensors to measure NO, NO2 and O2. Initially, the Nova analyzer performed well, but by the end of the 275-hour break in using conventional diesel fuel its readings were becoming erratic and began to show considerable drift over time. Attempts were made to recalibrate the instrument so emissions data could be taken for the winter grade S2 fuel, but the problem continued. The Nova analyzer was shipped back to the factory on October, 8th and the electrochemical NOx sensors were replaced. Despite the use of several filters and a condensate removal pump in the unit the sensors were apparently damaged by the presence of the various sulfur compounds present in the conventional fuel exhaust stream. On November 9th and 10th a Relative Accuracy Test Audit (RATA) was performed by Alaska Source Testing (AST) which compared the performance of the Nova analyzer with the compliance level analyzers used by AST. This test indicated that the Nova analyzer was still not functioning properly and that even if it was it lacked the low level resolution to measure the CO produced by the engine. (A complete copy of the report generated by AST has been included with this report for reference.) Based on the recommendations of Bill Hudson at AST a new set of emissions measurement equipment was rented to perform the final emissions measurements used to compare the various fuels.

Throughout this test program the air intake system was a consistent source of problems. The turbocharger had to be replaced early on. Shortly thereafter the air filter collapsed. Finally, the emissions results consistently indicated that the engine was not getting enough air at high power levels. Of these failures the turbocharger was the easiest to explain. On September 16th UAF staff members heard a new and distinctive sound coming from the turbocharger and shut down the engine to investigate. The turbo housing was blackened on the inside and the turbine seamed to have excessive play. When the Detroit Diesel mechanic came to inspect the unit on the 21st he confirmed that the turbocharger was bad and indicated that the turbochargers on these engines were known to have problems and were under factory recall.

Explaining the filter failure was a little more difficult. By going back through the data set the pressure drop across the filter could be charted and the exact time of failure determined. At about 3:00 AM on November 9th the pressure drop across the filter peaked at approximately 15kPa. At this point the filter likely tore and the pressure began to oscillate from high to low as the air flow caused the filter to flap. By 5:00 AM the filter was completely destroyed and the laminar flow element was filled with debris that had broken loose from the filter over the preceding hours. In the end, the filter had to be replaced and the laminar flow element returned to the factory for cleaning and recalibration, but no real damage was done to the engine as the laminar flow element filtered out the debris released from the filter. The only real question is why this failure occurred. According to the maintenance manual the filter should be replaced once the pressure drop reaches 5kPa. With this in mind it is obvious that a pressure drop of 15kPa would probably be enough to cause failure, but why was the pressure drop this high? Looking at the data from the previous day there is an interesting and, as of yet, unexplained trend. Over the course of just a few hours the pressure across the filter went from about 7kPa at full power to around 13kPa at full power. On the day of failure this trend is repeated with the pressure drop reading around 8kPa when the full power run began and increasing to about 15kPa before the filter ultimately failed. When the engine is operated at high power levels there is a visible mist coming out of the crankcase breather, and one possible explanation is that because the engine was operating at high power for extended periods this mist was allowed to build up and eventually plug the air filter. It seems unlikely that this alone could have caused such a drastic increase in pressure across the filter, but after this experience the crankcase breather was run outside the conex just to be safe.

With the engine running at full power, emissions tests have consistently shown high CO levels. These high CO levels remained despite changes in weather, new filters, and even a new turbocharger. The consistency of these results led UAF researchers to believe them to be an intrinsic characteristic of the engine, possibly caused by wear in the injectors, and resulting in poor fuel spray patterns and incomplete combustion. At the completion of testing the injectors were replaced and no change in emissions was observed. This effectively ruled out wear associated with the use of the Synthetic fuels as a possible cause of the problem. At this point UAF researchers began to experiment with the engine and discovered that by simply allowing the intake to pull cool air from the bottom of the conex rather than hot air from the top a noticeable improvement in emissions could be achieved. A discussion with a Detroit Diesel sales rep confirmed that the intake system was designed for the 1800rpm engine and was therefore marginal for 1200rpm applications. In this particular case the extra restriction of the flow measurement equipment and the fact that air was being drawn from the hot upper area of the conex were enough to make a significant difference in overall air flow and therefore emissions readings at full load.

On Dec 4, 2004 a fuel leak was discovered in the fuel pump for the bulk fuel storage tank. The ambient outdoor temperate was indicating -22 F at the UAF entrance sign located about 500 yards from the fuel storage facility. A graduate student arrived to refuel the generator, and noted that while in use, the pump (a Fill-Rite Series 300 high flow pump) leaked at the major pump body seal. The leak persisted for the first couple of minutes of operation then stopped. The pump was used again on Sunday, December 5 at similar temperatures with similar results. The pump was purchased as a used unit and the meter indicated that 14,276 gallons had been pumped since it was installed at UAF. This was the first real cold spell of the winter, and as a result, it was not clear if the leak at the pump was caused by the use of the Syntroleum fuel (some seal materials depend on the swelling caused by aromatics in the fuel, which Syntroleum fuel is lacking) or if it was caused simply by the use of seals not suitable for use in arctic conditions. After consulting with the local supplier two replacement seal kits were purchased, one arctic grade seal kit and one conventional seal kit. Upon disassembly of the pump it was discovered that a conventional seal kit had originally been installed. Further analysis revealed no degradation of the existing seals when compared to the new conventional seal kit. Based on this information it was the opinion of the supplier and the UAF staff that the leak was most likely the result of operating the pump at sub-zero temperatures without the arctic grade seal kit installed.

Injector Testing:

One of the concerns with operating on the synthetic fuel is the buildup of deposits in the injectors. Under normal operating conditions there are small amounts of soot and other residue that stick to the combustion surfaces. These deposits generally have little to no effect and are eventually burned off or break free from whatever surfaces they form on. However, if these deposits form in the injector nozzles fuel delivery problems can result. With conventional fuels this is rarely a problem because the fuels themselves act as a solvent and keep the injector nozzles clean. However, the synthetic fuels consist almost entirely of straight chain hydrocarbons and have virtually no solvent capacity. For this reason UAF has taken several steps to investigate this issue.

After completion of the long-term test 3 of the 4 injectors were sent to SWRI for flow testing. Shown below are excerpts from SWRI's report showing the results of these tests.

Injector flow performance tests were conducted with series 60 cam shaft speed set at 1000 rpm and fuel temperature maintained between 96 to 100 degree of Fahrenheit. Test fuel used in the performance test was S-2 Synthetic Diesel Fuel, provided by Syntroleum Corporation.

After each injector was properly mounted onto the test rig, flow performance test began. When 200cc injected effluence fuel was collected or an equivalent time duration had elapsed, a test run was terminated. Injection volume per stroke was then calculated by dividing the volume of fuel collected with the total number of injection events which is registered via an electronic counter. For each test article four test runs were conducted to obtain the average and other associated statistics.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Test results for the four injectors supplied are as follows:

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Reviewing these results, we may reach the following conclusions and comments:

a. Each tested injector is very consistent in its four runs of flow performance indicated by the corresponding standard deviation value.
b. Two used injectors, D2 and D3 have injection rates very close to a known baseline value, although they are slightly higher.
c. Injection rate for D1 is significantly higher than those of D2 and D3. Higher injection rate could be caused by erosion or corrosion to the injector spray holes.
d. Injector D4, which was operated with Fischer Trop fuel, did not produce any injections in the four test runs conducted, although these test runs seemed to be running normal in terms of mechanical and electronic operations. A typical cause for this phenomenon is spray holes fully plugging.
e. Further investigation is needed to pin point the root causes for the behavior these

injectors displayed.

In the above report SWRI has labeled the injectors D1 through D4. It should be stated that injector D4 was an injector that had failed while running on Fish Oil BioDiesel and was not one of the injectors run on the synthetic fuel. It was included in this test batch for the sake of convenience. The notes on the chart indicate that during testing at SWRI the injector was run on the Fisher-Tropsch synthetic fuel because none of the fish oil was available. From these results it is apparent that no significant injector fouling had occurred during the 2200+ hours of testing at UAF.

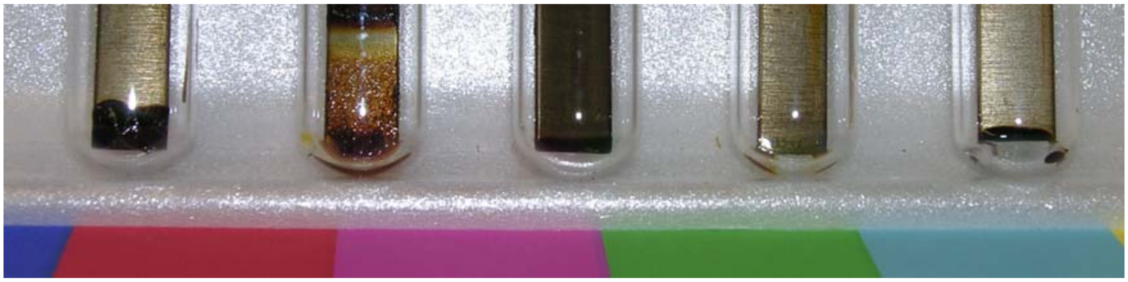
There is some question about the role lube oil in the cylinders plays in the formation of deposits in the injector nozzles. As a surrogate for injectors exposed to fuels and oils at elevated temperatures, fuels contaminated with used crankcase oil in a ratio of 25:1 were heated to 190°C in a muffle oven for 23 hours. Sample volumes of 1 ml were placed in 10 ml Pyrex tubes and a mild steel strip, as a nucleation site, was placed in each sample tube. Controls with no crankcase oil added were heated in the muffle oven along with the contaminated samples.

After heating, both the S-1 and S-2 Winter blend volatilized leaving a small amount of carbonaceous residue in the sample tubes (Figures 3 & 5). Approximately 10% to 20% of the S-2 fuel remained in the sample tube and no deposits were visible. A small amount of carbonaceous residue remained on the nucleation strips from the S-1 and S-2 Winter blend in the oil contaminated samples whereas there was none on the strips in the uncontaminated samples (Figures 2 & 4). The lack of residue on the strip in the oil contaminated S-2 may be attributed to the contaminants staying in solution in the remaining non volatilized liquid. The quantity of deposits on the strip in the conventional fuel was much greater than that on the strips in Syntroleum. The only test strip in the uncontaminated fuels to have deposits was the one in the conventional #2 diesel fuel. These results can be seen in the photos below.

Figure 1. Samples – pre test

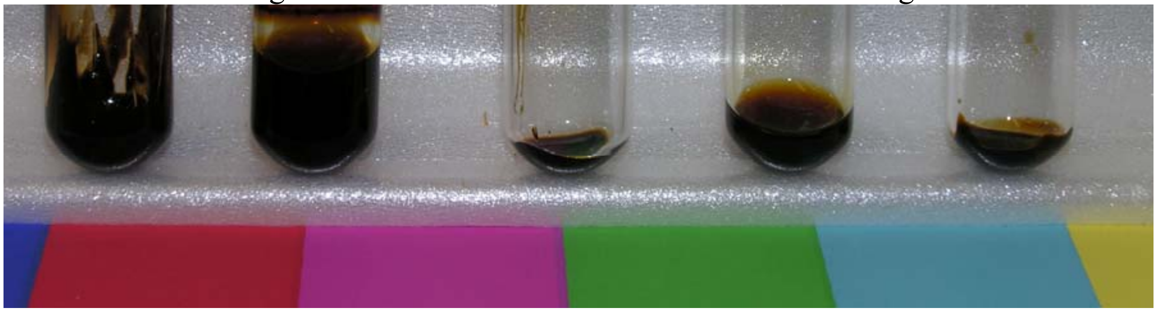
From left to right, S2 Winter, S2 Winter with oil, S2, S2 with oil, S1, S1 with oil, biodiesel, biodiesel with oil, #2 diesel, and #2 diesel with oil

Figure 2. Nucleation strips from oil contaminated samples after heating



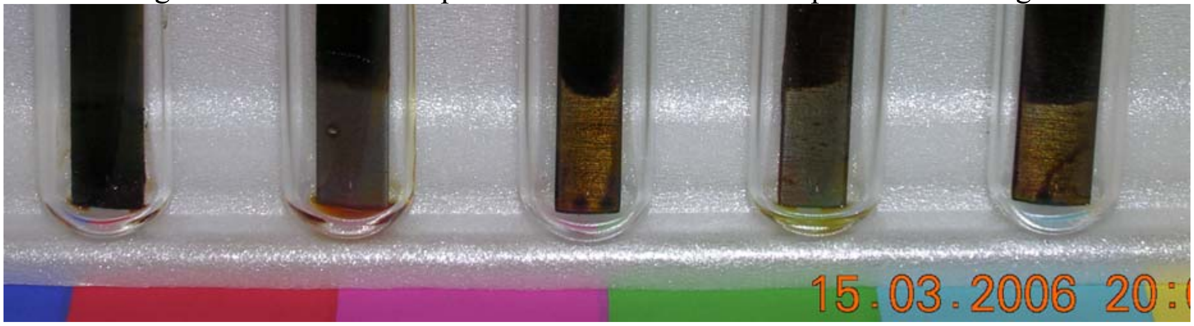
From left to right, conventional diesel, biodiesel, S2 Winter, S2, and S1

Figure 3. Oil contaminated fuel residue after heating



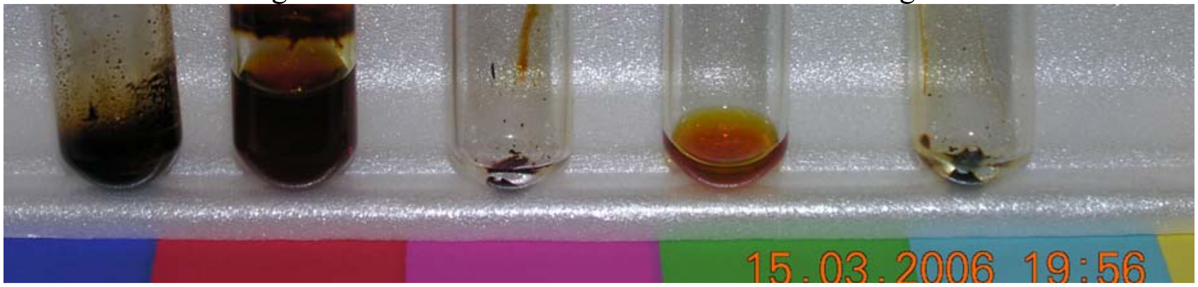
From left to right, conventional diesel, biodiesel, S2 Winter, S2, and S1

Figure 4. Nucleation strips from uncontaminated samples after heating



From left to right, conventional diesel, biodiesel, S2 Winter, S2, and S1

Figure 5. Uncontaminated fuel residue after heating



From left to right, conventional diesel, biodiesel, Syntroleum S1 & S2 blend, Syntroleum S2, and Syntroleum S1

The presence of the crankcase oil was associated with increased deposits on the test strips in all fuels except for the Syntroleum S-2. This would support the theory that despite the cleaner burning qualities of the Syntroleum synthetic fuels the presence of small amounts of lube oil in combination with the low solvency of these Fischer-Tropsch fuels could cause deposits to form on the injectors. However, more research is needed to come up with a definitive answer to these questions.

CONCLUSION:

As emissions regulations continue to tighten and environmental impact becomes more of a concern there will be a need for ultra clean diesel engines both for heavy-duty vehicles and industrial power generation. With little to no Sulfur and the ability to be produced from just about any hydrocarbon feedstock Fischer-Tropsch fuels appear to be an ideal fit in enabling the development of ultra clean diesel technology. However, the very properties that make Fischer-Tropsch fuels so attractive are also the biggest obstacles that have to be overcome. Fischer-Tropsch fuels can be produced from a variety of sources, but the energy losses associated with this conversion add to the overall cost and environmental impact of using the fuel. Similarly, being Sulfur free allows the use of exhaust treatment technologies that will significantly reduce pollution, but because Sulfur is one of the primary lubricating agents in conventional diesel, lubrication becomes a critical issue when using these fuels.

With this in mind, the Detroit Diesel Series 50 engine was specifically chosen for this program. The design of the Detroit Diesel Unit Injection system basically ensures that any damage in the engine as a result of the fuel will take place in the injectors. This in turn allows damage to quickly be ascertained in terms of overall engine performance.

Based on the results given in the previous section, this project can be considered a resounding success. The Syntroleum synthetic fuel was run through the engine for over 2200 hours with no signs of damage or degradation due to the fuel. Despite low lubricity values found in laboratory experiments key performance indicators such as fuel consumption actually improved over the life of the project. In addition, emissions data showed a decrease in all emissions components measured when using the Syntroleum fuel and indicated that no change was needed in the engine injection timing or operating procedure. Concurrent tests at other locations have shown problems with injector fouling and deposits using the Syntroleum fuel in specific engines, but none of these issues were experienced on the Detroit Diesel engine used at UAF.

Future / Related Work:

A separate report can be found for Task 9.2 showing the results of fuel cell tests conducted using the Syntroleum synthetic fuel. In addition, there were several projects started under this award that have yet to be completed. At this time, work is continuing with regard to vibration analysis and heat recovery. For more information on any of these projects please contact the UAF Energy Center / AETDL.

APPENDIXES:

A. Data Acquisition Channels

B. Aseem Telang Thesis “EMISSIONS TESTING OF SYNTROLEUM FUELS IN DIESEL POWER PLANTS SUITABLE FOR ALASKA”

C. Sastry Kanthikiran Thesis “TESTING OF SYNTROLEUM SYNTHETIC FUELS SUITABLE FOR ALASKA”

D. Southwest Research Institute Injector Flow Rate Report

E. Alaska Source Testing Emissions Report

APPENDIX A:

Data acquisition channels

data units	data label	purpose
Deg C	Cooling Water Inlet	temperature of jacket water entering diesel engine from the radiator
Deg C	Cooling Water Outlet	temperature of jacket water leaving diesel engine at thermostat housing
Deg C	Exhaust Temperature	temperature of engine exhaust leaving turbocharger
Deg C	Intake Manifold Air	air temperature at inlet of intake manifold
Deg C	Turbo Outlet Air	temperature of air leaving turbocharger
in wc	Differential pressure	differential pressure across the laminar flow element
C	ambient Temperature	temperature in the generator enclosure less than 1/2 meter from intake of the air filter
%	Relative Humidity	relative humidity of air in the generator enclosure less than 1/2 meter from intake of air filter
%	CO	analog output from CO channel of NOVA emissions analyzer
%	CO2	analog output from CO2 channel of NOVA emissions analyzer
ppm	NO	analog output from NO channel of NOVA emissions analyzer
ppm	NO2	analog output from NO2 channel of NOVA emissions analyzer
ppm	HC	analog output from HC channel of NOVA emissions analyzer
%	Opacity	opacity meter analog output
kg	load cell	output of load cell under clean fuel day tank
Deg C	Load Cell Temp	temperature of load cell base under day tank
Deg C	DAQ temp	air temperature in the upper portion of DAQ system
inH2o	Day tank pressure	analog output from liquid level pressure transmitter in day tank
Deg C	outdoor temp	ambient outdoor temperature on east side of generator enclosure about 1/2 meter above ground level, thermocouple kept clear of snow and was not directly lit by sunlight between late October and the end of February
%	O2	analog output from O2 channel of NOVA emissions analyzer
Deg C	Opacity TC	temperature of exhaust at outlet of muffler
Deg C	laminar flow element inlet tc	temperature of air entering laminar flow element
Deg C	return fuel temp_cool	temperature of fuel in return line after passing through heat exchanger
Deg C	return fuel temp_hot	temperature of fuel in return line before entering heat exchanger
Deg C	supply fuel temp	temperature of fuel in supply line leaving racor primary filter
Deg C	day tank base_tc	temperature of air near base of clean fuel day tank
Volts	exhaust flow	analog output from Kurz exhaust flowmeter
Volts	jacket water flow	analog output from jacket water flow meter via ratecounter/totalizer
Volts	compressor pressure	analog output of pressure transducer at outlet of

		turbocharger
Volts	intake air pressure	analog output of pressure transducer in inlet air duct between air filter and laminar flow element
Volts	exhaust pressure	analog output of pressure transducer in exhaust line near exhaust manifold
Volts	intake manifold pressure	analog output of pressure transducer in air duct near inlet manifold
millibar	Barometric pressure	barometric pressure near air filter inlet inside generator enclosure
Deg C	Aftercooler East	temperature of after cooler via thermocouple resting in heat exchanger fins
Deg C	Aftercooler North	temperature of after cooler via thermocouple resting in heat exchanger fins
Deg C	Aftercooler South	temperature of after cooler via thermocouple resting in heat exchanger fins
Deg C	Aftercooler West	temperature of after cooler via thermocouple resting in heat exchanger fins
Volts	HC output	analog output of HC analyzer
Deg C	ECOM TC	temperature of sample flow entering ECOM emissions analyzer
Deg C	HC TC	temperature of sample flow entering hydro carbon analyzer
°C	Coolant temp CAN	coolant temperature (CANbus)
°C	FuelTemp CAN	fuel temperature (CANbus)
°C	Engine oil temp CAN	engine oil temperature (CANbus)
	Engine hours CAN	hours of engine operation (CANbus)
rev	Total revs CAN	total engine revolutions (CANbus)
%	% of available torque	% of available torque (CANbus)
RPM	Engine Speed	engine speed (CANbus)
%	Actual Engine % Torque	actual engine % torque (CANbus)
l/hr	Fuel flow	diesel engine fuel consumption (CANbus)
kPa	Oil Press kPa	oil pressure (CANbus)
Kpa/bit	Fuel Delivery Pressure	fuel delivery pressure (CANbus)
Kpa/bit	Engine Oil Pressure	engine oil pressure (CANbus)
Kpa/bit	Crank Case Pressure	crank case pressure (CANbus)
kPa	boost pressure kPa gage	boost pressure at intake manifold (CANbus)
°C	Air inlet temp	air temperature at intake manifold (CANbus)
V	Voltage	Detroit Diesel system voltage (CANbus)
l	Total fuel used	total fuel consumed, liters (CANbus)
Hz	Freq	generator frequency (LoadTec)
volts	V(1-2)	load bank voltage between phases 1 and 2 (LoadTec)
volts	V(2-3)	load bank voltage between phases 2 and 3 (LoadTec)
volts	V(3-1)	load bank voltage between phases 3 and 1 (LoadTec)
amps	A(1)	phase 1 current (LoadTec)
amps	A(2)	phase 2 current (LoadTec)
amps	A(3)	phase 3 current (LoadTec)
volts	V(avg)	average load bank voltage (LoadTec)
amps	A(avg)	average load bank current (LoadTec)
KW	KW	Real power (LoadTec)
KVA	KVA	Complex power (LoadTec)
	PwrFactor	power factor (LoadTec)

KVAR	KVAR	Reactive power (LoadTec)
volts	CtrlV(1)	load bank control voltage (1) (LoadTec)
volts	CtrlV(2)	load bank control voltage (2) (LoadTec)
degF	ExhTemp	load bank temperature
degF	DeltaTemp	load bank temperature
degF	CabTemp	load bank temperature
degF	AmbTemp	load bank temperature
Hz	CtrlFreq	load bank control frequency (LoadTec)

vibration data via engine mounted accelerometers

triaxial accelerometer
triaxial accelerometer
triaxial accelerometer
single axis accelerometer, horizontal axis perpendicular to longitudinal axis of engine
single axis accelerometer, horizontal axis perpendicular to longitudinal axis of engine

Report on Reformer/Fuel-Cell Evaluation of F-T Fuel

DOE award DE-FC26-01NT41099

Final Report

March 15, 2006

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DISCLAIMER:

ABSTRACT:

Fischer-Tropsch synthetic fuels manufactured using the Syntroleum process are comprised primarily of straight chain hydrocarbons, and have virtually no aromatic content, and contain no sulfur. Recent research in fuel cells operating on conventional hydrocarbon fuels show that aromatics and sulfur compounds complicate the reforming of these fuels to hydrogen, and that fuel that are low in these compounds would be preferable for these applications.

The US DOE has funded several projects at the University of Alaska Fairbanks to evaluate the current state of technology with regards to fuel cells operating on diesel fuel. UAF agreed to use some fuel supplied by Syntroleum in diesel reformers provided by these other programs to verify that these fuels were indeed well suited to the operation of fuel cells. In particular, UAF worked with SOFTCo and INEEL (reformer suppliers) and Acumentrics (a solid oxide fuel cell supplier) to demonstrate this technology.

This report summarizes the results of an initial demonstration using a diesel reformer operating on Syntroleum synthetic fuel to power a 5 kW SOFC. It must be noted that in this demonstration, the reformer and fuel cell were from two separate suppliers, and the system was not well integrated, but it did operate in a stable fashion during the short demonstration. Furthermore, the synthetic diesel fuel operated in a much more stable fashion than the EPA low sulfur distillate fuel, indicating that F-T liquids are an ideal liquid fuel for these applications.

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EXECUTIVE SUMMARY:

Fischer-Tropsch synthetic fuels manufactured using the Syntroleum process are comprised primarily of straight chain hydrocarbons, and have virtually no aromatic content, and contain no sulfur. Recent research in fuel cells operating on conventional hydrocarbon fuels show that aromatics and sulfur compounds complicate the reforming of these fuels to hydrogen, and that fuel that are low in these compounds would be preferable for these applications.

The US DOE has funded several projects at the University of Alaska Fairbanks to evaluate the current state of technology with regards to fuel cells operating on diesel fuel. UAF agreed to use fuel supplied by Syntroleum in diesel reformers provided by these other programs to verify that these fuels were indeed well suited to the operation of fuel cells. In particular, UAF worked with SOFTCo and INEEL (reformer suppliers) and Acumentrics (a solid oxide fuel cell supplier) to demonstrate this technology.

This report summarizes the results of an initial demonstration using a diesel reformer operating on Syntroleum synthetic fuel to power a 5 kW SOFC. It must be noted that in this demonstration, the reformer and fuel cell were from two separate suppliers, and the system was not well integrated, but it did operate in a stable fashion during the short demonstration. Furthermore, the synthetic diesel fuel operated in a much more stable fashion than the EPA low sulfur distillate fuel, indicating that F-T liquids are an ideal liquid fuel for these applications.

EXPERIMENTAL:

The primary goal of this test was to demonstrate the compatibility of Fischer-Tropsch synthetic fuels with next generation fuel cell technologies. To accomplish this a reformer and solid oxide fuel cell were paired and set up at Idaho National Engineering and Environmental Laboratories for testing. A description of the experimental setup and test procedures are given in the sections below.

Equipment:

The primary test setup consisted of a 5kW Acumentrics Solid Oxide fuel cell and a SOFCo-EFS fuel processor. These components were chosen based on their availability and advertised performance. The Solid Oxide fuel cell is capable of running on H_2, CH_4, and CO and therefore allows the exhaust stream from the fuel processor to be used directly without any clean up on the gas. This is important because other fuel cells (PEM in particular) require extremely pure Hydrogen streams to run effectively. The SOFCo-EFS fuel processor relies on catalytic partial oxidation to break up the fuel and was rated at 10kW. This means that at full output the Fuel processor has the capacity to produce 10 kW of electricity when paired with an appropriately sized Solid Oxide fuel cell.

The pictures below show the fuel cell and fuel processor used in this experiment.

Acumentrics Solid Oxide Fuel Cell

SOFCo-EFS Fuel Processor

The only additional piece of equipment needed was a steam generator. The fuel processor required a steady flow of steam to vaporize the fuel and assist in reformation, and at this point that was not included as part of the package that was sent from SOFCo-EFS.

Fuels Tested:

In order to have a base for comparing the performance of the reformer and fuel cell system two fuels were tested. The first fuel was the Syntroleum Fischer-Tropsch synthetic fuel and the second was a low sulfur diesel produced by Chevron Phillips Chemical Company.

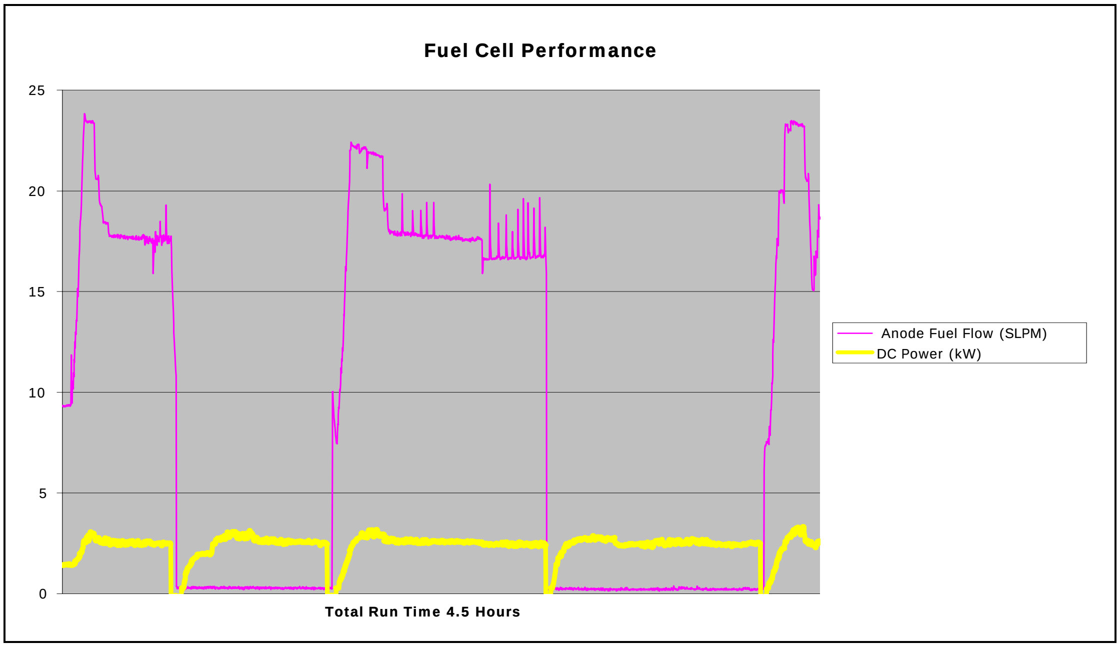
The Syntroleum synthetic fuel used for this demonstration was what the company refers to as S2. This fuel is designed to be comparable to a conventional number 2 diesel fuel in terms of energy content and operational characteristics. This synthetic fuel is produced from natural gas. It consists entirely of straight chain Hydrocarbons and is basically Sulfur free. When used in reciprocating engines an additive package is used to enhance lubricity, but this particular batch of fuel did not have this additive package included. The "conventional" diesel fuel used for comparison was a 2007 Emissions Certified low sulfur fuel. This fuel is comparable to a normal number 2 diesel but has had Sulfur removed to comply with 2007 standards. This is important because over time the Sulfur in normal fuels would react with the catalyst in the fuel processor causing the efficiency to drop off. There is still a small amount of Sulfur in the fuel, (2007 regulations require 15ppm or less) but at this level the effect on the fuel processor would be nonexistent over the time period associated with this demonstration.

Test Procedure:

To eliminate the need for an elaborate control system a relatively simple test procedure was developed. Both the fuel cell and fuel processor would first be started and run independently of one another. During this time both were allowed to warm up and their base performance could be verified to ensure everything was working properly. Once this was complete the reformer output and fuel cell power levels could be set. To avoid having to interface between the two pieces of equipment the reformer output was set at a level higher than required by the fuel cell and additional reformate was simply vented. Once the fuel processor output was verified, the reformate switch was activated which shut off the flow of natural gas to the fuel cell and allowed the system to begin operating on the reformate stream. This procedure was duplicated for each of the fuels tested.

RESULTS / DISCUSSION:

Despite only operating for a short period of time the results from this demonstration are fairly clear. The graph below shows approximately a four and a half hour run in which the fuel cell was run on reformate streams derived from both the Syntroleum synthetic fuel and the 2007 Emission Certified low Sulfur fuel. The graph contains data on the natural gas flow rate into the fuel cell (Anode Fuel Flow) as well as the fuel cell DC power output. There are two sections in the graph where the natural gas input drops to zero indicating that the fuel cell is operating on reformate. For the first of these occurrences the fuel cell is operating on a Syntroleum based reformate stream and for the second it is operating on a low Sulfur diesel reformate.



From the previous chart it is clear that the fuel cell operates well on both the Syntroleum synthetic fuel reformate and the 2007 low Sulfur diesel reformate, but to really determine the true results / benefits of using the synthetic fuel further work is needed. According to engineers and technicians on site, the fuel processor ran noticeably smoother when operating on the synthetic fuel. Unfortunately, the data on reformer performance belongs to SOFCo-EFS and is not included in this report.

Efficiency:

One thing that should be noted is the overall system efficiency. When operating on natural gas the DC efficiency of the Acumentrics fuel cell averages around 24-25%. When the operating efficiency of the fuel processor and inverter are taken into account the total system efficiency drops to well below 20% when running on both conventional and synthetic diesel fuels. These efficiencies do not compare well with competing technologies such as diesel generators, which often achieve efficiencies of up to 40%.

However, it should be noted that this system as demonstrated was not designed to maximize efficiency. In a well integrated system, the energy required for the reformation reaction should be provided with the high grade waste heat from the fuel cell, and the sizes of the fuel cell and reformer should be matched. Modeling activities show that if these conditions are met, efficiencies of close to 50% can be achieved.

CONCLUSION:

Despite lower than expected efficiencies, this demonstration was a success. The fuel cell reformer system ran as well or better on the Syntroleum synthetic fuel as it did on conventional fuel, and there were no failures or problems that could be linked to the use of the synthetic fuel.

The total system efficiency was lower than expected, but this was mainly due to the performance of the Acumentrics fuel cell and was not a product of the fuel being used. Competing solid oxide fuel cells from other manufacturers have demonstrated efficiencies of over 50% running on natural gas, which is roughly twice the efficiency of the Acumentrics system. If a system had been built around one of these more efficient fuel cells it is possible that the overall system efficiency could come close to matching the 40% mark achieved by diesel generators. In fact, the fuel cell system may actually have a small advantage for small-scale applications where the efficiencies of diesel generators often drop. The question then becomes when does this small efficiency advantage offset the cost and reliability issues associated with using these fuel cell / reformer systems

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