OAK RIDGE
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FUNGIBLE AND COMPATIBLE BIOFUELS: LITERATURE SEARCH, SUMMARY, AND RECOMMENDATIONS

September 30, 2010

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1. PURPOSE

1.1 PURPOSE OF STUDY

The purpose of this study is to summarize the various barriers to more widespread distribution of biofuels through our common carrier fuel distribution system, which includes pipelines, barges and rail, fuel tankage, and distribution terminals, and with a special focus on biofuels, which may come into increased usage in the future. Addressing these barriers is necessary to allow the more widespread utilization and distribution of biofuels, in support of a renewable fuels standard and possible future low-carbon fuel standards. By identifying these barriers early, for fuels not currently in widespread use, they can be addressed in related research and development. These barriers can be classified into several categories, including operating practice, regulatory, technical, and acceptability barriers. Possible solutions to these issues are discussed, including compatibility evaluation, changes to biofuels, regulatory changes, and changes in the distribution system or distribution practices. No actual experimental research has been conducted in the writing of this report, but results are used to develop recommendations for future research and additional study as appropriate.

This project addresses recognized barriers to the wider use of biofuels in the areas of development of codes and standards, industrial and consumer awareness, and materials compatibility issues.

Specific information tasks for the report include the following. Where possible, the information provided is linked to characteristics of specific biofuels, both current and emerging.

- **Background and current operating practices.** Fuel blending, pipelines, and distribution practices have developed over a long period of time and operate very efficiently and safely for fuels of specific types. This section will describe how the current pipeline and distribution system are constructed and operated and how this may limit the ability to refinery-blend and distribute biofuels.

- **Regulatory barriers to expanded distribution of biofuels.** Fuels that are shipped over common carrier distribution must be acceptable to all parties receiving the fuel, and this has resulted in the development of fungibility specifications for fuels. Fuels accepted by pipelines must generally meet fungibility specifications, compatibility specifications, and all legal requirements. This section will describe how current fungibility specifications and pipeline specifications affect the ability to refinery-blend and distribute biofuels.

- **Technical barriers to pipeline distribution of biofuels.** Legal requirements and fungibility specifications aside, there may also be valid compatibility reasons for not introducing specific biofuels into the common carrier distribution system. This section will discuss the actual physical and technical barriers to biofuel distribution which must be solved to allow the more widespread distribution of biofuels.

- **Additional barriers and concerns.** This section will describe other barriers to more widespread distribution of biofuels which do not fall readily into the other categories. Examples of these include cross contamination of product, ground water contamination, consumer acceptance and perception, lack of operating experience with a new fuel, and compatibility concerns with existing and future engines and vehicles.

- **Possible solutions to problems outlined.** The barriers outlined above can be overcome by a number of means, some of which are most applicable to a given barrier and some of which may be easier or more difficult to implement. These solutions fall into the categories of verification of performance and compatibility of possible future biofuels, chemical modification of biofuels, changes in current fuel specifications, modifications of fuel distribution procedures and operating practices, or modifications to the current fuel distribution system.

1.2 DEFINITION OF FUNGIBILITY

Fungible fuels are those fuels in common use, with common specifications, distributed in a comingled manner, and with sufficient specifications and quality control that they, within a given type, can be substituted for each other without concern of source or end use. Fungible fuels of specific types can be intermixed during distribution and storage without concerns relative to quality or specifications. Fuel specifications are published by a number of regulatory agencies, including ASTM, the U.S. Environmental Protection Agency, and state agencies, and then adopted as controlling specifications for the receipt, distribution, and delivery of fuels on common carrier systems. There are many fungible fuel specifications, and they vary by fuel type, fuel grade, area of the country where sold, and season [26, 37, 40, 50, 61, 95, 102, 118, 125, 145, 149, 162].

1.3 DEFINITION OF COMPATIBILITY

Compatible fuels are fuels that would be considered compatible with the infrastructure transporting them, both from the standpoint of no damage by or to the equipment and from the standpoint of no harm from or to other fuels using the same distribution infrastructure [104]. Compatible fuels would also be suitable for use in the vehicle or application intended, in a manner indistinguishable from other fuels. Distribution system compatibility in a fuel may require additional specifications to be met, beyond a fuel's regulated and performance specifications, and these additional requirements are normally included in a fungible fuel specification.

2. DESCRIPTION OF FUEL MANUFACTURING AND DISTRIBUTION IN THE UNITED STATES

The following description of petroleum refining and distribution is taken from public sources on this subject, ranging from books to company and association websites. This description is intended to set the stage for a discussion of the differences between biofuels and petroleum-derived fuels and how these differences might affect distribution operations.

Petroleum fuels are manufactured in the United States from crude oil at oil refineries and are then distributed to terminals for final distribution to service stations and end users. Most commonly, crude is received at refineries by pipeline, barge, tanker, or rail and distributed by pipeline, rail, barge, or truck. Most crude oil and finished fuels are moved by pipeline. The United States consumes about 19.5 million barrels per day of finished petroleum-based fuels, mainly as gasoline, diesel fuel, jet fuel, and heating oil. Of this, 43% is refined in the United States, and 57% is received from other countries [152]. U.S. oil refining, fuel distribution, and fuel specifications have grown and evolved over many years to meet demand, product requirements, and quality requirements and now represent a large entrenched infrastructure and a correspondingly large investment, designed specifically for processing and distribution of petroleum-based products.

2.1 CRUDE REFINING

In the processing of crude oil, an oil refinery uses distillation (separation by boiling point) to split crude into a number of fractions for further processing at more specialized process units. Distillation is also used at the output of many of these units to separate finished streams from materials recycled for further processing. Various types of process units can remove sulfur, nitrogen, or oxygen, add hydrogen, reshape molecules, or split or combine molecules. These individual refinery streams are then transferred to blending operations where they are combined to produce finished fuels of required specifications. The balancing of a refinery operation is complex and adjusted both daily and seasonally to compensate for product demands, product shipping cycles, crude characteristics, and process unit operation. Diesel fuel is typically composed of three to five blending streams and gasoline of five to seven blending streams, which are blended to meet the specifications for the given product, season, and region of use. Products can be blended in real time, on line, and immediately put into a pipeline or other form of transportation or batched to storage tanks for later shipment.

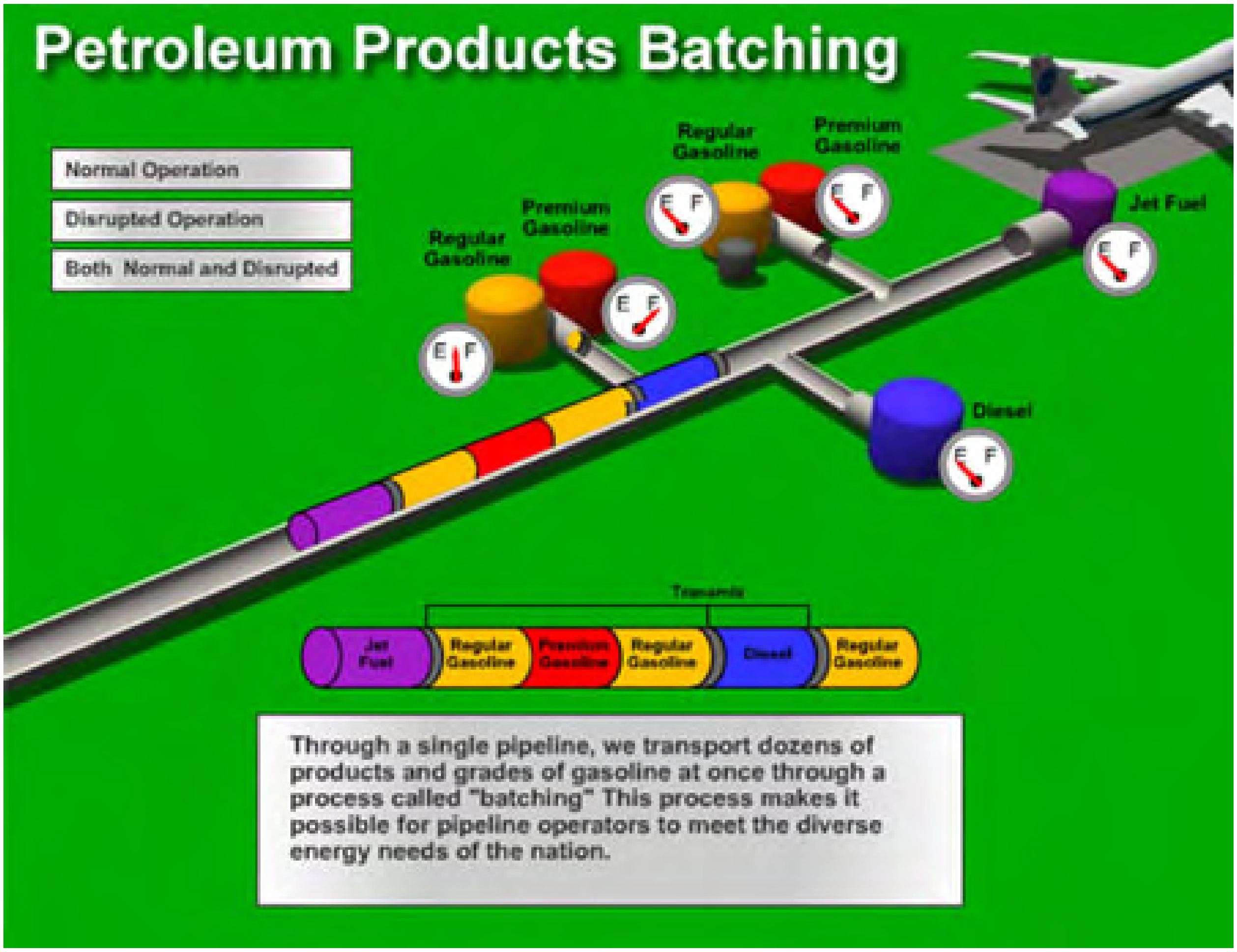
2.2 PIPELINE DISTRIBUTION

The majority of the distribution infrastructure, mainly pipelines, tanks, and related equipment, is composed of low carbon and low alloy steels, and controlling rust and corrosion is of primary importance. This is largely monitored by a series of standard rust and corrosion tests and periodic thickness measurements and controlled through the use of corrosion and rust inhibitor additives. Generally, pipelines only allow specific additives to be used, at minimum concentrations necessary to achieve a desired result. Petroleum products leaving a refinery will often be above ambient temperature and will contain some dissolved water from various refining operations. In addition, water can sometimes enter finished products through storage tanks or by contact in barges and tankers. With time and cooling, this water will drop out in storage tanks and can be disposed of. Storage tanks are designed to allow the accumulation of water and dirt for periodic removal. Since water bottoms are often considered hazardous waste, there is limited opportunity for continuous removal and disposal at product terminals. As long as the water or dirt is not reentrained into product being sold, it causes no harm to remain in contact with petroleum-derived fuels, although bacteria growth must be controlled at the water-petroleum interface. Tank inlets and suctions are designed to minimize stirring of a product during normal operations to prevent reentrainment of water or dirt.

Pipelines run products in cycles, with batches of one type of product being followed by a batch of another product. Large batches of a given product may originate from several refineries and breakout tanks and end up at multiple terminals along a pipeline. Fungibility allows the co-mingling of product without concern for source or end user. Products follow a defined sequence to minimize cross-contamination and to allow ability to detect product and batch changes. Normally, batch detection is done by monitoring for fluid density changes between the sequential batches. Between batches, a small amount of co-mingled product, known as interface or transmix, is generated and is normally segregated for refractionation to diesel and gasoline or returned to a refinery for processing. Figure 1 shows a typical batch sequence for refined pipeline products.

2.3 TERMINAL BLENDING

At a product terminal, individual tanks store specific products, which are then sent to a truck loading rack for distribution to service stations or other users. Tanker trucks can have one large compartment or several smaller compartments. Occasionally, smaller pipelines may send product directly to an end user such as an airport or for a dedicated service station located near a terminal. For biofuels, the loading rack at a product terminal is currently the most common entry point into the distribution system. On-line blending equipment is used to blend a petroleum-based product with biofuels, proportionally by volume,



Through a single pipeline, we transport dozens of products and grades of gasoline at once through a process called "batching" This process makes it possible for pipeline operators to meet the diverse energy needs of the nation.

Source: (*www.pipeline101.com*)

Figure 1. Typical batch sequence for refined pipeline products. [167]

during truck loading. The biofuels (ethanol and fatty ethyl methyl esters, or FAME) are brought into a terminal by truck, rail, or barge and kept in dedicated tanks until blended. FAME is the most common form of biodiesel in use today and is often referred to as biodiesel. In this report, the term *FAME* is used to describe 100% FAME, *FAME biodiesel* is used to describe blends of FAME and diesel fuel, and *biodiesel* is used to describe other forms of bio-derived diesel fuels.

Refinery blending of products differs in several ways from blending done at a terminal. First, a refinery has a number of blending streams available and generally has multiple options to achieve a fuel specification. A refinery has an analytical laboratory and on-line monitoring equipment that allows blending to product specifications. A refinery also has storage tankage and more options for dealing with any off-specification product. In contrast, a terminal has only the capability to blend to volume percentage, during truck loading, between two components. These blended components must be designed to meet a final product specification after blending, since a terminal does not typically have the capability (in the form of additional blend streams, additional storage tankage, or analytical equipment) to blend to specification or to adjust off-specification product.

2.4 EXAMPLE PIPELINE DISTRIBUTION MAP

Figure 2 provides an example of part of the petroleum distribution infrastructure in the United States. The map displays the distribution and storage holdings of Nu Star Logistics, one of the ten largest U.S.-based pipeline companies, with over 8000 miles of pipeline transporting over 800,000 barrels per day. This particular pipeline network (including a variety of pipeline types, such as crude, refined, ammonia, single-use, etc.) is centered in the Midwest, as are the crude oil storage facilities. There are a number of product terminals on the east and west coasts that are not served by a Nu Star pipeline. These are either reached by rail, truck, barge (likely for port cities), third-party pipelines, or a combination thereof. This particular map is included for illustrative purposes and does not portray the entire U.S. fuel distribution infrastructure.

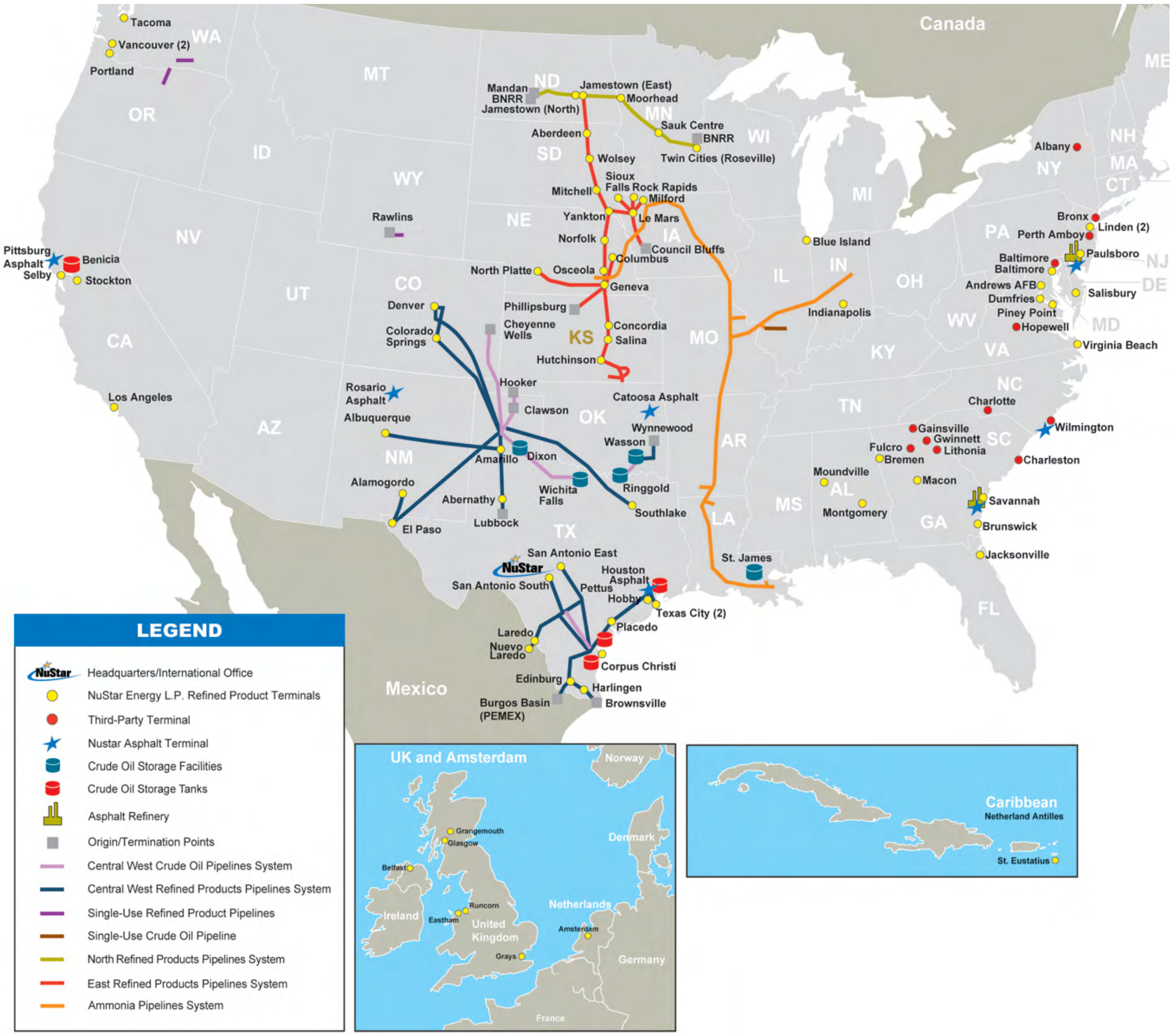


Figure 2. Nu Star Logistics distribution map. [118] Note that there are at least ten major pipeline companies operating in the United States, and this particular map has been included to illustrate one of them. It does not provide a total picture of pipeline infrastructure.

3. INCORPORATING BIOFUELS INTO THE CURRENT DISTRIBUTION SYSTEM

3.1 ISSUES WITH OXYGENATED BIOFUELS

Current biofuels (ethanol and FAME) contain oxygen and are polar molecules. This polarity makes them behave differently than hydrocarbon fuels and results in the need for different handling and distribution practices. This polarity results in a greater affinity for other things, such as water, dirt, and surfaces. Water, which is normally present in the fuel distribution system for reasons described above, can be dissolved into a biofuel at greater amounts than in a corresponding petroleum fuel, and this can result in product quality problems during use. FAME can dissolve substantially more water than can petroleum fuels [111, 114], and ethanol is highly soluble with water and can dissolve large amounts of water into an ethanol-gasoline mix; ethanol can segregate out of an ethanol gasoline mix and into a water phase [42]. Dissolved water in biofuels can also contribute to corrosion and stress corrosion cracking. Stress corrosion cracking of mild steel may be of particular concern with ethanol [124], and further study of ethanol-induced corrosion is one of the recommendations of this report. The polarity of ethanol and FAME can also make the separation of dirt and water more difficult or slower than for petroleum fuels. Low-level FAME contamination in jet fuel is also of current concern and is being studied. Possible solutions to this issue include careful batch sequencing or the use of a separate, parallel pipeline to segregate jet fuel from FAME biodiesel.

3.2 CURRENT PRACTICES AND PROPOSED SOLUTIONS

The current practices of adding FAME and ethanol during truck loading minimizes the opportunity for contact with water and dirt but may be more difficult for the larger volumes of biofuels required in the future. Expansion of the use of bio-derived fuels would be easier if they did not require separate shipping to multiple distribution points but could be handled with existing infrastructure at refineries. The problems cited can be alleviated by modifications to the fuels themselves or by modifications to the distribution equipment and practices. Table 1 outlines some of the distribution problems associated with biofuels usage, with a variety of solutions including fuel, equipment, or operating practice modifications.

Examination of the table indicates the possibility of multiple or combined solutions ranging from product changes, equipment modifications, and changes in operating practices. None of these changes are particularly difficult from a science or engineering viewpoint, but some may require considerable investment in modifying distribution or refining equipment. It is likely that final solutions will be a combination of several of these options. Additional study, development, and research by the Department of Energy and the companies involved should provide the necessary information and guidance to allow such decisions to be made.

Table 1. Distribution problems related to biofuels and possible fixes

Distribution problem	Fuel fix	Equipment fix	Operating fix
Water in product	Less polar form of biofuel, such as butanol vs. ethanol or converting oils or fats to hydrocarbons rather than esters	Design tankage to minimize contact between water and product, use of separators to remove water	Drain water bottoms more frequently, combined with careful monitoring*
Dirt in product	Less polar form of biofuel	Design tanks to reduce reentrainment of dirt,* use filtration to remove dirt	Keep tanks clean, combined with careful monitoring*
Cross-contamination of products	Less polar form of biofuel	Equipment for better interface detection and separation of transmix	Batch sequencing, combined with careful monitoring and separation of transmix*
Corrosion and rust of mild or low alloy steel	Make fuel more petroleum-like, reduce dissolved water, reduce fuel polarity, selection and use of effective corrosion inhibitors	Use corrosion resistant steels	Monitoring and maintenance, corrosion inhibitors*
Material compatibility other than corrosion and rust	Make fuels more petroleum-like	Change to more compatible materials	Maintenance and monitoring*

*Current practices may need to be executed more frequently with biofuels.

4. CURRENT STATE OF THE MARKET

4.1 RFS2 REQUIREMENTS

The Renewable Fuel Standard (RFS1) was established by the U.S. Energy Policy Act of 2005. It was the first specific renewable fuel volume mandate in U.S. history. It mandated that by 2012 at least 7.5 billion gallons of renewable fuel be blended into gasoline annually. RFS1 delineated three specific types of renewable fuel: grain ethanol, ethanol from cellulosic sources, and biomass-based diesel, which was defined but not mandated. Under the Energy Independence and Security Act of 2007, the Renewable Fuel Standard was revised and its scope expanded in an effort to accelerate energy independence and security, to keep pace with emerging renewable fuel technologies, and to provide greater detail concerning the ways in which the mandate is to be met. This set of extensive revisions became known as RFS2 [51].

RFS2 significantly increases the renewable fuel volume mandate, starting with 9 billion gallons required by 2008 and increasing yearly to 36 billion gallons by 2022. The mandate also applies to blending with diesel fuels as well as with gasoline. Consequently, the number and types of renewable fuels that fall under the RFS2 are increased over those of RFS1. Renewable fuels covered under RFS2 now fall into one of five categories: cellulosic biofuel made from cellulose, hemicellulose, or lignin sources; biomass-based diesel defined as any non-co-processed diesel fuel from renewable sources; advanced biofuel, which is defined as any renewable fuel not made from corn starch; renewable biofuel, which is meant to include corn-based ethanol; and a special class that includes cellulosic-based diesel fuel. Each of these categories has its own corresponding volume mandate and lifecycle greenhouse gas emissions requirements, summarized in Figure 3 and Table 2.

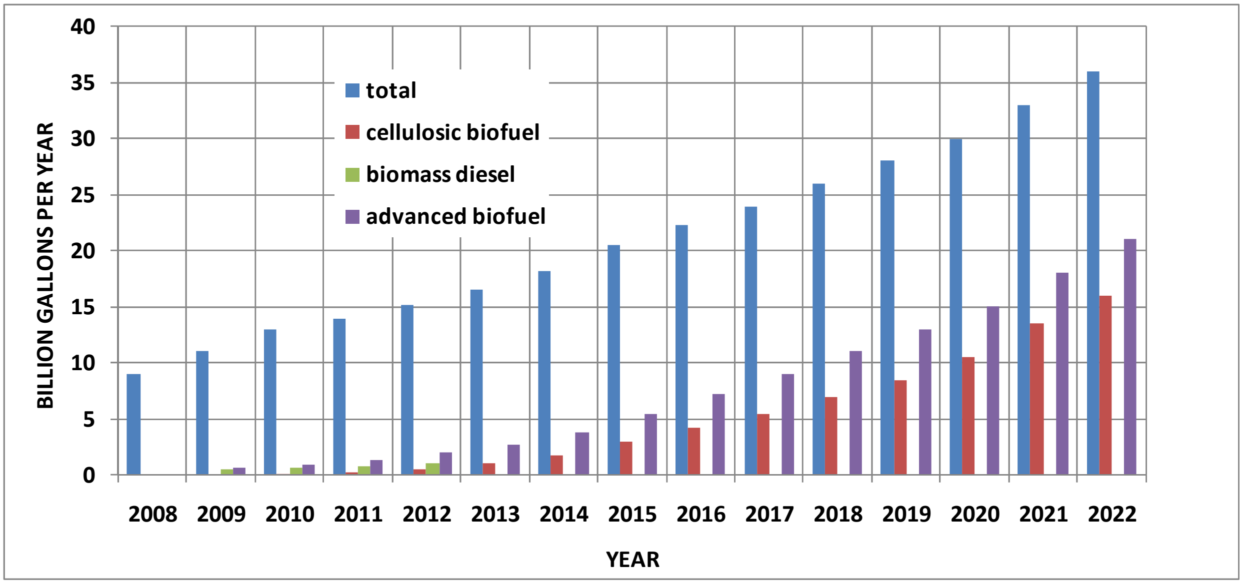


Figure 3. RFS2 mandated annual biofuels usage. [51]

Table 2. RFS2 fuel categories [51]

Fuel type	2010 mandated volume (billion gallons)	2022 mandated volume (billion gallons)	Life-cycle GHG reductions^	Possible fuels included	Example feedstocks
Cellulosic biofuel	0.1	16	60%	Ethanol	Corn stover, switchgrass
Biomass-based diesel	0.65	TBD	50%	FAME, Green diesel, Algae biodiesel	Soy, palm, rapeseed, algae oil
Advanced biofuel	0.95	21	50%	Green gasoline	Sugar cane, agricultural residue
Renewable biofuel	12.95 – CBA*	36 – CBA*	20%	Ethanol	Corn starch
Cellulosic biodiesel#	N/A	N/A	60%	Pyrolysis oil-based biodiesel	Wood chips

* Can be adjusted—Renewable biofuel volume is the difference between the total yearly volume mandate and the sum of the individual volume mandates for the cellulosic, biomass-based diesel, and advanced categories. The EPA can determine that the yearly mandate for an individual category cannot feasibly be met, but it does not have the authority to reduce the total RFS2 volume mandate. Renewable biofuels derived from grain are limited to 15 billion gallons per year.

^Each fuel category has a corresponding life-cycle greenhouse gas (GHG) emissions reduction requirement when compared to the petroleum-based fuel counterpart (either gasoline or diesel).

Cellulosic biodiesel is a special category that is comprised of cellulosic biomass-based diesel fuel. When this fuel also provides a greenhouse gas emissions reduction of at least 60% compared to petroleum diesel, the fuel can be used to satisfy either the cellulosic requirement or the biomass-based diesel requirement.

The RFS2 regulations also provide specific rules governing land use for biofuel feedstocks. Numbers and credits are affixed to each gallon of qualifying biofuel produced. Once the biofuel is transported to the end user, the credits are detached and become tradable commodities and serve as proof that individual mandates have been met by the fuel manufacturer, blender, or importer. All of these improvements to RFS1 create a policy climate that places emphasis on both biofuel diversification and biofuel cost. RFS2 will play a dominating role in biofuels utilization for the foreseeable future.

4.2 CURRENT PRODUCTION OF ETHANOL AND FAME

Table 3 summarizes available information concerning current or recent biofuels production and capacity in the U.S. for biofuels discussed in this report.

Table 3. Current U.S. biofuels production

Fuel	U.S. production (billion gallons)	U.S. production capacity (billion gallons)	Year of available data
FAME [171]	0.545	2.74	2009
Ethanol [170]	11.88	13.03	2010

4.3 HOW THE CURRENT MARKET DEALS WITH COMPATIBILITY AND FUNGIBILITY ISSUES

The two major current biofuels in the United States, ethanol as a gasoline blending component and FAME as a diesel blending component, are either expressly or de facto prohibited in pipelines operated by most of the ten largest pipeline companies. The compatibility and fungibility issues associated with both ethanol and FAME, as well as the other biofuels in this report, are discussed in greater detail later in this report and in the Excel workbook. The most notable compatibility issues are water solubility and stress corrosion cracking for ethanol, and fuel contamination and cold flow performance for FAME. Five of the ten largest U.S. pipeline companies expressly prohibit alcohols and ethers as "blending components in gasoline at (refinery) origin." Six of the ten companies either expressly prohibit FAME or place freeze and cloud point restrictions on diesel fuel that serve as de facto prohibitions on FAME blending at the refinery [26, 37, 40, 50, 61, 95, 102, 118, 125, 145, 149, 162].

While there are emerging exceptions to the above prohibitions (see the following discussion of Kinder Morgan's experience with biofuels fungibility), ethanol and FAME biodiesel are generally not transported via the existing petroleum pipeline infrastructure. They are generally rack-blended with gasoline or diesel fuel at distribution terminals, and the mixtures are then sent to service stations via truck.

4.4 CASE STUDY: THE KINDER MORGAN EXPERIENCE

Kinder Morgan Energy Partners, one of the largest oil pipeline companies in the United States, is one of the several companies that have successfully demonstrated biofuel transport through the petroleum pipeline infrastructure [95]. In 2008, Kinder Morgan began shipping neat ethanol through a 115-mile stretch of gasoline pipeline in Central Florida. To prevent or mitigate the major impedances to ethanol pipeline shipment—namely, water solubility, stress corrosion cracking, and the cleaning effect—the pipeline was first cleaned and all potential water sources were removed. Kinder Morgan utilized a proprietary mix of corrosion inhibitors in an effort to prevent stress corrosion cracking. Neat ethanol is, as of early 2010, routinely shipped on this pipeline, and no problems have been reported.

Kinder Morgan has also experimented with shipping FAME biodiesel over the Plantation pipeline network located in the southeastern United States. Initially, a B5 blend was shipped over 500 miles of diesel pipeline. The critical issue of FAME contamination of jet fuel was bypassed due to the existence of a parallel pipeline that allowed jet fuel and FAME biodiesel to remain segregated. The results of this experiment were ultimately positive. As of early 2010, Kinder Morgan allows the shipment of B2, B5, and/or B100 over 8000 miles of pipeline.

This case study demonstrates that while the water solubility, cleaning effect, contamination, and stress corrosion issues associated with ethanol and FAME pipeline shipping are significant, they are not insurmountable. Proper cleaning, chemical additives, segregation/batch sequencing, parallel pipelines, and monitoring can either eliminate or greatly mitigate these problems and make ethanol and FAME pipeline shipment possible.

5. FUEL SOURCES

5.1 FUELS CONSIDERED

The biofuels considered in this report are discussed in three sections, with more detail as the options are narrowed to biofuels considered to be of greater importance and higher likelihood for future use. The three sections are “all biofuels,” “all biofuels of higher priority,” and “biofuels of higher priority which would benefit from further study on certain key questions.” Each of these fuel sections is also classified by end use by separation into four categories: gasoline-like fuels, diesel-like fuels, biocrudes and refinery intermediates, and other fuels. Gasoline-like and diesel-like fuels are biofuels that are intended for combustion in spark-ignition and compression-ignition engines, respectively, and possess physical and chemical properties that are intended to be similar to gasoline or diesel fuel. These categories include fuels such as ethanol, butanol, and FAME. The biocrudes and intermediates category contains biofuels that are not fuels until they are further refined, in much the same way as petroleum crude is further refined into gasoline, diesel, etc. before reaching the end-user. Biocrudes and intermediates include pyrolysis oil and syngas. The other fuels category includes methane and hydrogen, fuels that do not have similar properties to either gasoline or diesel but nevertheless can be utilized in dedicated vehicles. These latter fuels are examined with the understanding that they, by nature, cannot be incorporated into the existing petroleum distribution infrastructure, but rather their own distribution infrastructures are extensive enough to warrant research into the fungibility prospects of their biomass-based equivalents.

5.2 ALL BIOFUELS

Table 4 lists all the fuels considered in the preparation of this report, classified by the types discussed previously. Each of these fuels is discussed in detail in the exhibits at the end of this report. Each fuel has two exhibits. The first consists of available fuel properties and environmental impact data for each fuel as compared to its petroleum-derived counterpart. The second exhibit consists of materials compatibility data, vehicle compatibility data, transporting precautions, environmental and health concerns, fungibility and distribution issues, current production, and overall advantages and disadvantages of distribution and use of each particular fuel, along with references.

Also included in the exhibits is information concerning the ten largest oil pipeline companies in the United States in terms of daily transported volume. This information includes pipeline network location and mileage, products transported, and prohibitions, particularly how these relate to biofuel distribution. Other exhibits include federal hazmat transport regulations, information on where specific biofuels can theoretically be inserted into the distribution chain, capital and operating cost analysis for several types of biofuel production facilities, and a list of federal and state policies and initiatives designed to drive increased biofuel usage. (The information contained in the exhibits can be acquired from the authors as an Excel workbook.)

The list of fuels considered in Table 4 was narrowed to those which are of higher priority or of greater interest to DOE during preliminary discussions of results. These fuels are discussed in greater detail in the next section.

Table 4. Fuel types considered

Fuels	Diesel-like fuels	Gasoline-like fuels	Biocrudes and intermediates	Other fuels
FAME	X			
Green diesel	X			
F-T diesel	X			
Algae biodiesel	X			
DME	X			
Glyme	X			
Ethanol-diesel blends	X			
Sesquiterpene	X			
Green gasoline		X		
F-T gasoline		X		
Ethanol		X		
Biobutanol		X		
Methanol		X		
Propanol		X		
Higher C alcohols		X		
Pyrolysis oils			X	
Syngas			X	
Lignin liques			X	
Sugars and alcohols			X	
Terpenes			X	
Isoprene			X	
Methane				X
Hydrogen				X

5.3 FUELS OF HIGHER PRIORITY OR INTEREST

From Table 4, ten fuels were chosen for examination in greater depth. These fuels are of higher priority or of greater interest as they are most likely to provide a significant portion of bio-derived fuels in the future. These fuels are listed in Table 5, which also summarizes the knowledge we were able to uncover about

Table 5. Detailed summary table for fuels considered to be of higher priority or greater interest

Compound, fuel, or component	Use, purpose	Advantages	Property issues	Infrastructure issues	Environmental characteristics	Compatibility questions	Areas needing further atudy	Cost compared to petroleum derived	References
FAME (biodiesel)	Diesel substitute or blend component	Currently in use, relatively easy to manufacture, generally higher cetane	Cold flow, stability, filter plugging, higher viscosity, lower energy content	Pick up of dirt and water, cleaning effect, contamination of other fuels, storage stability, prohibited in most pipelines	Relatively non-toxic, biodegerades easily	Problems with terne-coated steel (older vehicle fuel tanks), nitrile and natural rubber	Shipment over common carrier pipelines, cross contamination on other fuels	Same to higher depending on feedstock	8, 17, 36, 39, 89, 99, 101, 111,112, 114, 139, 146
Green diesel	Diesel substitute or blend component	Closest to drop-in replacement, option to optimize further	Very little information or production at present, chemistry may be somewhat different from petroleum derived fuels	None known	Similar to petroleum diesel, well understood	Similar to petroleum diesel, well understood	More definition of chemistry and properties, use as a blending component or finished fuel	Not known	76,92, 115, 130, 142, 155, 165
Fischer-Tropsch (F-T) diesel	Diesel substitute or blend component	Generally higher cetane, zero sulfur, option to optimize further	Possible cold flow problems, can be controlled with chemistry, slightly lower energy content	None known	Similar to petroleum diesel, well understood	Similar to petroleum diesel, well understood	Probably none, well understood	Higher	7, 34, 86, 93, 110
Algae biodiesel	Diesel substitute or blend component	Completely new source of fuel with potential for high volume	Cold flow, stability, filter plugging, higher viscosity, lower energy content, more unsaturates than fame	Pick up of dirt and water, cleaning effect, contamination of other fuels, storage stability, prohibited in most pipelines	Relatively non-toxic, biodegrades easily	Problems with terne-coated steel (older vehicle fuel tanks), nitrile and natural rubber	Same as FAME + study of detailed chemistry and properties, production, and logistics	Not known	33, 108
Green gasoline	Gasoline substitute or blend component	Closest to drop-in replacement, option to optimize further	Very little information or production at present, chemistry may be somewhat different from petroleum derived fuels	None known	Similar to petroleum diesel, well understood	Similar to petroleum diesel, well understood	More definition of chemistry and properties, use as a blending component or finished fuel	Not known	None found
Fischer-Tropsch (F-T) gasoline	Gasoline substitute or blend component	Zero sulfur, option to optimize further	May have slightly lower energy content	None known	Similar to petroleum diesel, well understood	Similar to petroleum diesel, well understood	Probably none—well understood	Higher	93
Ethanol	Gasoline blend component	High octane, largest current biofuel volume, well understood	Lower energy content (up to 28% MPG penalty), requires special low RVP blend stock (readily available)	Segregation into and dissolving of water in distribution system, cleaning effect, prohibited in most pipelines	Miscible in water, toxic in high concentrations, biodegrades easily	Incompatible with hose and fuel tank material in older vehicles, but current approved as 10% blend in all vehicles	Potential for pipeline shipments, stress corrosion cracking	Similar to higher depending on feedstock	11, 20, 21, 42, 124, 143, 158, 163
Butanol	Gasoline blend component	Similar characteristics to ethanol, but differences compared to petroleum gasoline are much less, can be same or slightly higher octane, provides more renewable gallon credits for same oxygen blend limit	Limited experience with use of butanol	Goal is to ship blends over common carrier pipelines, but currently prohibited in most pipelines	Miscible in water (less than ethanol), toxic in high concentrations, should biodegrade easily, but requires more study	Similar characteristics to ethanol, but differences compared to petroleum gasoline are much less	Properties of various isomers and isomer mixtures, shipping studies for common carrier distribution system	Not known, probably higher than ethanol	1, 6, 10, 12, 25, 27, 70, 103, 121, 135, 154, 156
Pyrolysis oil	Biocrude, refiner feedstock	Direct route from biomass to liquid product	Stability problems, not miscible with petroleum crude, high water and oxygen content, high viscosity, corrosive, solids content	Can't be shipped as crude oil, must be stabilized before storage and shipment	Moderately toxic, biodegrades quickly	Deposits and filter plugging, settling of solids, corrosive to aluminum and mild steel	Amount of stabilization required to allow shipping as or with crude oil, study of stabilization methods	Probably lower than crude oil, but also lower fuel value and requires both stabilization and refining	22, 35, 44, 49, 119, 129, 140
Syngas	Biocrude, refiner feedstock	Can be derived from biomass, provides CO and H2 for refinery applications	Also contains CO2, H2O and other impurities, unless purified	Currently no infrastructure for shipping, generated at point of use	CO is highly toxic, syngas very flammable	Can be corrosive depending on impurities and presence of water, hydrogen difficult to seal and contain	Generation, distribution, and use of support liquid motor-fuel market	Depends on feedstock, process, and amount of purification needed	16, 58, 59, 64, 84, 100, 111

each of these fuels and identifies gaps in this knowledge. Since many of these fuels are just emerging or considered future options, identification of knowledge gaps could be important in planning future research and development activities. Each of the fuels listed in Table 5 is discussed here in greater detail to highlight possible issues or problems with each of them.

5.4 DIESEL-LIKE FUELS

FAME is used extensively as a diesel supplement due to its similarity to diesel both physically and chemically and due to its ability to be blended with diesel in any combination. Three major issues facing FAME biodiesel distribution are a higher cloud point than diesel, lower stability, and the cleaning effect. The higher cloud point may necessitate the use of heating or insulation along the distribution channels in colder climates to prevent separation from the diesel mixture and to minimize pumping work. Stability can lead to filter plugging issues, especially in cold weather, but can be largely controlled by additives. The cleaning effect, whereby accumulated sediments dissolve into the FAME, increasing the likelihood of filter plugging and injector deposits, necessitates proper washout of pipes and vessels and removal of all residual water and dirt. In addition, batch sequencing in the pipeline becomes an important issue due to the potential of FAME contamination of jet fuel. The polarity resulting from the high oxygen content in FAME can cause it to cling to pipe and vessel walls, making contamination of subsequent batches more likely. These issues have led most large U.S. pipeline operators to expressly prohibit FAME in pipelines. However, as discussed previously, a notable exception to this is Kinder Morgan.

Green diesel's major advantage over FAME is the deoxygenation that occurs during processing, so that green diesel does not display a cleaning effect and should exhibit improved storage stability. It also has a comparable cloud point to diesel, making it compatible with the existing oil pipeline in the opinions of several of its current producers. This potential, coupled with the current lack of extensive research on its compatibility and fungibility, makes green diesel a good candidate for future study.

Similarly, **Fischer-Tropsch (F-T) diesel** has the advantage of being non-oxygenated with a comparable cloud point to diesel. Many of its current producers also claim that it is compatible with the existing oil pipeline, necessitating further research into this fuel. It can be derived from gasified biomass, although most F-T fuel currently manufactured is derived from natural gas or coal.

Algae-derived FAME, derived from converting oils or fats extracted from algae to FAME, can be rich in unsaturated fats, leading to oxidation susceptibility. For this reason, algae biodiesel does not currently comply with the biodiesel regulations of the European Union. It also has a higher viscosity than diesel, which could result in additional pumping work to move it through a pipeline. Little information is available, since commercial production is limited and further research is needed.

5.5 GASOLINE-LIKE FUELS

Ethanol is extensively distributed and utilized as a fuel blend component throughout the United States. Its low freezing point makes it suitable for use in cold climates, it can be blended with gasoline in any combination, and it is currently approved as a 10% blend for all vehicles and as an 85% blend for flex-fuel vehicles. There are, however, several distribution-related challenges associated with ethanol. It is completely miscible with water and will separate from a gasoline mixture if enough water is present either in the pipeline or as water bottoms in a storage tank. Similarly to FAME, it also displays a cleaning effect, necessitating washout before utilizing ethanol. Additionally, numerous studies have cited ethanol's role in corrosion or stress corrosion cracking of pipeline walls. All of these challenges have led to many major U.S. pipeline operators expressly prohibiting ethanol and ethanol-gasoline mixtures in the pipeline. As discussed previously, Kinder Morgan is allowing the shipment of neat ethanol on one pipeline.

As with ethanol, **butanol** is also an oxygenated fuel that can be blended with gasoline in any combination and requires only minor modifications for use in existing vehicles. This fuel's producers also claim that butanol is compatible with the existing oil pipeline infrastructure, but these claims have yet to be verified. Further research into butanol is warranted. Butanol has four isomers (molecular arrangements), and there is little existing data regarding optimization of these isomers from either a manufacturing or fuel performance standpoint.

Both **green gasoline** and **Fischer-Tropsch gasoline** have thus far been the subject of very little published research. Initial studies indicate that the latter could potentially exhibit physical and chemical properties similar to those of gasoline.

5.6 BIOCRUDES AND REFINERY INTERMEDIATES

Pyrolysis oil is a promising biocrude, but there are several significant issues associated with its distribution in and compatibility with the crude pipeline infrastructure. It can have a very high oxygen and water content, which must be removed, it is highly corrosive, and it is chemically unstable due to the high char and solids content. Suspended char particles can also contribute to phase separation. In addition, its alkali metals content can lead to deposits in filters, boilers, etc. and can contribute to catalyst poisoning. The higher viscosity of pyrolysis oil compared to petroleum crude necessitates increased pumping work. The high oxygen content contributes to its polarity, causing pyrolysis oil residue to cling to pipe and vessel walls. It is likely that pyrolysis oil will need some intermediate upgrade step before it can be shipped long distances to an oil refinery for further processing.

Syngas derived from biomass is a gas at ambient conditions composed mainly of CO and H_2. Syngas is normally used as a feed to the manufacture of F-T fuels and can also be used as a fuel to supply heat in refining operations. The hydrogen is also useful for hydrotreating operations, necessary to upgrade fuels and to remove impurities. It would require a distribution infrastructure similar to that required by natural gas if shipped long distances. Syngas can promote corrosion if exposed to water. The hydrogen component is prone to leaks and the carbon monoxide component is highly toxic. This would necessitate additional modifications and maintenance in order to prevent syngas leaks.

One potential hurdle to the future utilization of biocrudes is the RFS2 legislation concerning co-processing. If a biocrude is co-processed with petroleum crude and the resulting mixture is refined to produce a diesel–biodiesel mixture, this fuel will not qualify as a biomass-based diesel fuel. Biomass-based diesel fuels can be blended with petroleum diesel, but they cannot, by RFS2 definition, be the product of co-processing operations. If the appropriate greenhouse gas emissions requirements are met, the resulting fuel would qualify as an advanced biofuel or cellulosic biofuel. This could potentially hinder the flexibility of the biocrude medium, specifically as it pertains to biodiesel production and distribution.

5.7 SHIPPING PYROLYSIS OIL AS CRUDE OIL OR CO-MINGLED WITH CRUDE

Crude oil is gathered from production fields and then consolidated and shipped through a large series of dedicated pipelines in the United States and Canada between production locations, shipping and receiving locations, storage facilities, and petroleum refineries. In this section, we provide a preliminary comparison of crude oil requirements and typical pyrolysis properties and chemistry, with the recommendation that this area of study be revisited next year. Crude oil is shipped as segregated batches, and the concept of fungibility has not been applied to these shipments. No doubt, trading of crude does take place, but controlled by the individual parties involved rather than by commonly accepted fungibility specifications such as those applied to finished petroleum products. Pipeline requirements for crude oil are designed to allow a given system to operate safely, in compliance with various laws, and within its engineering design capabilities.

The information discussed in this section was obtained from the Sunoco Pipeline L.P. website [168], www.sunocologistics.com. Five documents were selected to be representative of typical crude oil shipping requirements: Sunoco Pipeline L.P. Rules and Regulations Governing the Transportation of Crude Petroleum, Texas R.R.C. No. 11 and F.E.R.C. No. 3, Sunoco Pipeline L.P. Local Proportional Pipeline Tariff, Texas R.R.C. No. 11 and F.E.R.C. No. 142, and Sunoco Pipeline L.P. Viscosity Table. These references do not represent universal pipeline requirements for crude oil but are used to provide a comparison between typical crude oil and typical pyrolysis oil.

Crude oil varies greatly worldwide and is mainly described by three properties—density, percent sulfur, and viscosity—with these properties showing only limited correlation to each other. A summary of 98 crudes shown on the Sunoco Pipeline L.P. website indicates density ranging from 0.73 to 0.93 specific gravity or 21 to 61 API gravity (an inverse scale), sulfur ranging from 0.02 to 3.8%, and viscosity ranging from 2.7 to 1541 SUS at 60°F and averaging 163 SUS. Typically, crude with sulfur less than 0.5% is called sweet, and with sulfur greater than 0.5%, sour. Crude with a density of less than 0.87 kg/m^3 is called light; 0.87 to 0.92, medium; 0.92 to 1.00, heavy; and greater than 1.00, extra heavy.

Since crude oil is normally shipped in segregated batches, details of properties and chemistry are of interest to the pipeline company only to the extent that they affect operations or other batches of crude being shipped. Crude oil (direct liquid products) can be co-mingled with other products at point of origin or other reception points, such as gas condensate or other hydrocarbons (indirect liquid products), providing that the shipper, consignee, and destination are the same and that material entering the pipeline system meets appropriate specifications and requirements. Specifications for crude and mixtures of crude oil and other products that must be met for material to be accepted for shipment are shown in Table 6. These specifications were set assuming that the majority of materials shipped as crude oil would be, in fact, crude or condensate from natural gas collection wells. As such, they would probably require further definition if something as different as pyrolysis oil was shipped as crude oil or blended with crude oil. As a market develops, requirements will probably be revised and further defined to reflect operating experience and market demand.

A comparison between the crude requirements in Table 6 and the pyrolysis oil properties in the exhibits reveals a large discrepancy between pyrolysis oils and crude oil. Pyrolysis oil is not soluble in hydrocarbons but is soluble in water and alcohols. It contains both large amounts of water and chemically bound oxygen and smaller amounts of nitrogen. It can contain large amounts of carbon and smaller amounts of residual agricultural minerals (sodium, potassium, calcium, magnesium). Pyrolysis oil is denser than crude oil, can have high viscosity, and contains less carbon and hydrogen than crude oil with corresponding lower energy content. The upgrading of pyrolysis oil to match crude requirements for shipment appears to be extensive, and it is unclear if this would be economically and technically feasible. Other options for pyrolysis oil would be to use as fuel for boilers, turbines, or large, slow-speed engines, all of which may be more accepting of lower grade fuels or mixing of lower grade with current grade fuels. Residual metals in the pyrolysis oil (Na, K, Ca, Mg) may also prove difficult to remove and could act as poisons for upgrading catalysts and for emissions control catalysts when upgraded pyrolysis oil is burned as a fuel. The authors of this report recommend further study of the upgrade options for pyrolysis oil and further study of the compatibility of its use as a refinery feed to supplement crude oil.

Table 6. Representative crude requirements for pipeline shipments [168]

Property	Limit per Texas R.R.C. No. 11 and 40	Limit per F.E.R.C. No. 3 and 142
Vapor pressure, petroleum	9 psi summer, 10.7 psi winter @ 100°F	12 psi at 100°F
Vapor pressure, condensate or other indirect product	11.5 psi summer, 13.7 psi winter at 100°F	12 psi at 100°F
Proportion of indirect product	<20%	
Vapor pressure	In compliance with all federal, state, and local requirements	In compliance with all federal, state, and local requirements
API gravity	20 to 65	20 to 120
Evaporative loss correction	0.2% for API gravity below 50	
Foreign sediment and water	<2%	<1% with <0.3% water
Contamination	Incrustation of tanks n ot excessive	Incrustation of tanks not excessive
Contamination	Sediment in tanks 4 in. below bottom of pipeline connection	Sediment in tanks 4 in. below bottom of pipeline connection
Contamination	Iron <75 ppm	
Contamination	Lead <0.05 ppm in naphtha fraction	
Contamination	Organic chlorides <5 ppm	
Contamination	Excessive metals, chemicals, salts, refinery or process plant by-product	
Temperature	<120°F	
Viscosity	Additional tariff charged when viscosity exceeds 150 SUS at 100°F, up to 118% of base tariff	Additional tariff charged when viscosity exceeds 110 SUS at 60°F, up to 30% of base tariff
Viscosity	<250 SUS at 100°F	<300 SUS at 60°F, >200 SUS not accepted if degrades pipelline capacity
Additives	Carrier reserves right to inject or to approve injection of corrosion inhibitors or drag reducing agens	Carrier reserves right to inject or to approve injection of corrosion inhibitors

6. A MARKET FOR BIO-DERIVED HYDROCARBONS

Today's fuels are blended from a number of refinery intermediate streams (about five to seven for gasoline and three to five for distillate fuels). The resulting finished fuels contain a large number of compounds with various molecular weights. Overall, gasoline contains about 300 individual compounds, and distillate fuels, about 2500. The use of multiple processing options and resulting blending streams allows maximum utilization of crude oil and multiple options for blending to allow for refinery optimization. Some molecules are desirable for building required properties or meeting specifications, some are more neutral in effect but expand fuel volumes in a cost-effective manner, and some are undesirable in certain products but may be helpful in others.

With biofuels, it may not be economical to supply the entire range of property and specification requirements of today's petroleum fuels, and it may be more efficient if bio-derived materials are used as blending streams along with petroleum-derived components for fuel blending. Overall, bio-derived blending streams can be utilized via three paths to market: (1)They can be manufactured and used within a specific refinery fuel blending operation. (2) The biofuel blend streams could be transported to a specific refinery or blending site by proprietary or common carrier pipeline or other means such as truck or barge for private sale to an energy company. Finally, (3) certain biofuel blending streams can be sold or traded on the open market.

Platts (www.platts.com), in their *Refiner* newsletter [169], lists pricing for the blendstocks and intermediate refinery components, and their website also lists partial specifications. Prices are shown for April 3, 2009, and change daily (this date was chosen because it happened to be the date of a sample newsletter that could be freely downloaded). These materials are typically traded in volume increments of 50,000 barrels. Table 7 provides specifications, use, and representative pricing for commonly traded blending streams and refinery intermediates. The table shows product information listed in the newsletter. When batches of these products are actually traded, a full analysis is normally required.

The properties of the more highly valued streams could be targeted for biofuel manufacturing and would consist of mixed, longer chain paraffins for distillate blending and aromatics and isoparaffins for gasoline blending.

Table 7. Commonly traded fuel blending streams and refinery intermediates[a] [169]

Product	Chemistry	Use	Pricing	Sulfur, max (%)	API gravity	RVP (psi)	R+M/2 octane	RON	N+A, min (%)	P, min (%)
Alkylate	C5 to C8 isoparaffins	Gasoline blending	Gasoline + $0.20			5.5	92-93			
Reformate	Mixed aromatic, isoparaffin, and	Gasoline blending	Gasoline + $0.46	0.5	30-55	0.5-2.5		95-100		
Raffinate	Reformate with BTX removed	Gasoline blending	Gasoline – $0.08	0.5	60-70	2.0-6.0		55-65		
Xylene	Pure aromatic	Gasoline blending or petrochemical	$2.10							
Toluene	Pure aromatic	Gasoline blending or petrochemical	$1.85							
Low sulfur straight run	Mixed paraffinic	Distillate blending or cat cracker feed	$1.24/gallon	0.3	20-22					
Standard naphtha	Mixed paraffinic	Reforming feed	$1.25		56-60				40	
Paraffinic naphtha	Mixed paraffinic	Gasoline blending	$407/mt	500 ppm	65 max	12.5 max				65
Heavy naphtha	Mixed paraffinic	Reforming feed	$1.25		56				40	

[a] This table shows information listed in Platts' *Refiner* newsletter defining general characteristics of these products. When batches are actually traded, a full analysis is required.

7. ENTRY POINTS FOR BIO-DERIVED PRODUCTS INTO FUEL INFRASTRUCTURE

Bio-derived fuels or intermediates could enter the existing refining and distribution infrastructure based on their properties and composition. Table 8 indicates entry points for bio-products of various properties and composition. These possibilities are based on current refining, blending, and distribution practices and would be expected to evolve in the future.

Table 8. Possible entry points for bio-derived materials into petroleum fuel infrastructure

Entry point	Oxygenated feed	Deoxygenated, partially refined feed	Oxygenated blending component	Hydrocarbon blending component	Finished fuel
Refinery feed	Yes, but oxygen may limit feed percentage or require preprocessing	Yes, but must resemble refinery unit feed	NO	NO	NO
Refinery blending operation	NO	Yes, but must be similar to current blend streams	NO	YES	YES
Terminal	NO	NO	Yes, but must meet ethanol or FAME specifications	NO	YES

8. COST ESTIMATES FOR BIO-DERIVED FUELS

Table 9 summarizes the cost data for several biofuels production facilities. More detailed cost information can be found in the exhibits. The table displays examples of biofuel manufacturing plants and shows annual volume of biofuel produced, capital and operating costs, and feedstock cost.

It should be noted that there is a large variation in capital costs, ranging from roughly $6.6 million for a 4 million gallon/year (MMGPY) FAME facility to $341 million for a 35 MMGPY F-T diesel facility. Cellulosic ethanol and F-T diesel facilities appear to require significantly larger capital investment than do grain ethanol, FAME, and pyrolysis oil facilities. This may be partially attributable to the fact that the latter three are preexisting technologies that have been studied and iterated extensively, whereas the former two are relatively new and less researched technologies. If examined on a volume basis, the operating costs for all facilities also differ.

Both Table 9 and the exhibits clearly demonstrate that feedstock cost is by far the most significant component of operating costs—for example, amounting to 80% of total operating costs in the FAME facility study. Feedstock costs are also volatile, and small shifts in price can translate into substantial shifts in operating costs for a biofuel producer. This subsection is not intended to provide set price guidelines for building, operating, and maintaining a biofuels production facility but, rather, to provide a relative comparison between the current prices of various biofuels.

Table 9. Summary of capital and operating costs for several biofuels facilities

Product	Volume (million gallons/year)	Volume (barrels/ day)	Capital costs ($ million)	Yearly operating costs ($ million)	Feed	Feed costs	Operating + feed costs ($/gallon)
Pyrolysis oil [94,111,132, 164]	30	1950	48	9.6	Wood chips	$30 per dry ton	0.32
Ethanol [11,163]	25	1630	27.9	22	Grain		0.88
Ethanol [11,163]	50	3260	294	76	Cellulosic		1.52
Methanol [163]	87	5675	254	56.5	Biomass syngas		0.65
F-T diesel [111,147, 163]	35	2283	341	87.5	Biomass syngas		2.50
FAME [38,69]	4	260	6.6	8	Yellow grease	$0.17 per lb	2.00
FAME [38,69]	4	260	6.6	12.5	Soy oil	$0.31 per lb	3.13
FAME [38,69]	10	650	8.8	18	Yellow grease	$0.17 per lb	1.80
FAME [38,69]	10	650	8.8	29.2	Soy oil	$0.31 per lb	2.97

Limited cost data analysis references were available, and much of the data is unconfirmed by multiple sources. Specific capital, operating, and feedstock costs are thus associated with specific studies and may not necessarily be applied as general cost guidelines for all biofuels production facilities.

Some of the studies used for cost estimates examine several different types of biofuels facilities, such as one study that examined F-T diesel, ethanol, and pyrolysis oil, and another that examined F-T diesel, ethanol, and methanol. Most, however, specialize in one particular type of biofuel. Each study has a specific set of methods employed in its cost data analysis which result in capital and operating cost conclusions that are not necessarily directly comparable. The operating cost figure in the FAME study, for example, includes profits gained by selling the by-product glycerin at $0.26 per pound. One of the pyrolysis oil studies applies its analysis for the n^{th} number facility, as opposed to a pioneer plant, while others are not specific as to which facility is being studied. As was stated earlier, this subsection is not meant to provide price guidelines for building and operating a biofuels production facility but, rather, to provide a relative comparison between the projected prices of biofuels production and how this, along with numerous other factors, might determine the extent of their role in the U.S. biofuels portfolio.

9. CONCLUSIONS AND RECOMMENDATIONS

The expansion and further development of the biofuels industry will require that a number of decisions and investments be made. It is likely that ethanol will remain a major renewable fuel component and will continue to be terminal blended, with manufacturing of ethanol separate from oil refineries and with separate transportation to the blend site. Although EPA no longer requires oxygen in reformulated gasoline for nonattainment areas (*Federal Register,* May 8, 2006 [Vol. 71, No. 88, Rules and Regulations, pp. 26691–26702]), its use as a renewable fuel component is likely to continue and grow due to existing capacity, familiarity, financial incentives or tax breaks, and requirements of state or federal laws related to pollution reduction, farm support, or renewable content. It is technically possible that ethanol could be refinery blended and shipped over pipelines, but the economic benefits of doing this would depend on where ethanol is manufactured and used, form of transportation available, and pipeline capacity to handle the resulting larger gasoline/ethanol volumes. It would also require continued removal and monitoring of water in the distribution system and further study of the potential issues of ethanol-induced rust, corrosion, or stress corrosion cracking in distribution equipment. Elastomeric gaskets, seals, and piping would also have to be proven or changed to be compatible with ethanol fuels, but this is not expected to be a major roadblock.

Oils, fats, and greases are normally converted to fatty acid methyl esters or FAME, which is the most common form of biodiesel. FAME and FAME blends with diesel fuel are polar and therefore subject to water contamination, can contaminate other fuels shipped after biodiesel, can have a cleaning effect, and can have cold flow, filtration, or long-term stability problems. FAME quality issues were probably more frequent during the development of the industry and start-up of new manufacturing plants and have been largely eliminated with ASTM specifications covering both B100 and blends, with more manufacturing and distribution experience, and with the use of stability and filtration additives. FAME is normally added at a product terminal during truck loading, using on-line rack blending similar to that used for ethanol. This practice keeps the B100 FAME segregated from other products and results in the faster turnover of product. Production of FAME will likely increase in the future, due to the use of palm oil, increased use of waste oils and fats, and because of the algae potential for manufacturing fats and oils from CO_2 and water. There is limited experience with the shipping of FAME biodiesel over pipelines, and it appears to be successful. This experience is with pipelines that do not also ship jet fuel, but there is ongoing work relative to contamination and detection of contamination of jet fuel with FAME which may help support more flexible shipping practices in the future.

Currently, ethanol and FAME are largely manufactured from purpose-grown crops, with starch and sugar plants being used to supply ethanol fermentation and oil plants being used to supply oil and fats for FAME production. An emerging method for biofuel production is from gasified or pyrolyzed biomass on a large scale. Gasification results in CO and H_2, which can be recombined to liquid hydrocarbons using Fischer-Tropsch processing. Pyrolysis results in a liquid known as pyrolysis oil, which could be considered as a bio-derived crude oil. Unfortunately, such pyrolysis oil is heavily contaminated by residual plant compounds, has a very high oxygen and water content, has a high total acid number and corresponding low pH, and is relatively unstable. This could be an important source of fuel, providing these problems can be overcome economically. Pyrolysis oil could be upgraded in several steps: In the first step, it could be upgraded sufficiently to allow it to be shipped in a manner similar to crude oil; in the second step, it could be upgraded sufficiently to be used as a refinery unit feed; in the third step, it could be refined sufficiently to be used directly as a fuel blending component with petroleum-derived blending streams; and in the fourth step, it could be refined sufficiently to act as a final fuel and direct substitution for diesel fuel or gasoline. The authors speculate that the easiest entry point into existing infrastructure would be to upgrade sufficiently to allow the shipping of pyrolysis oil in a similar manner to crude oil, which would allow entry to the refining, blending, and distribution infrastructure already in use for petroleum-derived fuels. The options for this level of upgrading and the degree of upgrading required are recommended as a topic for additional study.

In addition to producing ethanol by fermentation of sugar, starch, or cellulose, or the conversion of oils and fats to FAME, these materials can also be converted to other hydrocarbon components using catalytic (refining-like) processes. There are many options—some are under current investigation, some may already be in use for fuel manufacturing or for making other industrial chemicals, and some have been discussed but not experimentally investigated. Further study of the processes and information available about each process is recommended. Overall, the recommendations for further study are summarized in Table 10. These tasks have been used to form a basis for discussions related to continuing this research.

Table 10. Recommendations for further study

Recommendation number	Feed material	Fuel	Recommended areas for future investigation
1	Sugar, starch, cellulose	Ethanol	Study of rust, corrosion, and stress corrosion cracking of mild and low alloy steel by ethanol and ethanol containing fuels and related industrial experience
2	Sugar, starch, cellulose	Ethanol	Study of control and removal of water bottoms from fuel distribution system and related industrial experience
3	Fats, oils	FAME biodiesel	Study of issues associated with shipping FAME biodiesel over common carrier distribution system, including batch sequencing with and possible contamination of jet fuel, and related industrial experience
4	Biomass	Pyrolysis oil	Study of the issues, options, and degree of upgrading required to allow pyrolysis oil to be treated like crude oil for shipping purposes
5	Sugars, starch, oils, fats	Hydrocarbon fuel blending components	Study of the options and current state of knowledge relative to converting biofeeds to fuel compatible hydrocarbons

10. REVIEW OF COMMENTS RECEIVED AND SUGGESTED MODIFICATIONS OR ADDITIONS FOR FUTURE STUDY

This report, in draft form, was distributed to four integrated oil companies, two of which provided comments with the understanding that the comments do not represent official company views and would not be attributed to the companies or individuals. DOE also provided guidance and comments relative to priorities for a possible continuation of this research. All of these comments have been combined in this section, without attribution, as possible technical recommendations for future work. We note that many of these recommendations are beyond the scope of the current study and have been or are being addressed in other studies. They are listed here for completeness and to help provide guidance for this and other projects.

1. Suggestion was made to de-emphasize study of ethanol-related infrastructure issues, since ethanol has already been and is being heavily studied in other projects. (These are topics 1 and 2 in Table 10.)

2. Provide more information or recommendations related to health effects of new biofuels with discussion related to the amount or type information that might be required for EPA approval of these new fuels. (This would be a new addition to Table 10.)

3. Extend infrastructure compatibility evaluation to include service stations, current vehicles, and future vehicles. Provide survey of types of materials in current use and industry plans for material changes or upgrading. Provide summary of approvals necessary for fueling equipment. (This would be a new addition to Table 10.)

4. Discuss in more detail how oxygen in fuels affects engine operation and infrastructure compatibility. Discuss changes that could mitigate these effects. (This would be a new addition to Table 10.)

5. Expand study of pyrolysis oils in the areas of chemistry, properties, and material compatibility. (This is an expansion of topic 4 in Table 10.)

6. Topics 3 and 5 in Table 10 should remain as written.

7. Review and coordinate research with other labs or companies working on infrastructure-related issues in order to disseminate results, gather information, build synergy, and avoid duplication.

11. REFERENCES

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EXHIBITS

Oil Pipelines
E.1. Products of the Largest U.S. Interstate Oil Pipeline Companies

Largest U.S. Interstate Oil Pipeline Companies	**Ethanol**	**Biodiesel**	**Butane**	**Iso-Butane**	**Ethane**	**Demethanized NGL**	**Propane**	**Propylene**	**crude**	**Unleaded Gasoline**	**Gasoline Blendstock**	**Jet Fuel**	**Diesel**	**Kerosene**	**Natural Gasoline**	**Fuel Oil**	**Biodiesel Fuel Oil**
Magellan	E grade DN"	prohibited#, freeze/cloud point resitrictions	H grade	I grade	no	no	L grade	no	no	yes*	yes*	yes	yes	no	W grade	Y grade	ZB grade
Plains All-American									yes								
ConocoPhillips	prohibited^	freeze/cloud point restrictions	dedicated line	dedicated line	dedicated line	dedicated line	dedicated l	dedicated l	yes	yes*^		yes	yes	no	no	yes	no
Colonial	prohibited^	prohibited	no	no	no	no	no	no		yes*^	yes*	no	yes	Grade 51, 53-57		yes	no
Sunoco	prohibited	prohibited	yes	no	no	no	no	no	yes	yes*	yes*	yes	yes	yes	no	yes	no
Enterprise	yes"	freeze/cloud point restrictions	yes	yes	yes	dedicated line	yes	yes	yes	yes*		yes	yes		yes		
ExxonMobil	prohibited^		dedicated line	dedicated line	dedicated line		dedicated l	dedicated l	yes	yes^					dedicated line		
NuStar Logistics			yes			yes	yes		yes	yes	yes	yes	yes				
Buckeye Partners	prohibited^	prohibited	yes			yes	yes			yes*^	yes	yes	yes	yes		yes	no
Kinder Morgan	dedicated line"^	allowed&								yes*^	yes*	yes	yes				

Notes: _*oxygen content restrictions_
^alcohols and ethers prohibited as blending components in gasoline at origin
"corrosion inhibitor required, max 1.00 vol% water
#up to 5% biodiesel mixtures allowed in XZ-grade ULSD shipments from Houston to East Houston only
&biodiesel permitted in pure form or as B5 or B2 blends in 8000 miles of pipeline, freeze/cloud point must adhere to ASTM standards by region, yellow grease as feedstock prohibited
E grade ethanol specs include:
1) min 98 vol% ethanol content
2) only allowable denaturants are unleaded gasoline and natural gasoline
3) 0.5 mass% water max

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Enterprise Products Partners LP, www.epplp.com, 12/09
ExxonMobil Pipeline Co., www.exxonmobilpipeline.com, 12/09
Magellan Pipeline Company LLC, www.magellanlp.com, 12/09
NuStar Logistics LP, www.nustarenergy.com, 12/09
Oil & Gas Journal, "Special Report: Natural Gas Pipeline Profits Surge; Oil Flat", 9/1/2008
Plains All-American Pipeline LP, www.paalp.com, 12/09
Sunoco Pipeline Co., www.sunocologistics.com, 12/09
TEPPCO Partners LP, www.teppco.com, 12/09
Williams Energy Partners LP, E grade DN fuel ethanol specifications, 4/2003
Kinder Morgan, www.kne.com, 2/10

Oil Piplines

E.2. Pipeline Descriptions of the Largest U.S. Interstate Oil Pipeline Companies

Largest U.S. Interstate Oil Pipeline Cos.	**Mileage***	**Pipelines**	**Location**
Magellan	9500 refined/1100 ammonia	refined, ammonia	Pipeline in midwest, from Texas to Wisonsin, with inland terminals in the southeast and marine terminals in the gulf
Plains All-American	8387*, 3 mil bpd	refined, crude, LPG, 3rd party	Pipeline from midwest to western Canada, with crude/refined/LPG/natural gas storage facilities across US
ConocoPhillips	11000	refined, crude, LPG	Pipeline from Texas to northwest and Chicago, with product terminals across US
Colonial	5591*, 2.3 mil bpd	refined	Pipeline from gulf to northeast
Sunoco	2200 refined/3350 crude	refined, crude	Pipeline from Texas to Chicago and northeast/Philadelphia metro area, with additional crude pipeline in northwest
Enterprise	48000	refined, crude, natural gas, NGL, petrochemicals	Pipeline partners from gulf up through midwest, northwest, and northeast, with some pipeline in southeast
ExxonMobil	4559*	refined, crude, LPG, NGL, petrochemicals	Pipeline from gulf to Michigan, northeast, southeast, southwest and California, with trans-Alaskan pipeline
NuStar Logistics	8147, 824K bpd	refined, crude, ammonia	Pipeline from gulf to Texas and midwest, terminals and storage facilities across country
Buckeye Partners	5400	refined, LPG, NGL, petrochemicals	Pipeline network from Chicago to Philadelphia metro areas, with smaller pipelines in Florida, Texas, and midwest
Kinder Morgan	8000+, 2 mil bpd	refined, NGL	Pipeline network in Southeast, Southwest and California, NGL pipeline in Great Lakes region north through Canada

Notes: **2007 mileage from "Special Report: Natural Gas Pipeline Profits Surge; Oil Flat" , Oil & Gas Journal, 9/1/2008,*
all other mileage and daily production data from company websites 12/4/2009

references:

Buckeye Partners, www.buckeye.com, 12/09
Colonial Pipeline Co., www.colpipe.com, 12/09
ConocoPhillips Pipeline LP, www.conocophillipspipeline.com, 12/09
Enterprise Products Partners LP, www.epplp.com, 12/09
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Magellan Pipeline Company LLC, www.magellanlp.com, 12/09
NuStar Logistics LP, www.nustarenergy.com, 12/09
Oil & Gas Journal, "Special Report: Natural Gas Pipeline Profits Surge; Oil Flat", 9/1/2008
Plains All-American Pipeline LP, www.paalp.com, 12/09
Sunoco Pipeline Co., www.sunocologistics.com, 12/09
TEPPCO Partners LP, www.teppco.com, 12/09
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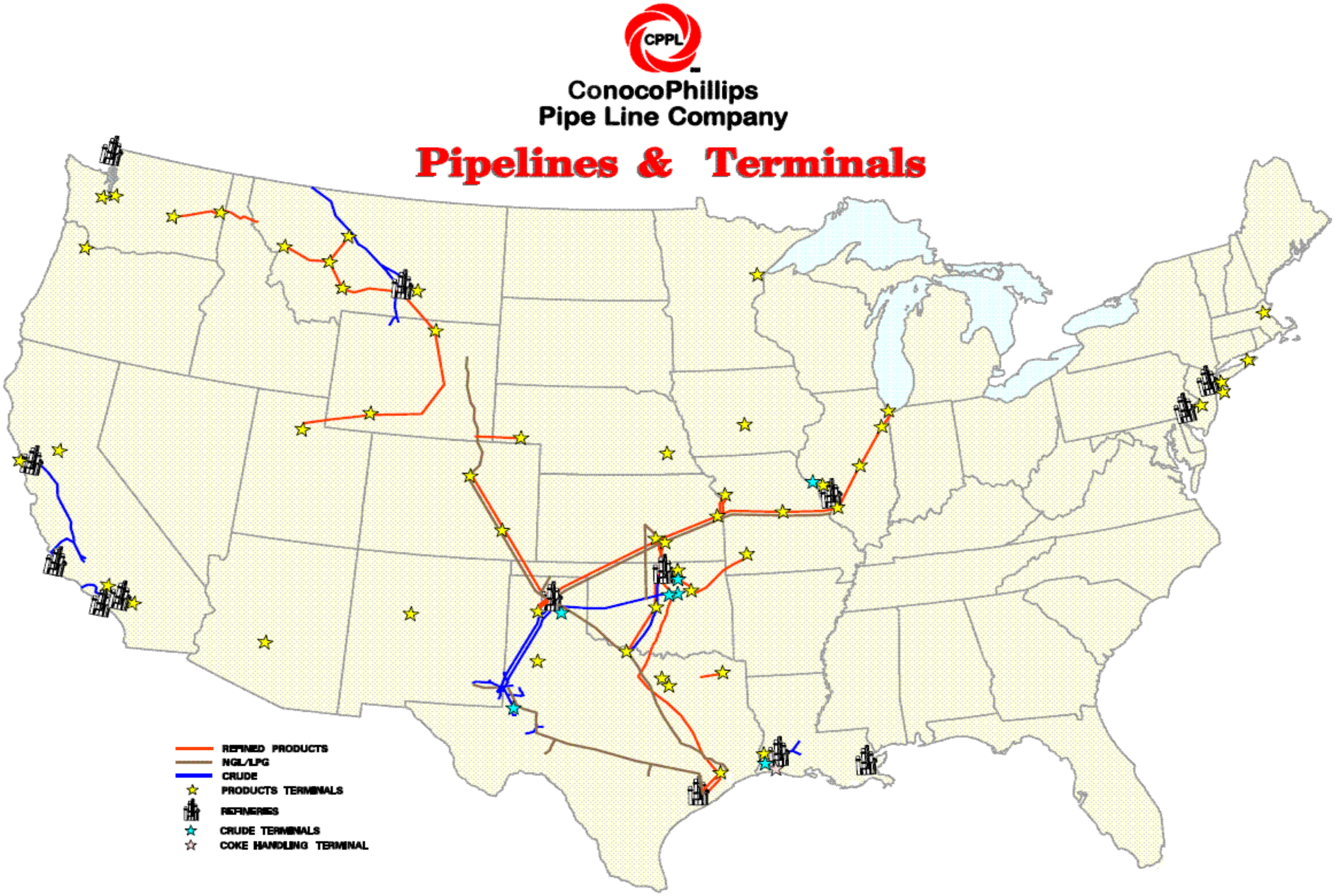
Kinder Morgan, www.kne.com, 2/10

Oil Pipelines

E.3. Maps of the Pipelines and Terminals of the Largest U.S. Interstate Oil Pipeline Companies

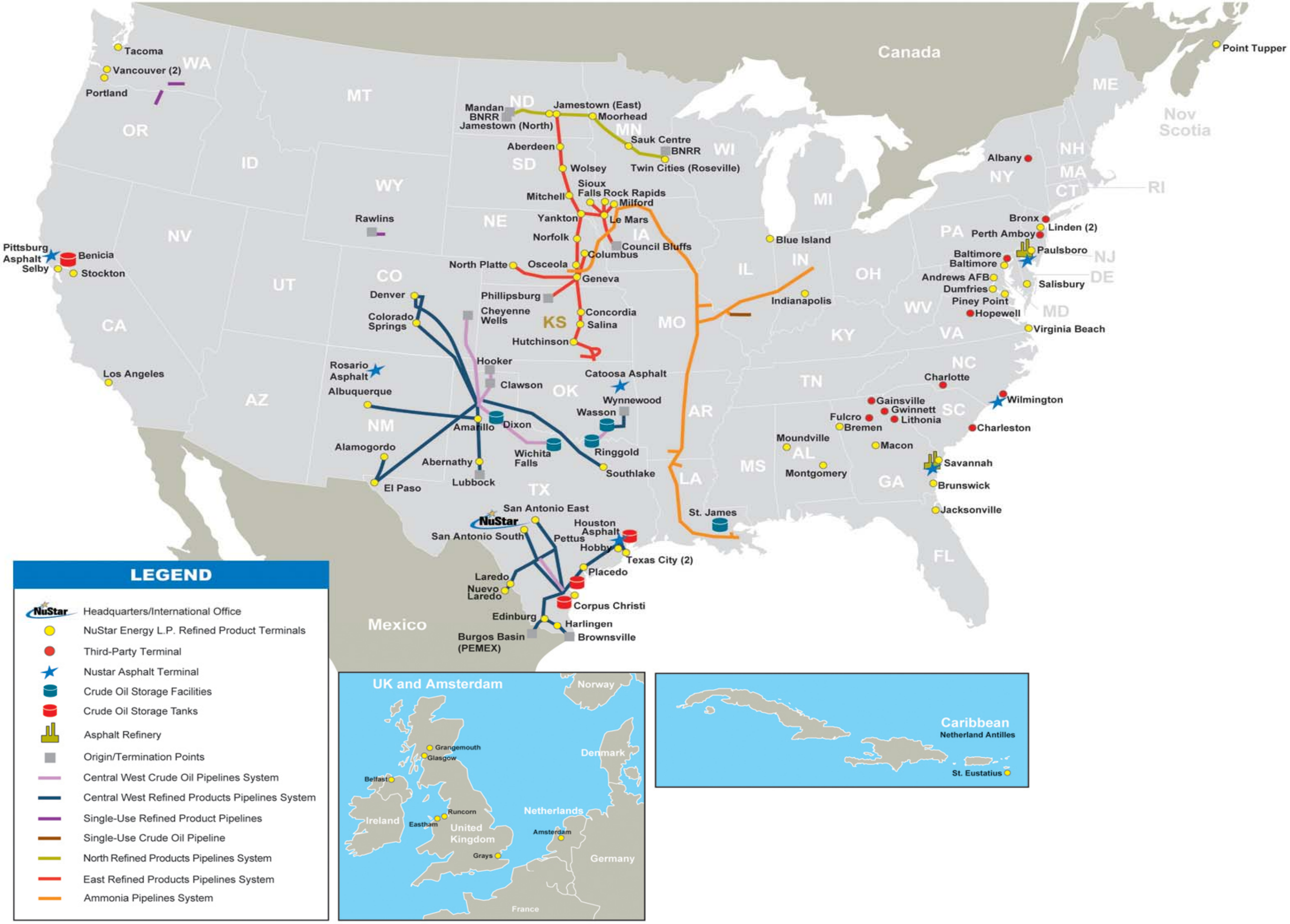
ConocoPhillips



Oil Pipelines

E.3. Maps of the Pipelines and Terminals of the Largest U.S. Interstate Oil Pipeline Companies

NuStar



Oil Pipelines

E.3. Maps of the Pipelines and Terminals of the Largest U.S. Interstate Oil Pipeline Companies

Buckeye Partners

Oil Pipelines

E.3. Maps of the Pipelines and Terminals of the Largest U.S. Interstate Oil Pipeline Companies

references:

Buckeye Partners, www.buckeye.com, 12/09
ConocoPhillips Pipeline LP, www.conocophillipspipeline.com, 12/09
NuStar Logistics LP, www.nustarenergy.com, 12/09

Hazardous Materials Transport

E.4. Transportation Options for Hazardous Fuels

Hazardous materials descriptions and proper shipping names		Quantity limitations				
	Hazard Class	Passenger aircraft/rail	Cargo aircraft only	Rail	Vessel	Public Highway
Butanols	3	60 L	220 L	private track	yes	yes
Coal gas, compressed	2.3	Forbidden	Forbidden	yes	yes	yes
Coal tar distillates, flammable	3	60 L	220 L	private track	yes	yes
Diesel fuel	3	60 L	220 L	private track	yes	yes
Dimethyl ether	2.1	Forbidden	150 kg	yes	on-deck only	yes
Esters, n.o.s.	3	60 L	220 L	private track	yes	yes
Ethanol and gasoline mixture *or* Ethanol and motor spirit mixture *or* Ethanol and petrol mixture, *with more than 10% ethanol*	3	5 L	60 L	private track	yes	yes
Ethanol *or* Ethyl alcohol *or* Ethanol solutions *or* Ethyl alcohol solutions	3	60 L	220 L	private track	yes	yes
Gasohol *gasoline mixed with ethyl alcohol, with not more than 10% alcohol*	3	5 L	60 L	private track	yes	yes
Gasoline *includes gasoline mixed with ethyl alcohol, with not more than 10% alcohol*	3	5 L	60 L	private track	yes	yes
Hydrocarbons, liquid, n.o.s.	3	60 L	220 L	private track	yes	yes

Hazardous Materials Transport

E.4. Transportation Options for Hazardous Fuels

Hazardous materials descriptions and proper shipping names		Quantity limitations				
	Hazard Class	**Passenger aircraft/rail**	**Cargo aircraft only**	**Rail**	**Vessel**	**Public Highway**
Hydrogen, compressed	2.1	Forbidden	150 kg	yes	on-deck only	no tunnels
Isobutane *see also* Petroleum gases, liquefied	2.1	Forbidden	150 kg	yes	on-deck only	yes
Isobutanol *or* Isobutyl alcohol	3	60 L	220 L	private track	yes	yes
Isoprene, stabilized	3	1 L	30 L	private track	yes	yes
Kerosene	3	60 L	220 L	private track	yes	yes
Methane, compressed *or* Natural gas, compressed *(with high methane content)*	2.1	Forbidden	150 kg	yes	on-deck only	yes
Methane, refrigerated liquid *(cryogenic liquid) or* Natural gas, refrigerated liquid *(cryogenic liquid), with high methane content)*	2.1	Forbidden	Forbidden	yes	on-deck only	no tunnels
Methanol	3	1 L	60 L	private track	yes	yes
Petroleum crude oil	3	60 L	220 L	private track	yes	yes
Petroleum distillates, n.o.s. *or* Petroleum products, n.o.s.	3	60 L	220 L	private track	yes	yes
Petroleum gases, liquefied *or* Liquefied petroleum gas	2.1	Forbidden	150 kg	yes	on-deck only	yes

Hazardous Materials Transport

E.4. Transportation Options for Hazardous Fuels

Hazardous materials descriptions and proper shipping names		Quantity limitations				
	Hazard Class	**Passenger aircraft/rail**	**Cargo aircraft only**	**Rail**	**Vessel**	**Public Highway**
Petroleum oil	3	60 L	220 L	private track	yes	yes
Propane *see also* Petroleum gases, liquefied	2.1	Forbidden	150 kg	yes	on-deck only	yes
n-Propanol *or* Propyl alcohol, normal	3	60 L	220 L	private track	yes	yes
Shale oil	3	60 L	220 L	private track	yes	yes
Terpene hydrocarbons, n.o.s.	3	60 L	220 L	private track	yes	yes

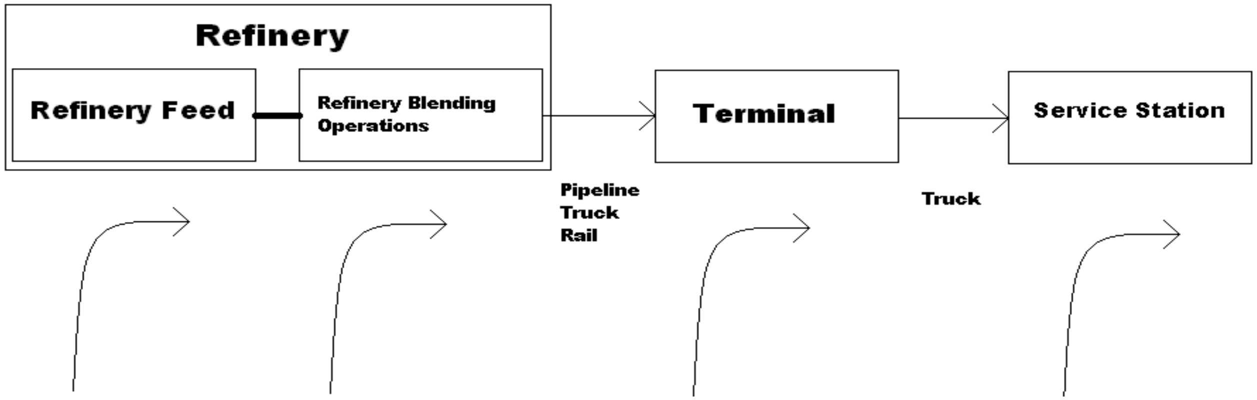
Hazard Class:
2.1 - flammable gas
2.3 - poisonous gas
3 - flammable and combustible liquid

references:
Department of Transportation, "Title 49, Subtitle B, Chapter 1,
Subchapter C - Hazardous Materials Regulations", www.goaccess.gov, 12/8/09

Distribution Chain

E.5. Inserting Biofuels into the Current Distribution Chain

Inserting biofuels into the current distribution chain



1) pyrolysis oil
potential use as refinery feed
2) algae oil
potential use as refinery feed
3) terpene
potential use as refinery feed
4) isoprene
potential use as refinery feed

1) FAME[a]
proven successful in common carrier pipeline
2) sesquiterpene
not miscible in water, VP similar to diesel, low cloud
3) Fischer-Tropsch fuel
"can be directly fed into current infrastructure"
4) ethanol
some pipeline spurs allow ethanol blends

1) ethanol
miscible in water
2) diglyme
miscible in water
3) methanol
miscible in water
4) biobutanol
miscible in water
5) green diesel
high cloud point makes traditional storage difficult
6) FAME
current practice is to blend at terminals due to FAME ban in many pipelines

1) DME
exists as a gas at STP, requires separate distribution network a la propane
2) methane
exists as a gas at STP, requires separate distribution network
3) hydrogen
exists as a gas at STP, requires separate distribution network

Notes:
High barrier for gaseous fuels due to current refinery-terminal-service station system's accommodation of liquid fuels only. Gaseous fuels necessitate separate distribution network, such as the one currently in place for propane.

Limited studies concerning entering FAME and ethanol in current oil pipelines. In addition, FAME and ethanol are currently expressly banned in most pipelines.

references: please see individual fuel property and compatibility worksheets for appropriate references
[a] McElroy, Anduin Kirkbride, "Pipeline Potential", Biodiesel Magazine, 2/2007

Costs

E.6. Projected Capital and Operating Costs for FAME, Pyrolysis Oil, Ethanol, Methanol, Hydrogen, and Fischer-Tropsch

Projected Capital and Operating Costs:

FAME
Capital costs for 4 million gal/yr (260 bpd) facility: $6,627,540.00
Capital costs for 10 million gal/yr (650 bpd) facility: $8,820,760.00

Operating costs for 4 million gal/yr facility using yellow grease feedstock: $8,042,396.00
Operating costs for 4 million gal/yr facility using soybean oil feedstock: $12,502,396.00

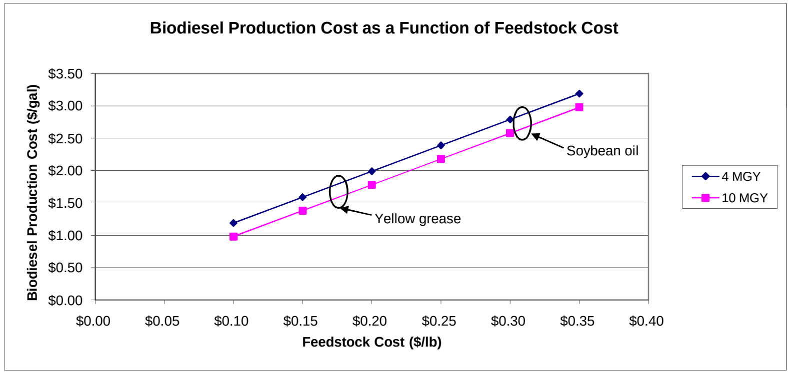
Operating costs for 10 million gal/yr facility using yellow grease feedstock: $18,041,034.00
Operating costs for 10 million gal/yr facility using soybean oil feedstock: $29,191,034.00

Notes:
Operating costs include gains made by selling by-products, including glycerin priced at $0.26 per lb

Study assumes feedstock costs per lb. are $0.17 for yellow grease and $0.31 for soybean oil

Feedstock is approximately 80% of total operating cost

Feedstock cost ($/lb)	Biodiesel production cost ($/gal)	
	4 MGY	10 MGY
$0.10	$1.19	$0.98
$0.15	$1.59	$1.38
$0.20	$1.99	$1.78
$0.25	$2.39	$2.18
$0.30	$2.79	$2.58
$0.35	$3.19	$2.98


Biodiesel Production Cost as a Function of Feedstock Cost

references: Fortenbery, Randall T., "Biodiesel Feasibility Study: An Evaluation of Biodiesel Feasibility in Wisconsin", University of Wisconsin Staff Paper No. 481, 3/2005
Coltrain, David, "Biodiesel: Is It Worth Considering?", Risk and Profit Conference, Kansas State University, 8/2002

Pyrolysis Oil

Capital costs: $48,291,646.00

Operating costs: $9,600,000.00

Notes:
Facility uses fast pyrolysis process

Facility produces 16,091 kg/hr of bio-crude (on the order of 30 million gal/yr, 1950 bpd)[a]

Assumes wood chip feedstock price of $30/dry ton

Operating costs include annual revenue of $210,000.00 due to annual net electricity export of 4.7 MM kWh

references: Ringer, M., Putsche, V., and Scahill, J., "Large Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis", NREL Technical Report TP-510-37779, 11/2006
[a] Katikaneni, Sai P. R., Bakhshi, Narendra N., and Huffman, Don, "The New Bio-Crude: A Renewable Substitute for Petroleum?", Energy Conversion and Engineering Conference, 8/1996

Capital costs: $200-280 million

Product Value (PV): $2 - $3 per gallon gasoline equivalent (GGE)

Notes:
Analysis for nth facility

PV = production cost of fuel, including 10% return on investments

Corn stover feedstock cost = $75 per short ton

Feedstock capacity = 2000 dry tonne (Mg) stover per day

Process involves production of pyrolysis oil and then hydroprocessing to diesel/gasoline-range fuel

Equipment, chemical, and labor prices in 2007 dollars

references: Anex, Aden, Kazi, Fortman, Swanson, Wright, Satrio, Brown, Daugaard, Platon, Kothandaraman, Hsu, Dutta, "Techno-Economic Comparison of Biomass-to-Transportation Fuels Via Pyrolysis, Gasification, and Biochemical Pathways", accepted to Fuel 2/10

Capital costs: $200-287 million

Product Value (PV): $2.11 - $3.09 per gallon gasoline equivalent (GGE)

Notes:
Analysis for nth facility

PV = production cost of fuel, including 10% return on investments

Corn stover feedstock cost = $75 per short ton

Feedstock capacity = 2000 dry tonne (Mg) stover per day

Production = 134 - 220 million L/year

Equipment, chemical, and labor prices in 2007 dollars

references: Wright, Satrio, Brown, Daugaard, "Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels", accepted to Fuel 2/10

Costs

E.6. Projected Capital and Operating Costs for FAME, Pyrolysis Oil, Ethanol, Methanol, Hydrogen, and Fischer-Tropsch

Ethanol

Capital costs for 25 MMGPY (1630 bpd) grain ethanol facility: $27,900,000.00

Capital costs for 50 MMGPY (3260 bpd) cellulosic ethanol facility: $294,000,000.00

Operating costs for 25 MMGPY grain ethanol facility: $22,000,000.00

Operating costs for 50 MMGPY cellulosic ethanol facility: $76,000,000.00

Notes:
25 MMGPY grain ethanol in 1999 prices, 50 MMGPY cellulosic ethanol in 2005 prices

references: Wright, Mark M. and Brown, Robert C., "Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms", Center for Sustainable Environmental Technologies - Iowa State University, Biofuels, Bioproducts, and Biorefining 1:49-56, 2007

Capital costs: $380-390 million

Product Value (PV): $5 - $5.50 per gallon gasoline equivalent (GGE)

Notes:
Analysis for nth facility

PV = production cost of fuel, including 10% return on investments

Corn stover feedstock cost = $75 per short ton

Feedstock capacity = 2000 dry tonne (Mg) stover per day

Equipment, chemical, and labor prices in 2007 dollars

references: Anex, Aden, Kazi, Fortman, Swanson, Wright, Satrio, Brown, Daugaard, Platon, Kothandaraman, Hsu, Dutta, "Techno-Economic Comparison of Biomass-to-Transportation Fuels Via Pyrolysis, Gasification, and Biochemical Pathways", accepted to Fuel 2/10

Capital costs: $327-501 million

Product Value (PV): $5.13 - $6.50 per gallon gasoline equivalent (GGE)

Notes:
Analysis for nth facility

PV = production cost of fuel, including 10% return on investments

Corn stover feedstock cost = $83 per short ton

Feedstock capacity = 2000 dry tonne (Mg) stover per day

Ethanol production = 124-210 million L/year

Equipment, chemical, and labor prices in 2007 dollars

references: Anex, Aden, Kazi, Fortman, Kothandaraman, Hsu, Dutta, "Techno-Economic Comparison of Process Technologies for Biochemical Ethanol Production from Corn Stover", Fuel 2010

E.6. Projected Capital and Operating Costs for FAME, Pyrolysis Oil, Ethanol, Methanol, Hydrogen, and Fischer-Tropsch

Methanol
Capital costs for 87 MMGPY (5675 bpd) methanol facility: $254,000,000.00

Operating costs for 87 MMGPY methanol facility: $56,500,000.00

Notes:
87 MMGPY methanol in 2002 prices

Methanol produced from syngas from unspecified biomass feedstock

references: Wright, Mark M. and Brown, Robert C., "Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms", Center for Sustainable Environmental Technologies - Iowa State University, Biofuels, Bioproducts, and Biorefining 1:49-56, 2007

Hydrogen
Capital costs for 182 MMGPY (11870 bpd) hydrogen facility: $244,000,000.00

Operating costs for 182 MMGPY hydrogen facility: $53,500,000.00

Notes:
182 MMGPY hydrogen in 2002 prices

Hydrogen produced from syngas from unspecified biomass feedstock

references: Wright, Mark M. and Brown, Robert C., "Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms", Center for Sustainable Environmental Technologies - Iowa State University, Biofuels, Bioproducts, and Biorefining 1:49-56, 2007

Costs

E.6. Projected Capital and Operating Costs for FAME, Pyrolysis Oil, Ethanol, Methanol, Hydrogen, and Fischer-Tropsch

Fischer-Tropsch
Capital costs for 35 MMGPY (2280 bpd) F-T facility: $341,000,000.00

Operating costs for 35 MMGPY F-T facility: $87,500,000.00

Notes:
35 MMGPY F-T in 2002 prices

F-T produced from syngas from unspecified biomass feedstock

references: Wright, Mark M. and Brown, Robert C., "Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms", Center for Sustainable Environmental Technologies - Iowa State University, Biofuels, Bioproducts, and Biorefining 1:49-56, 2007

Capital costs: $500-610 million

Product Value (PV): $4.50 - $5 per gallon gasoline equivalent (GGE)

Notes:
Analysis for nth facility

PV = production cost of fuel, including 10% return on investments

Corn stover feedstock cost = $75 per short ton

Feedstock capacity = 2000 dry tonne (Mg) stover per day

Process involves gasification of corn stover, FT processing, and then hydroprocessing to diesel/gasoline-range fuel

Equipment, chemical, and labor prices in 2007 dollars

references: Anex, Aden, Kazi, Fortman, Swanson, Wright, Satrio, Brown, Daugaard, Platon, Kothandaraman, Hsu, Dutta, "Techno-Economic Comparison of Biomass-to-Transportation Fuels Via Pyrolysis, Gasification, and Biochemical Pathways", accepted to Fuel 2/10

Capital costs: $500-600 million

Product Value (PV): $4 - $5 per gallon gasoline equivalent (GGE)

Notes:
Analysis for nth facility

PV = production cost of fuel, including 10% return on investments

Corn stover feedstock cost = $75 per short ton

Feedstock capacity = 2000 dry tonne (Mg) stover per day

Process involves gasification of corn stover, FT processing, and then hydroprocessing to diesel/gasoline-range fuel

Equipment, chemical, and labor prices in 2007 dollars

references: Swanson, Satrio, Brown, Platon, "Techno-Economic Analysis of Biomass-to-Liquids Production Based on Gasification Scenarios", accepted to Fuel 2/10

Costs

E.7. Cost Summary for Several Biofuels

PRODUCT	VOLUME		CAPITAL COSTS	YEARLY OPERATING COSTS	FEED	FEED COSTS	OPERATING + FEED COSTS
	MMGPY	BPD	MM$	MM$			$ per gallon
pyrolysis oil	30	1950	48	9.6	wood chips	$0.30/dry ton	$0.32
ethanol	25	1630	27.9	22	grain		$0.88
ethanol	50	3260	294	76	cellulosic		$1.52
methanol	87	5675	254	56.5	biomass syngas		$0.65
FT fuel	35	2283	341	87.5	biomass syngas		$2.50
FAME	4	260	6.6	8	yellow grease	$0.17/lb	$2.00
FAME	4	260	6.6	12.5	soy oil	$0.31/lb	$3.13
FAME	10	650	8.8	18	yellow grease	$0.17/lb	$1.80
FAME	10	650	8.8	29.2	soy oil	$0.31/lb	$2.97

Policy Drivers for Increased Biofuels Usage

Omnibus Budget Reconcilliation Act of 1990 - IRS, Customs
Tax credit for small ethanol producers. Tariff on most imported ethanol.

1998 ammendment to 1992 Energy Policy Act - EPA, DOE
Portion of new vehicle purchases by some fleets (including federal and many state govs) must be alternative fuel vehicles.
1998 ammendment includes biodiesel as alternative fuel.

Biomass Research and Development Act of 2000 - DOE, USDA
Provides grants for biomass research and demonstration projects.

2001 Value-Added Producer Grants Program - USDA
Provides grants for independent producers of value-added agricultural activities, e.g. biofuel production. Scheduled to end FY2007, extended.

Farm Security and Rural Investment Act of 2002 - USDA
Provides grants and loans for renewable energy projects and energy efficiency improvements, e.g. construction of biofuel plants.

Commodity Credit Corporation's Bioenergy Program - USDA
Payments for alternative fuel producers, feedstocks included animal fats and recycled oils. Ended June 2006.

2004 American Jobs Creation Act - IRS
Incentives to biofuel producers (feedstocks include animal fats, vegetable oils, recycled oils). Biodiesel must meet ASTM D6751 standard.

2005 Energy Policy Act - IRS, DOE
Provides tax incentives for small biodiesel producers, expired in 2008. Establishes Renewable Fuels Standard.
Also provides loan guarantees for construction of facilities that produce ethanol from cellulose, MSW, or sugar cane.

Renewable Fuels Standard - EPA
Mandates 7.5 billion gallons of biofuels used by 2012. Mandates widespread blending of biofuels into petroleum fuels.
Provides additional incentives for cellulosic ethanol producers.

Tax Relief and Healthcare Act of 2006 - IRS
Depreciation allowance for cellulosic ethanol plant property owners.

2007 Energy Independence and Security Act (proposed expansion of Renewable Fuels Standard [RFS2]) - EPA
Mandates increased biofuels production from 9 billion gal/yr in 2008 to 36 billion gal/yr in 2022.
Includes cellulosic (advanced, i.e. non-corn feedstock) biofuel, biodiesel, and non-road biofuel requirements.

Policy Drivers

E.8. Policy Drivers for Increased Biofuels Use

Year	Mandated Biofuels Usage (billion gallons)
2008	9
2009	11.1
2010	12.95
2011	13.95
2012	15.2
2013	16.55
2014	18.15
2015	20.5
2016	22.25
2017	24
2018	26
2019	28
2020	30
2021	33
2022	36

2008 Farm Bill - USDA

Establishes tax credits for cellulosic ethanol use, among other biofuels incentives that are yet to be funded.

Food, Conservation, and Energy Act of 2008 - IRS, USDA

Tax credits for cellulosic ethanol producers and incentives for biorefineries.

State Initiatives

Low Carbon Fuel Standard - mandates at least 10% reduction in 2007 carbon intensity in transportation fuels by 2020, carbon intensity based on life-cycle global warming intensity.
Fuel providers must track and reduce the life-cycle global warming intensity of their products.
Mandated by the state of California, 11 other states considering adopting similar proposals.

Every state and the District of Columbia have incentives and/or mandates designed to encourage the production and use of renewable energy sources, including biofuels.
These measures include, but are not limited to, the following:

~ tax exemptions
~ fueling infrastructure grants
~ payments for production
~ state tax credits
~ renewable fuel usage mandates
~ state fleet requirements

references: Yacobucci, Brent D., "Biofuels Incentives: A Summary of Federal Programs", Congressional Research Service Report for Congress, 7/29/2008
Database of State Incentives for Renewables & Efficiency, US Department of Energy and North Carolina Solar Center, www.dsireusa.org, 2009
U.S. Energy Information Administration, "Biofuels in the U.S. Transportation Sector", 2/2007
Georgia Forestry Commission, "Summary of State Incentives and Legislation for Renewable Energy Production", 9/2007
Farrell, Alexander E. and Sperling, Daniel, "A Low-Carbon Fuel Standard for California", 8/2007
Mueller, Stefan, "Assessing the Climate Change Impact of Biofuels", BioCycle Conference on Renewable Energy from Organics Recycling, 10/2007
Environmental Protection Agency, RFS2, www.epa.gov, 1/2009

Diesel Fuels

E.9. FAME (Fatty Acid Methyl Esters)--Properties

Properties

	Soybean Methyl Ester	Rapeseed Methyl Ester	Poultry Fat Methyl Ester	No. 2	US FAME Specifications ASTM D6751-06a	EU FAME Specifications EN 14214: 2003	*Comments*
Molecular Formula	C18 to C19	C18 to C19		C8 to C25			
Molecular Weight (g/mol)	300 (approx)	300 (approx)		200 (approx)			
Elemental Composition (mass%)							
Carbon	78	81		84-87			
Hydrogen	11	12		13-16			
Oxygen	11	7		0			
Density (g/cm3) at 15deg C	0.87	0.88		0.81-0.89		0.86-0.9	
Vapor Pressure kPa at 38 degC	<1	<1		<1			
Boiling Point		350	342 [d]	188-343			
Flash Point (degC)		179	143 [d]	74	min 120	min 130	*Higher flashpoint of FAME influenced by alcohol content from production process*
Pour Point (degC)	-3	-15		-23			*FAME low temperature issues*
Cloud Point (degC)		-6 [a]	6.5 [d]	-15 [a]	Report		
High Heating Value (MJ/L)							
Low Heating Value (MJ/L)	~32	~37		35-37			*SME lower energy density*
Water solubility in fuel (ppm)		850		<50			
Water content in fuel (mg/kg)						500 max	
Fuel Miscibility							
Solvation Potential		High		Low			
Flammability Limits (Vol%)							
Lower				1			
Higher				6			
Acid Number			0.39 [d]				
Cetane Number	52	62		40-55	47 min	51 min	*FAME generally higher cetane*
Viscosity (mPa-s)	3.0-6.0	3.0-6.0		2.6-4.1			
Kinematic viscosity (mm^2/s)			4.39 [d]		1.9-6.0	3.5-5.0	
Lubricity (um) *		140 [a]		405 [a]			*High Frequency Reciprocating Rig Test wear scar < 380 um indicates good lubricity*
							RME better lubricity than No. 2 Diesel
Toxicity							
Acute: Rodent Inhalation LC50 (g/m3)							
Acute: Rat oral LD50 (mg/kg)		> 5000 [b]		12000-17500 [c]			
Acute:Fish LC50 and bacteria EC50 (mg/L)		> 100 [b]					
Subchronic: Rabbit dermal 8 ml/kg applied for 14 days				67% mortality [c]			
Chronic: Mouse dermal 0.05 ml/kg applied 3 X per week for 62 wks				extreme irritation [c]			
Mutagenicity: Salmonella typhimurium Modified Ames Asssay				Negative [c]			
Partition coefficient (Kow)							
Log Kow at 25 degC							
Bioconcentration factor (L/kg) [j]		No bioconcentration expected [b]					
Soil adsorption				Strongly adsorb [c]			
Half-life in water at typical env. conditions							
Half-life in atmosphere							
Biodegradation		Readily biodegradable [b]					
Appearance		Yellowish liquid [b]		clear to yellow [c]			
Odor		Mild [b]		Mild [b]			
Odor threshold (mg/m3)							
CAS Number				68334-30-5			

references (FAME and No. 2):
Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997
a) Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996
b) Lantmänen Ecobränsle AB, Sweden, MSDS, www.ecobransle.se
c) CITIGO No. 2 Diesel, MSDS, May 2006, http://www.martineagle.com/MSDS/CitgoLowSulfurDiesel.pdf
d) Sunsoil Inc., Poultry Fat, B100, Midwest Laboratories Report Number 09-334-2203, 11/30/09

references (FAME specification):
Hannu Jaaskelainen, Biodiesel Fuel Standards, http://www.dieselnet.com/tech/fuel_biodiesel_std.html

Diesel Fuels
E.10. FAME--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
nitrile	lead
natural rubbers	tin
polyurethane	brass
	bronze
	zinc
	galvanized metals

Compatible Materials

elastomers	metals
Teflon	aluminum
Viton	stainless steel
fluorinated plastics	carbon steel
nylon	
most fiberglass	

Vehicle Compatibility

Not compatible with terne-coated steel, commonly used for fuel tanks
Nitrile and natural rubber hoses must be replaced with Viton
Compatible with Viton, typically used for most seals and gaskets
Rapeseed Methyl Ester cloud point higher than No. 2 diesel (-6 degC vs. -12 degC), leading to potential issues in cold climates

Advantages

Can be blended with diesel in any combination
Biodiesel does not separate from blends if kept above cloud point
Non-toxic
Biodegrades quicker than diesel
Requires little or no modification for use in existing engines

Disadvantages

Cleaning Effect, whereby accumulated sediments in storage tanks dissolve in FAME fuels, potentially plugging filters and causing injector deposits
Stability can be an issue with certain feedstocks

Diesel Fuels
E.10. FAME--Compatibility and Environmental Issues

Transporting precautions
Trucks/railcars must be constructed of aluminum, carbon steel, or stainless steel
Proper inspection or washout before loading
Generally only diesel or biodiesel are acceptable residuals
No residual water allowed
Hoses and seals must be made from compatible materials
Heating/insulation may be needed to keep above cloud point

Environmental/Health concerns
Non-toxic
Biodegrades quicker than diesel

Compatibility/Fungibility issues
Expressly prohibited in many oil pipelines
Freeze/cloud point restrictions on diesel/blends serve as a defacto biodiesel ban in many oil pipelines
Cleaning effect leads to deposits and plugged filters both in transport and in engines
Ability to biodegrade quicker than diesel means biodiesel cannot be stored as long as diesel
Relatively high freeze and cloud points mean potential biodiesel transport may require insulation/heating
Transport by rail: requires additional private track or existing diesel transport tracks

Current production
2008 US biodiesel production: 700 million gallons
2008 US biodiesel production capacity: 2.69 billion gallons

references:
Lindhjem and Pollack, National Renewable Energy Laboratory, "Impact of Biodiesel Fuels on Air Quality and Human Health: Task 1 Report", www.nrel.gov, 5/2003
National Biodiesel Board, "US Biodiesel Production Capacity", www.biodiesel.org, 6/22/2009
National Renewable Energy Laboratory, "Biodiesel Handling and Use Guide: 4th Edition", Revised 1/2009
National Biodiesel Board, "Materials Compatibility", www.biodiesel.org, 2004
Columbia Engineered Rubber, Inc., www.columbiaerd.com, 2010
Alvarado, Peter J., "Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks", JOM 48 (7) pp. 22-25, 1996

Diesel Fuels

E.11. Green Diesel--Properties

"The advantages of hydrotreating [green diesel] over transesterification [biodiesel] are that the former is compatible with the current infrastructure, the process leads to a deoxygenated and thus stable product that is fully compatible with petroleum-derived diesel fuels, the product exhibits high cetane number and low sulfur content."
Reference:
Helwani, Othman, Aziz, Fernando, Kim (2009) Technologies for Production of Biodiesel Focusing on Green Catalytic Techniques: A Review, Fuel Processing Technology, Vol. 90, 1502 - 1514.

UOP green diesel and Neste Oil NExBTL diesel are produced by hydrogen saturation and deoxygenation of vegetable oils through catalytic refining.
References:
Snare, Maki-Arvela, Simakova, Myllyoja, Murzin (2009) Overview of Catalytic Methods for Production of Next Generation Biodiesel from Natural Oils and Fats, Russian Journal of Physical Chemistry B, Vol. 3, pp. 3-17.
Kalnes, Marker, Shonnard, Koers, *Green Diesel and Biodiesel a Technoeconomic and Life Cycle Comparison* , 1st Alternative Fuels Technology Conference, February 2008, Prague, Czechoslovakia

Properties

	UOP* Green Diesel	Neste Oil** NExBTL Diesel	No. 2 Diesel	
Molecular Formula			C8 to C25	
Molecular Weight (g/mol)			200 (approx)	
Elemental Composition (mass%)				
Carbon			84-87	
Hydrogen			13-16	
Oxygen	0	0	0	*No oxygen*
Density (g/cm3) at 15deg C	0.78	0.775 - 0.785	0.81-0.89	
Vapor Pressure kPa at 38 degC			<1	
Boiling Point			188-343	
Flash Point (degC)			74	
Pour Point (degC)			-23	
Cloud Point (degC)	-10 to +5	-5 to -30	-15 [a]	
High Heating Value (MJ/L)				
Low Heating Value (MJ/L)	34	~ 34	35-37	*Similar energy content*
Water Solubility at 21 degC				
Water in fuel (ppm)			<50	
Water content in fuel (mg/kg)				
Fuel Miscibility				
Solvation Potential			Low	
Flammability Limits (Vol%)				
Lower			1	
Higher			6	
Acid Number				
Cetane Number	70 to 90	84 - 99	40-55	*Higher cetane*
Viscosity (mPa-s)			2.6-4.1	
Kinematic viscosity (mm^2/s)		2.9 - 3.5		
Lubricity (um)			405 [a]	

Diesel Fuels
E.11. Green Diesel--Properties

Toxicity	
Acute: Rat oral LD50 (ml/kg)	9 [c]
Acute: Rabbit dermal LD50 (ml/kg)	> 5 [c]
Acute:LC50 for freshwater fish (Juven. Am. Shad) (ppm)	2400 [c]
Acute:LC50 for saltwater fish (Menhaden) (ppm)	10 [c]
Acute:LC50 for aquatic invertebrate (shrimp) (ppm)	10 [c]
Acute:Aquatic plants - No observable effect concentration (mg/L)	
Subchronic: Rabbit dermal 8 ml/kg applied for 14 days	67% mortality [c]
Chronic: Mouse dermal 0.05 ml/kg applied 3 X per week for 62 wks	extreme irritation [c]
Mutagenicity: Salmonella typhimurium Modified Ames Asssay	Negative [c]
Teratogenicity: Mouse oral Lowest observable effect conc. (% calories)	
Partition coefficient (Kow)	
Log Kow at 25 degC	
Bioconcentration factor (L/kg)	
Transport between Environmental Compartments	
Air, water, soil, sediment (% mass distribution)	
Half-life in water at typical env. conditions	
Half-life in atmosphere	
Photodegradation half-life in air	
Biodegradation in water/sediment for 30 days	
Appearance	clear to yellow [c]
Odor	Mild [b]
Odor Threshold (mg/L)	
CAS number	68334-30-5

* UOP LLC, a Honeywell Company
** Neste Oil Oyj, Espoo, Finland

references (UOP Green Diesel):	Kalnes, Marker, Shonnard, Koers, *Green Diesel and Biodiesel a Technoeconomic and Life Cycle Comparison* , 1st Alternative Fuels Technology Conference, February 2008, Prague, Czechoslovakia
references (Neste NExBTL Diesel):	Rantanen, Linnaila (2005) NExBTL - Biodiesel Fuel of the Second Generation, SAE Technical Paper 2005-01-3771
references (No. 2):	Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997 a) Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996 b) Hess Material Data Safety Sheet No. 9909, Diesel Fuel, 10/18/2006, http://www.hess.com/ehs/msds/9909DieselFuelAllTypes.pdf c) CITIGO No. 2 Diesel, MSDS, May 2006, http://www.martineagle.com/MSDS/CitgoLowSulfurDiesel.pdf

Diesel Fuels

E.12. Green Diesel--Compatibility and Environmental Issues

Advantages

Higher cetane number than both petroleum diesel and FAME
Higher energy content than biodiesel
Similar properties to petroleum diesel due to lack of oxygen
Requires little or no modification to run in existing diesel engines
Low cloud point - suitable for use in cold weather
Can be blended with petroleum diesel

references:

UOP, UOP/Eni Ecofining Process for Green Diesel Fuel, www.uop.com, 2007
Netse Oil, Press Release 6/18/08, www.nesteoil.com, 2008
Rantanen, Linnaila (2005) NExBTL - Biodiesel Fuel of the Second Generation, SAE Technical Paper 2005-01-3771

Diesel Fuels

E.13. F-T (Fischer-Tropsch Fuel)--Properties

Properties	SunDiesel*	ExxonMobil F-T Diesel from Natural Gas Feedstock	No. 2	
Molecular Formula			C8 to C25	
Molecular Weight (g/mol)			200 (approx)	
Elemental Composition (mass%)				
Carbon	85.79		84-87	
Hydrogen	15.54		13-16	
Oxygen			0	
Sulfur (ppm)	0.3	0	311 [c]	*Lower sulfur content*
Density (g/cm3)	0.7612	0.774	0.81-0.89 at 15 deg C	
Vapor Pressure kPa			<1 at 38 degC	
Boiling Point (degC)			188-343	
Flash Point (degC)		60	74	
Pour Point (degC)	-20.5		-23	
Cloud Point (degC)	-15.5		-15 [a]	
High Heating Value (MJ/kg)	47.2		54 [b]	
Low Heating Value (MJ/kg)	44.6		41-44	*Similar energy content for LHV*
Water Content (mass%)			negligible	
Water Solubility at 21 degC				
Water in fuel (ppm)			<50	
Fuel Miscibility				
Solvation Potential			Low	
Flammability Limits (Vol%)				
Lower			1	
Higher			6	
pH			8 - 9	
Cetane Number	80	74	40-55	*Higher cetane number*
Viscosity (mPa-s)	1.180	2.059	2.6-4.1	*Lower viscosity*
Lubricity (um)			405 [d]	

Diesel Fuels

E.13. F-T (Fischer-Tropsch Fuel)--Properties

Toxicity	
Acute: Rat oral LD50 (ml/kg)	9 [e]
Acute: Rabbit dermal LD50 (ml/kg)	> 5 [e]
Acute:LC50 for freshwater fish (Juven. Am. Shad) (ppm)	2400 [e]
Acute:LC50 for saltwater fish (Menhaden) (ppm)	10 [e]
Acute:LC50 for aquatic invertebrate (shrimp) (ppm)	10 [e]
Acute:Aquatic plants - No observable effect concentration (mg/L)	
Subchronic: Rabbit dermal 8 ml/kg applied for 14 days	67% mortality [e]
Chronic: Mouse dermal 0.05 ml/kg applied 3 X per week for 62 wks	extreme irritation [e]
Mutagenicity: Salmonella typhimurium Modified Ames Asssay	Negative [e]
Teratogenicity: Mouse oral Lowest observable effect conc.	
Partition coefficient (Kow)	
Log Kow at 25 degC	
Bioconcentration factor (L/kg)	
Transport between Environmental Compartments	
Air, water, soil, sediment (% mass distribution)	
Half-life in water at typical env. conditions	
Half-life in atmosphere	
Photodegradation half-life in air	
Biodegradation in water/sediment for 30 days	
Appearance	clear to yellow [e]
Odor	Mild [f]
Odor Threshold (mg/L)	
CAS number	68334-30-5

* SunDiesel is a biomass to liquid fuel, which is manufactured using a Fischer-Tropsch process and produced by CHOREN Industries GmbH of Germany

references (SunDiesel): Ng, Biruduganti, Stork, *Comparing the Performance of SunDiesel and Conventional Diesel in a Light-Duty Vehicle and Heavy-Duty Engine* , SAE Technical Paper 2005-01-3776

references (ExxonMobil F-T Diesel): Alleman, McCormick, Fischer-Tropsch Diesel Fuels - Properties and Exhaust Emissions: A Literature Review, SAE Technical Paper 2003-01-0763

references (No. 2): Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997
a) Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996
b) Hess, Boehman, Tijm, Waller, *Experimental Studies of the Impact of CETANER on Diesel Combustion and Emissions*, SAE Technical Paper 2000-01-2886
c) Bertola, Boulouchos, *Oxygenated Fuels for Particulate Emissions Reduction in Heavy-Duty Di-Diesel Engines with Common-Rail Fuel Injection*, SAE Technical Paper 2000-01-2885
d) Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996
e) CITIGO No. 2 Diesel, MSDS, May 2006, http://www.martineagle.com/MSDS/CitgoLowSulfurDiesel.pdf
f) Hess Material Data Safety Sheet No. 9909, Diesel Fuel, 10/18/2006, http://www.hess.com/ehs/msds/9909DieselFuelAllTypes.pdf

Diesel Fuels

E.14. F-T--Compatibility and Environmental Issues

Vehicle Compatibility
Cloud point comparable to No. 2 diesel, suitable for use in cold climates
"Requires little or no modification for use in current diesel engines" according to the CHOREN group

Advantages
"Requires little or no modification for use in current diesel engines" according to the CHOREN group
produces lower NOx and PM emissions than diesel in engines due to low aromatic content
"can be directly fed into the infrastructure of existing distribution channels" according to the CHOREN group
high energy content
Higher cetane number than diesel

references:

CHOREN Industries, "Biomass-to-Liquid Fuels (BtL) - Made by CHOREN process, Environmental Impact, and Latest Developments", Automobile and Environment at Belgrade EAEC Congress, May 2005
Intelligent Energy Europe, Fischer-Tropsch Diesel, www.refuel.eu, 2010
Kamara, Coetzee, Overview of High-Temperature Fischer-Tropsch Gasline and Diesel Quality, Energy & Fuels, 2009, 23, 2242-2247.

Diesel Fuels

E.15. Algae Biodiesel--Properties

Properties

	Microalgal Biodiesel	No. 2	US FAME Specifications ASTM D6751-06a	EU FAME Specifications EN 14214: 2003	
Molecular Formula		C8 to C25			
Molecular Weight (g/mol)		200 (approx)			
Elemental Composition (mass%)					
Carbon		84-87			
Hydrogen		13-16			
Oxygen		0			
Density (g/cm3) at 15deg C	0.864	0.81-0.89		0.86-0.9	
Vapor Pressure kPa at 38 degC		<1			
Boiling Point		188-343			
Flash Point (degC)	115	74	min 120	min 130	*Higher flash point*
Pour Point (degC)		-23			
Cloud Point (degC)		-15 [a]	Report		
High Heating Value (MJ/L)	35 [a]	36-40 [b]			*Similar energy content*
Low Heating Value (MJ/L)		35-37			
Water Solubility at 21 degC					
Water in fuel (ppm)		<50			
Water content in fuel (mg/kg)				500 max	
Fuel Miscibility					
Solvation Potential		Low			
Flammability Limits (Vol%)					
Lower		1			
Higher		6			
Acid Value (mg KOH /g)	0.374 [a]	Max 0.5 [b]	Max 0.5 [a]		
Cetane Number		40 - 55	47 min	51 min	
Viscosity (mPa-s)		2.6 - 4.1			
Kinematic viscosity (mm^2/s)	5.2	3.2 - 4.6	1.9-6.0	3.5-5.0	*Higher kinematic viscosity*
Lubricity (um)		405 [a]			

Diesel Fuels

E.15. Algae Biodiesel--Properties

Toxicity	
Acute: Rat oral LD50 (ml/kg)	9 [c]
Acute: Rabbit dermal LD50 (ml/kg)	> 5 [c]
Acute:LC50 for freshwater fish (Juven. Am. Shad) (ppm)	2400 [c]
Acute:LC50 for saltwater fish (Menhaden) (ppm)	10 [c]
Acute:LC50 for aquatic invertebrate (shrimp) (ppm)	10 [c]
Acute:Aquatic plants - No observable effect concentration (mg/L)	
Subchronic: Rabbit dermal 8 ml/kg applied for 14 days	67% mortality [c]
Chronic: Mouse dermal 0.05 ml/kg applied 3 X per week for 62 wks	extreme irritation [c]
Mutagenicity: Salmonella typhimurium Modified Ames Asssay	Negative [c]
Teratogenicity: Mouse oral Lowest observable effect conc. (% calories)	
Partition coefficient (Kow)	
Log Kow at 25 degC	
Bioconcentration factor (L/kg)	
Transport between Environmental Compartments	
Air, water, soil, sediment (% mass distribution)	
Half-life in water at typical env. conditions	
Half-life in atmosphere	
Photodegradation half-life in air	
Biodegradation in water/sediment for 30 days	
Appearance	clear to yellow [c]
Odor	Mild [d]
Odor Threshold (mg/L)	
CAS number	68334-30-5

references (FAME specification):

Hannu Jaaskelainen, Biodiesel Fuel Standards, http://www.dieselnet.com/tech/fuel_biodiesel_std.html
a) Xu, Miao, Wu, High Quality Biodiesel Production from a Microalga Chlorella Protothecides by Heterotrophic Growth Fermenters, 2006, 126, 499-507.

references (No. 2):

Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997
a) Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996
b) Xu, Miao, Wu, High Quality Biodiesel Production from a Microalga Chlorella Protothecides by Heterotrophic Growth Fermenters, 2006, 126, 499-507.
c) CITIGO No. 2 Diesel, MSDS, May 2006, http://www.martineagle.com/MSDS/CitgoLowSulfurDiesel.pdf
d) Hess Material Data Safety Sheet No. 9909, Diesel Fuel, 10/18/2006, http://www.hess.com/ehs/msds/9909DieselFuelAllTypes.pdf

Diesel Fuels

E.16. Algae Biodiesel--Compatibility and Environmental Issues

Advantages

Comparable heating value to diesel, higher than FAME
Low cold filter plugging point indicates good cold weather performance

Disadvantages

High viscosity means increased pumping work required for transport
Rich in unsaturated fats, leading to oxidation susceptibility, will not comply with Euro biodiesel regulations unless further processed

references: Miao, Wu, *Biodiesel Production from Heterotrophic Microalgal Oil, Bioresource Technology* , 2006, 97, 841-846
Chisti, Yusuf, *Biodiesel from Microalgae* , *Biotechnology Advances* , 2007, 25, 294-306

Diesel Fuels

E.17. DME (Dimethyl Ether)--Properties

Properties

	Dimethyl ether	No. 2	*Comments*
Molecular Formula	CH3-O-CH3	C8 to C25	
Molecular Weight (g/mol)	46.1	200 (approx)	
Elemental Composition (mass%)			
Carbon	52	84-87	
Hydrogen	13	13-16	
Oxygen	35	0	
Density (g/cm3) at 20deg C	1.91E-03	0.81-0.89	
Vapor Pressure kPa at 25 degC	593	<1	*DME gaseous*
Boiling Point (degC)	-24.8	188-343	
Flash Point (degC)	-5.5	74	
Pour Point (degC)		-23	
Cloud Point*		-15	
High Heating Value (MJ/L)			
Low Heating Value (MJ/L)		35-37	
Water Solubility at 25 degC (g/L)	35.3		
Fuel Miscibility			
Solvation Potential		Low	
Flammability Limits (Vol%)			
Lower	3.4	1	
Higher	18	6	*DME highly flammable*
Acid Number			
Cetane Number		40-55	
Viscosity (mPa-s)		2.6-4.1	
Lubricity (um) *		405	
Toxicity			
Acute: Rat inhalation (ppm)	164000		
Acute:Freshwater Fish - No observable effect concentration (mg/L)	> 4000		
Acute:Daphnia - No observable effect concentration (mg/L)	> 4000		
Acute: Algae	Predicted to be nontoxic		
Chronic: Rat - No observable effect concentration (ppm)	2000 ppm		
Genotoxicity - Bacteria, DME 0-75%	None		
Teratogenicity - Rat, DME 0-20,000 ppm	None		
Partition coefficient (Kow)	octanol-water		
Log Kow at 25 degC	0.1		
Bioconcentration factor (L/kg) [j]	0.7		*Low potential for bioconcentration in aquatic organisms*
Photodegradation half-life in water	2.2 years		
Photodegradation half-life in air	5.4 days		
Biodegradation - 2 mg/L in activated sludge for 28 days	5% degredation		
Appearance	Colorless gas [a]		
Odor	Slightly ethereal [a]		

DME references:	US EPA High Production Volume Information System, DME Detailed Chemical Results, http://iaspub.epa.gov/oppthpv/quicksearch.display?pChem=100157 a) Praxair Material Safety Data Sheet, Dimethyl Ether, P-4589-D, May 2009
No. 2 Diesel references:	*Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels SwRI 7507, November 1996 Christopher A. Sharp

E.18. DME--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
Viton	lithium aluminum hydride
silicon rubber	aluminum hyrdide
natural rubber	
butyl rubber	
neoprene	

Compatible Materials

elastomers	metals
Teflon	Carbon Steel
Buna N	Stainless Steel
	Aluminum
	Brass
	Copper

Vehicle Compatibility

Not compatible with Viton and natural rubber, commonly used materials for gaskets, seals, and hoses
Exists as a gas at STP, must be compressed for use as engine fuel

Advantages

Only minor modification needed to run in existing engines
Short carbon chain compound leads to low PM, NOx, and CO emissions

Disadvantages

Exists as gas under normal operating conditions
Highly flammable
Soluble in water

Transporting Precautions

Must be compressed to a liquid for ease of transport

Environmental/Health concerns

No known adverse ecological effects
Highly flammable

Compatibility/Fungibility issues

Only minor modification needed to run in existing engines
Must be compressed to a liquid for ease of transport

references:
Air Liquide, www.airliquide.com, 12/2009
Avantec Performance Chemicals, www.inventec.dehon.com, 12/2009
Praxair, "Dimethyl Ether MSDS", www.praxair.com, 10/15/2007
Problem Solving Products Inc., www.pspglobal.com, 12/2009
Columbia Engineered Rubber, Inc., www.columbiaerd.com, 2010
Alvarado, Peter J., "Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks", JOM 48 (7) pp. 22-25, 1996

Diesel Fuels

E.19. Glyme--Properties

Air Products and Chemicals, Inc. developed a process for the production of diglyme and triglyme from coal-derived synthesis gas. This could be adapted for biomass derived synthesis gas. However issues related to the toxicity of glymes may have prevented further development.
"A series of literature searches was conducted regarding the health hazards associated with 1,2-dimethoxyethane (monoglyme), diglyme, and triglyme. The literature implies that glymes are teratogens and reproductive toxins."
Reference:
Air Products and Chemicals, Inc. (1998) Alternative Fuels and Chemicals from Synthesis Gas, Quarterly Report, DOE contract number DE-FC22-95PC93052.

Properties

	Diglyme	No. 2	*Comments*
Molecular Formula	C6H14O3	C8 to C25	
Molecular Weight (g/mol)	134.2	200 (approx)	
Elemental Composition (mass%)			
Carbon	53.7%	84-87	
Hydrogen	10.4%	13-16	
Oxygen	35.8%	0	
Density (g/cm3)	0.938 at 25 degC	0.81-0.89 at 15 deg C	
Vapor Pressure kPa	0.395 at 25 degC [i]	<1 at 38 degC	*Low vapor pressure for an organic solvent*
Boiling Point (degC)	161.85	188-343	
Flash Point (degC)	57 [b]	74	
Pour Point (degC)		-23	
Cloud Point (degC)	< -17 [f]	-15 [a]	
High Heating Value (MJ/L)	26 [d]	46 [b]	*Lower energy content*
Low Heating Value (MJ/L)	23 [c]	35-37	
Water Solubility in fuel at 21degC (ppm)	Complete	<50	*Water is soluble in diglyme*
Fuel Miscibility	at least 45 vol% completely miscable in diesel fuel [e]		
Solvation Potential	High for organics [h]	Low	*Excellent organic solvent*
Flammability Limits (Vol%)			
Lower	1.5	1	
Higher	17.4	6	*Wider flammability range*
Acid Number			
Cetane Number	126 [c]	40-55	
Viscosity (mPa-s)	0.989	2.6-4.1	
Lubricity (um)	783 [g]	265 [c]	*High Frequency Reciprocating Rig Test wear scar < 380 um indicates good lubricity*
			No. 2 Diesel better lubricity than diglyme

Diesel Fuels

E.19. Glyme--Properties

Toxicity			
Acute: Rat inhalation (ppm)	1000 [b]		
Acute:LC50 for fish, daphnia and algae	> 1000 mg/L [k]		*Relativlely non-toxic for studied aquatic species*
Chronic: Mouse oral (mg/Kg)	1250 - Teratogenic; 5 - Reproductive [b]	367- Lowest reported [d]	
Partition coefficient (Kow)	octanol-water		
Log Kow at 25 degC	-0.36 [k]		
Bioconcentration factor (L/kg) [j]	< 100 [i]		*Not expected to significantly bioaccumulate*
Soil adsorption	When released into soil, largely evaporates, moderately biodegrades, and can leach into groundwater [i]		*Distributes primarily to water and secondarily to soil [k]*
Half-life in water at typical env. conditions	> 1 year [k]		
Half-life in atmosphere	< 1 day [i]		
Photodegradation half-life in air	7.33 hours [k]		
Biodegradation	Not readily biodegradable [k]		
Appearance	Clear, colorless liquid [i]		
Odor	Slight aromatic odor [i]		

references (diglyme):

Wallace, W.J.; Mathews, A.L., *Density, Refractive Indices, Molar Refractions, and Viscosities of Diethylene Glycol Dimethyl Ether-Water Solutions at 25 C* , **J. Chem. Eng. Data**, 1964, 9, 267-268.
a) Stull, D.R., Vapor Pressure of Pure Substances Organic Compounds, Ind. Eng. Chem., 1947, 39, 517-540
b) Honeywell, Burdick and Jackson Material Safety Data Sheet, http://www51.honeywell.com/sm/rlss/bandj/common/documents/2.4.67_msds.pdf
c) Ren, Huang, Miao, Jiang, Liu, Wang, *Effect of the Addition of Diglyme in Diesel Fuel on Combustion and Emissions in a Compression-Ignition Engine* , **Energy and Fuels**, 2007, 21, 2573-2583.
d) Ferro Fine Chemicals, Product Data Sheet, diglyme, http://www.d-orland.com/pdf/Diglyme.pdf
e) Air Products and Chemicals for DOE, *Alternative Fuels and Chemicals From Synthesis Gas* , Quarterly Report Jan1-March 31, 1998.
http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=98C35367D8BB64EC81F1D3F36F8998A0?purl=/2008-izPpak/webviewable/
f) Howard Hess, *Effect of Oxygenated Cetane Improver on Diesel Engine Combusiton and Emissions*
http://www.ems.psu.edu/~boehman/altfuels.html
g) Bertola, Boulouchos, *Oxygenated Fuels for Particulate Emissions Reduction in Heavy-Duty Di-Diesel Engines with Common-Rail Fuel Injection* , SAE Technical Paper 2000-01-2885
h) Merck Index, 11th Edition, 3148
i) J.T. Baker MSDS, http://www.jtbaker.com/msds/englishhtml/b3312.htm
j) EPA Methodology for Deriving Ambient Water Quality Criteria for the Protection of Human Health (2000), http://www.epa.gov/waterscience/criteria/humanhealth/method/tsdvol2.pdf
k) EPA 201-15023, Diglyme robust summary, http://www.epa.gov/hpv/pubs/summaries/diglyme/c15023rs.pdf

references (No. 2 diesel):

Bechtold, Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997
a) Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996
b) Hess, Boehman, Tijm, Waller, *Experimental Studies of the Impact of CETANER on Diesel Combustion and Emissions* , SAE Technical Paper 2000-01-2886
c) Bertola, Boulouchos, *Oxygenated Fuels for Particulate Emissions Reduction in Heavy-Duty Di-Diesel Engines with Common-Rail Fuel Injection* , SAE Technical Paper 2000-01-2885
d) ChemCas, http://www.chemcas.com/msds/cas/msds57/68476-34-6.asp

Diesel Fuels

E.20. Glyme--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
PVC	
nitrile	
Viton	

Compatible Materials

elastomers	metals
polyethylene	all metals

Vehicle Compatibility

Compatible with fuel tank materials (polyethylene or metals)
Not compatible with typical gasket, seal, and hose materials (nitrile and Viton)
Low cloud point - suitable for use in cold climates

Environmental/Health concerns

Highly toxic

Compatibility/Fungibility issues

Necessitates o-ring and hose replacement for material compatibility

references:
Bertola, Boulouchos, *Oxygenated Fuels for Particulate Emissions Reduction in Heavy-Duty Di-Diesel Engines with Common-Rail Fuel Injection*, SAE Technical Paper 2000-01-2885
Columbia Engineered Rubber, Inc., www.columbiaerd.com, 2010
Alvarado, Peter J., "Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks", JOM 48 (7) pp. 22-25, 1996

E.21. Ethanol--Properties

Properties

	Ethanol	E5	E10	E15	No. 2	*Comments*
Molecular Formula	C2H5OH				C8 to C25	
Molecular Weight (g/mol)	46.07				200 (approx)	
Elemental Composition (mass%)						
Carbon	52.2				84-87	
Hydrogen	13.1				13-16	
Oxygen	34.7				0	
Density (g/cm3) at 15deg C	0.79	0.835 [b]	0.833 [b]	0.8315 [b]	0.8362 [b]	
Vapor Pressure kPa at 38 degC	15.9				<1	
Boiling Point	78				188-343	
Flash Point (degC)	13	< 40 [b]	< 40 [b]	< 40 [b]	63 [b]	
Pour Point (degC)					-23	
Cloud Point (degC)		-1.2 [b]	-1.2 [b]	-0.1 [b]	-3.1 [b]	
Freezing Point (degC)	-114				-40 to -1	
High Heating Value (MJ/L)	23				37-40	
Low Heating Value (MJ/L)	21	35 [b]	34 [b]	33.5 [b]	36 [b]	*Lower energy content*
Water Solubility at 21 degC						
Water in fuel (Vol%)	100				Negligible	
Fuel Miscibility						
Solvation Potential					Low	
Flammability Limits (Vol%)						
Lower	4.3				1	
Higher	19				6	
Acid Number						
Cetane Number		51.8 [b]	50 [b]	48.3 [b]	52.2 [b]	
Viscosity (mPa-s)	1.19				2.6-4.1	
Kinematic viscosity at 40 degC mm^2/s		2.88 [b]	2.45 [b]	2.47 [b]	2.88 [b]	*Lower viscosity*
Lubricity (um)					405 [c]	
Toxicity						
Acute: Mouse oral LD50 (mg/kg)	8300 [e]					
Acute:LC50 for freshwater fish (trout) (mg/L)	11200 [e]					
Acute:LC50 for aquatic invertebrate (daphnia) (vol%)	1.5[e]					
Acute:Aquatic plants - No observable effect concentration (mg/L)	< 500 [e]					
Chronic: Rat oral No observable effect conc. (mass% in food)	< 5 [e]					
Teratogenicity: Mouse oral Lowest observable effect conc. (% calories)	25% [e]					
Partition coefficient (Kow)	octanol-water					
Log Kow at 25 degC	-0.31 [e]					
Bioconcentration factor (L/kg)	Low based on Kow					
Transport between Environmental Compartments						
Air, water, soil, sediment (% mass distribution)	13, 44.8, 42.1,0.039 [e]					
Half-life in water at typical env. conditions						
Half-life in atmosphere	6 days [d]					
Photodegradation half-life in air	15.4 hrs [e]					
Biodegradation in water/sediment for 30 days	91% [e]					
Appearance	clear, water-like liquid					
Odor Threshold (mg/L)	0.1 air, 100 water [d]					
CAS number	64-17-5					

references:

Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997
NIST Chemistry WebBook
b) Dominguez, Miguel, Arjona, Millan, The Effects of Ethanol-Diesel Blended Fuels on the Performance and Emissions of Unmodified Diesel Engines, 14th European Biomass Conference and Exhibition: Biomass for Energy, Industry and Climate Protection, Paris, Oct.
c) Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996
d) Spectrum Chemical Fact Sheet, http://www.speclab.com/compound/c64175.htm
e) US EPA High Production Volume Information System, Ethanol Detailed Chemical Results, http://iaspub.epa.gov/oppthpv/quicksearch.display?pChem=100220

Diesel Fuels

E.22. Ethanol--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
cork gasket material	lead
natural rubbers	aluminum
polyurethane	brass
PVC	terne
	zinc
	lead-based solder

Compatible Materials

elastomers	metals
thermoset-reinforced fiberglass	carbon steel
thermoplastic	stainless steel
Buna N	bronze
neoprene	
Viton	
Teflon	
nitrile	
polypropylene	

Vehicle Compatibility
Incompatible with terne-coated steel, commonly used for fuel tanks
Hoses constructed from natural rubbers must be replaced with Viton, nitrile, etc.

Advantages
Requires little or no modification for use in exisitng engines
Reduces PM, CO, NOx emissions

Disadvantages
Cleaning Effect
Miscible with water
Requires co-solvent

Diesel Fuels

E.22. Ethanol--Compatibility and Environmental Issues

Trasnporting Precautions
Vessels must be cleaned out to prevent contamination due to water and cleaning effect

Environmental/Health concerns
Toxic
Flammable

Compatibility/Fungibility issues
Miscible with water
Cleaning effect leads to deposits and plugged filters both in transport and in engines
Transport by rail: requires additional private track or existing gasoline transport tracks
Stress corrosion cracking observed in pipelines due to ethanol

Current production
2007 US ethanol production: 6.48 billion gallons
2007 US ethanol production capacity: 7.5 billion gallons
2008 projected US ethanol production capacity: 13.3 billion gallons

references:
Biofuels Digest, "US Ethanol Production Capacity to Increase to 13.3 Billion Gallons in 2008", www.biofuelsdigest.com, 1/9/2008
Biofuels Journal, "Annual and Monthly US Ethanol Production", www.biofuelsjournal.com, 12/5/2006
Department of Energy, "Handbook for Handling, Storing, and Dispensing E85", 7/2006
Fanick, National Renewable Energy Laboratory, "Fuel and Fuel Additive Registration Testing of Ethanol-Diesel Blend for O2Diesel, Inc.", www.nrel.gov, 2/2004
Pipeline Research Council International, "Stress Corrosion Cracking", 7/2006
Columbia Engineered Rubber, Inc., www.columbiaerd.com, 2010
Alvarado, Peter J., "Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks", JOM 48 (7) pp. 22-25, 1996

Diesel Fuels

E.23. Sesquiterpene (Farnesene)--Properties

"Sesquiterpenes and most fatty-acid-derived hydrocarbons are suitable for the production of diesel fuel and include **farnesene**, ethyl hexadecanoate, and pentadecane One advantage these molecules have over shortchain alcohols is their very low solubility in water."

Reference:

Rude, Schirmer, New Microbial Fuels: A Biotech Perspective, Current Opinion in Microbiology, 2009, 12, 274-281

Properties

	Farnesene	No. 2	
Molecular Formula	C15H24	C8 to C25	
Molecular Weight (g/mol)	204.4	200 (approx)	
Elemental Composition (mass%)			
Carbon	88.24	84-87	
Hydrogen	11.76	13-16	
Oxygen		0	
Nitrogen		0	
Density (g/cm3)	0.844-0.8790 at 25 degC [a]	0.81-0.89 at 15 deg C	
Vapor Pressure kPa	0.001 at 20 degC [b]	<1 at 38 degC	
Boiling Point (degC)	260 [a]	188-343	
Flash Point (degC)	110 [a]	74	*Higher flash point*
Pour Point (degC)	***	-23	
Cloud Point (degC)		-15 [a]	
High Heating Value (MJ/kg)	47* [c]	54 [b]	
Low Heating Value (MJ/kg)		41-44	
Water Content (mass%)	negligible	negligible	
Water Solubility at 21 degC			
Water in fuel (ppm)	insoluble [a, c]	<50	*Water insoluble*
Fuel Miscibility			
Solvation Potential		Low	
Flammability Limits (Vol%)			
Lower		1	
Higher		6	
pH			
Cetane Number	Low** [c]	40-55	
Viscosity (mPa-s)		2.6-4.1	
Lubricity (um)		265 [c]	
Toxicity			
Acute: Mouse oral LD50 (mg/kg)			
Acute:LC50 for freshwater fish (trout) (mg/L)			
Acute:LC50 for aquatic invertebrate (daphnia) (vol%)			
Acute:Aquatic plants - No observable effect concentration (mg/L)			
Chronic: Rat oral No observable effect conc. (mass% in food)			
Teratogenicity: Mouse oral Lowest observable effect conc. (% calories)			
Partition coefficient (Kow)			
Log Kow at 25 degC			
Bioconcentration factor (L/kg) [j]			
Transport between Environmental Compartments			
Air, water, soil, sediment (% mass distribution)			
Half-life in water at typical env. conditions			
Lifetime in atmosphere in presence of ozone	1 hr [e]		
Photodegradation half-life in air			
Biodegradation in water/sediment for 30 days			
Appearance	Colorless to light yellow liquid [d]		
Odor	Citrus, herbaceous [d]		
Odor Threshold (mg/L)			
CAS number	502-61-4		
Natural sources	Emitted to atm by plants and trees		

** The cetane number for farnesene is low but it can be hyrogenated to farnesane such that the cetane number is 58 [c]

*** Cold flow properties improved by hydrogenation of farnesene to farnesane [c]

references (farnesene):

NIST Chemistry WebBook, http://webbook.nist.gov/cgi/cbook.cgi?Name=farnesene&Units=SI
a) Sigma-Aldrich, MSDS, Product Number W383902
b) The Good Scents Company, http://www.thegoodscentscompany.com/data/rw1044061.html
c) Rude, Schirmer, *New Microbial Fuels: A Biotech Perspective*, Current Opinion in Microbiology, 2009, 12, 274-281
d) Bedoukian Research Inc, MSDS P3500-90, (e)-beta-farnesene, http://www.bedoukian.com/products/displayGraphic.asp?type=m&product=P3500-90, Aug. 3, 2007.
e) Kourtchev et al., Atmospheric Environment, Vol. 43, pg 3182, 2009.

references (No. 2)

Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997
Sharp, Christopher A., Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels, SwRI 7507, November 1996
Hess, Boehman, Tijm, Waller, *Experimental Studies of the Impact of CETANER on Diesel Combustion and Emissions*, SAE Technical Paper 2000-01-2886
Bertola, Boulouchos, *Oxygenated Fuels for Particulate Emissions Reduction in Heavy-Duty Di-Diesel Engines with Common-Rail Fuel Injection*, SAE Technical Paper 2000-01-28

Diesel Fuels

E.24. Sesquiterpene (Farnesene)--Complementary Information

Advantages
Not soluble in water

Disadvantages
Low cetane number
Poor cold flow properties

references: Bedoukian Research Inc, MSDS P3500-90, (e)-beta-farnesene, http://www.bedoukian.com/products/displayGraphic.asp?type=m&product=P3500-90, Aug. 3, 2007.

E.25. Green Gasoline--Properties

NO PUBLISHED DATA WAS FOUND FOR GREEN GASOLINE, BUT PERFORMANCE AND PROPERTIES ARE EXPECTED TO BE SIMILAR TO PETROLEUM DERIVED GASOLINE

Green Gasoline manufactured by upgrading pyrolysis oil is expected to be in production in 2014 (properties currently not published)

An announcement on January 12, 2010 on the Green Car Congress website:

> "The US Department of Energy has selected UOP, a Honeywell company, for negotiation of a $25 million award to build a demonstration unit in Hawaii to convert cellulosic biomass into renewable hydrocarbon transportation fuels. The demonstration unit will employ the RTP rapid thermal processing technology developed by Ensyn Corp. RTP rapidly heats biomass at ambient pressure to generate high yields of pourable, liquid pyrolysis oil. The pyrolysis oil—essentially a bio crude oil—will then be upgraded to green transport fuels using technology developed by UOP working with DOE, the DOE's National Renewable Energy Lab and Pacific Northwest National Laboratory (PNNL). The demonstration plant, which will be built at the Tesoro Corp. refinery in Kapolei, Hawaii, is expected to start up in 2014. In 2009, UOP and Ensyn Corp. launched a joint venture, Envergent Technologies, LLC, to offer technology and equipment to convert second-generation biomass into pyrolysis oil for power generation, heating fuel and for conversion into transportation fuels."
> http://www.greencarcongress.com/2010/01/uop-rtp-20100112.html?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+greencarcongress%2FTrBK+%28Green+Car+Congress%29

From website of Envergent, which is a joint company by UOP and Ensyn (green diesel manufacturers) posted on January 25, 2010:

> "UOP has been selected for negotiation of a $25 million award from the U.S. Department of Energy (DOE) to build a demonstration-scale unit that will convert cellulosic biomass into green transportation fuels. It's a pilot test that will run as part of the DOE's effort to help reduce U.S. dependence on foreign oil, spur the creation of the domestic bio-industry and create new jobs.
> The unit will include the RTP® rapid thermal processing technology to convert biomass to pyrolysis oil as well as a hydroprocessing unit to upgrade the pyrolysis oil to green transportation fuels –**primarily green gasoline."**
> http://blog.envergenttech.com/

Gasoline Fuels

E.26. Green Gasoline--Compatibility and Environmental Issues

NO PUBLISHED DATA WAS FOUND FOR GREEN GASOLINE, BUT COMPATIBILITY AND ENVIRONMENTAL EFFECTS ARE EXPECTED TO BE SIMILAR TO PETROLEUM DERIVED GASOLINE

Gaslline Fuels

E.27. Fischer-Tropsch Fuel (FT)--Properties

From website of FT Diesel Manufacturer, CHOREN:

> "Synthetic biofuel from CHOREN can at present only be used in diesel engines.
> The light components generated in its production (naphtha) can be used in refineries as part of gasoline.
> It is technically possible to produce pure fuel for gasoline engines, but it requires additional process stages and is not currently planned."
> http://www.choren.com/en/faq/

Companies that produce FT gasoline from biomass were not found after an extensive literature search.
Information on companies which utilize the FT process in biomass to liquid production but do not produce gasoline can be found in the following references:

Hofer, R. Sustainable Solutions for Modern Economies, Royal Society of Chemistry, 2010.
See Chapter: Green Fuels - Sustainable Solutions for Transportation, pages 154-157.

Andrews, A. and Logan, J., "Fischer-Tropsch Fuels from Coal, Natural Gas, and Biomass: Background and Policy", CRS Report for Congress, 2008.
See Section: Synthetic Fuel Plants, pages 7-15.

FT Gasoline derived from coal or natural gas produced by the South African Company, Sasol

Sasol FT gasoline properties published recently in 2009 article in journal, Energy & Fuels

Properties

	Coal-derived FT Gasoline	Natural Gas-derived FT Gasoline	Conventional So. African Gasoline
density at 20 deg C (g/cm^3)	0.729	0.748	0.729
vapor pressure (kPa)	67	72	72
sulfur (ppm)	< 10	< 10	150
oxygen (mass %)	0.14		0.09
olefins (mass %)	30	8	~12
aromatics (total) (vol %)	29	37	27
octane	93	95	93

Reference: Kamara, Coetzee, Overview of High-Temperature Fischer-Tropsch Gasline and Diesel Quality, Energy & Fuels, 2009, 23, 2242-2247.

Gasoline Fuels

E.28. Fischer-Tropsch Fuel (FT)--Compatibility and Environmental Issues

Advantages
Negligible sulfur content
Some flexibility in adjusting certain fuel properties

Disadvantages
Low octane

references: Kamara, Coetzee, Overview of High-Temperature Fischer-Tropsch Gasline and Diesel Quality, Energy & Fuels, 2009, 23, 2242-2247.

Gasoline Fuels

E.29. Ethanol--Properties

Properties	Ethanol	E10	E20	E50	E85	Gasoline	MTBE	*Comments*
Molecular Formula	C2H5OH					C4 to C12	C5H12O	
Molecular Weight (g/mol)	46.07					100-105	88.15	
Elemental Composition (mass%)								
Carbon	52.2				56-58	85-88	68	
Hydrogen	13.1				13-14	12-15	14	
Oxygen	34.7				29-30	0-4	18	
Density (g/cm3) at 15deg C	0.794 [b]	0.737 [b]	0.744 [b]	0.763 [b]	0.786 [b]	0.733 [b]	0.7404	
Reid vapor pressure (psi)	2	10.5	10.3	9	5	11	33	
Boiling Point (degC)	78				49-80	27-225	55.2	
Flash Point (degC)	13				slightly higher than gasoline	-43	-25	*Higher flashpoint*
Pour Point (degC)								
Cloud Point								
Freezing Point (degC)	-114					-40		
High Heating Value (MJ/L)	24					35		
Low Heating Value (MJ/L)	20 [b]	32 [b]	30 [b]	27 [b]	23 [b]	33 [b]		*Lower energy content*
Water Solubility at 21 degC							51260	
Water in fuel (Vol%)	100				100	Negligible		
Fuel Miscibility								
Solvation Potential								
Flammability Limits (Vol%)								
Lower	4.3				Wider than	1.4	1.6	
Higher	19				gasoline	7.6	8.4	
Acid Number								
Research Octane Number	116 [b]	95 [b]	98 [b]	102 [b]	107 [b]	88 [b]		*Higher octane*
Viscosity (mPa-s) at 20 degC	1.19				1.07-1.08	0.37-0.44		
Lubricity (um)								
Toxicity								
Acute: Mouse oral LD50 (mg/kg)	8300 [e]						1600-3900	
Acute: Mouse Inhalation LD50 (ppm)						101200 [c]		
Acute:LC50 for freshwater fish (trout) (mg/L)	11200 [e]						> 100 mg/L	
Acute:LC50 for aquatic invertebrate (daphnia) (vol%)	1.5[e]							
Acute:Aquatic plants - No observable effect concentration (mg/L)	< 500 [e]							
Chronic: Rat oral No observable effect conc. (mass% in food)	< 5 [e]							
Teratogenicity: Rat inhalation No observable effect conc. (ppm)	25% [e]					9000 [c]		
Partition coefficient (Kow)	octanol-water					octanol-water	octanol-water	
Log Kow at 25 degC	-0.31 [e]					2.13 to 4.85 [c]	1.24	
Bioconcentration factor (L/kg)	Low based on Kow						< 2	
Transport between Environmental Compartments								
Air, water, soil, sediment (% mass distribution)	13, 44.8, 42.1,0.039 [e]							
Half-life in water at typical env. conditions							streams 2.5 hr, rivers 9.5 hr, lakes 137 days	
Half-life in atmosphere	6 days [d]						3-6 days	
Photodegradation half-life in air	15.4 hrs [e]					0.8 to 16 days [c]		
Biodegradation in water/sediment for 30 days	91% [e]					Readily in aerobic cond. [c]	Slower than aromatic hydrocarbons [b]	
Appearance	clear liquid [c]					clear to amber [c]	clear, water-like liquid [a]	
Odor Threshold (mg/L)	0.1 air, 100 water [d]						Detectable 0.05, Recognizable 0.13 [a]	
CAS number	64-17-5							

references:

Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications, SAE Order Number R-180, 1997

a) NIST Chemistry WebBook

b) Bailey, Russel SAE Technical Paper 81044

c) Fisher Scientific MSDS, http://fscimage.fishersci.com/msds/89308.htm, March 2003

d) Spectrum Chemical Fact Sheet, http://www.speclab.com/compound/c64175.htm

e) US EPA High Production Volume Information System, Ethanol Detailed Chemical Results, http://iaspub.epa.gov/oppthpv/quicksearch.display?pChem=100220

references (MTBE)

EPA Chemical Fact Sheet, http://www.epa.gov/opptintr/chemfact/s_mtbe.txt

a) Amerada Hess Corporation, Material Safety Data Sheet No. 9922, Methyl tert-Butyl Ether (MTBE), April 1998

b) EPA, Summary of Workshop on Biodegradation of MTBE, February 2001, http://www.epa.gov/nrmrl/pubs/625r01001/625r01001.pdf

c) JT Baker MSDS, Gasoline, 10/14/2008, http://www.docs.citgo.com/msds_pi/UNLEAD.pdf

Conversion Factors

Bailey and Russel LHV in BTU/lb

19000	33.0499641	MJ/L	E0
18300	31.83233384	MJ/L	E10
17500	30.44075641	MJ/L	E20
15500	26.96181282	MJ/L	E50
13000	22.61313333	MJ/L	E85
11700	20.35182	MJ/L	E100

Gasoline Fuels

E.30. Ethanol--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
cork gasket material	lead
natural rubbers	aluminum
polyurethane	brass
PVC	terne
	zinc
	lead-based solder

Compatible Materials

elastomers	metals
thermoset-reinforced fiberglass	carbon steel
thermoplastic	stainless steel
Buna N	bronze
neoprene	
Viton	
Teflon	
nitrile	
polypropylene	

Vehicle Compatibility
Incompatible with terne-coated steel, commonly used for fuel tanks, especially in older vehicles
Hoses constructed from natural rubbers must be replaced with Viton, nitrile, etc.
Low freezing point, suitable for use in cold climates

Advantages
Can be blended with gasoline in any combination
Requires little modification for use in exisitng engines

Disadvantages
Cleaning Effect
Miscible with water

Trasnporting Precautions
Vessels must be cleaned out to prevent contamination due to water and cleaning effect

Environmental/Health concerns
Toxic
Flammable

Compatibility/Fungibility issues
Miscible with water
Cleaning effect leads to deposits and plugged filters both in transport and in engines
Transport by rail: requires additional private track or existing gasoline transport tracks
Stress corrosion cracking observed in pipelines due to ethanol

Current production
2007 US ethanol production: 6.48 billion gallons
2007 US ethanol production capacity: 7.5 billion gallons
2008 projected US ethanol production capacity: 13.3 billion gallons

references:
Biofuels Digest, "US Ethanol Production Capacity to Increase to 13.3 Billion Gallons in 2008", www.biofuelsdigest.com, 1/9/2008
Biofuels Journal, "Annual and Monthly US Ethanol Production", www.biofuelsjournal.com, 12/5/2006
Department of Energy, "Handbook for Handling, Storing, and Dispensing E85", 7/2006
Pipeline Research Council International, "Stress Corrosion Cracking", 7/2006
Columbia Engineered Rubber, Inc., www.columbiaerd.com, 2010
Alvarado, Peter J., "Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks", JOM 48 (7) pp. 22-25, 1996

Gasoline Fuels

E.31. BioButanol--Properties

Properties

	1-Butanol	Isobutanol	Gasoline	*Comments*
Molecular Formula	C4H9OH	C4H9OH	C4 to C12	
Molecular Weight (g/mol)	74.12	74.12	100-105	
Elemental Composition (mass%)				
Carbon	16.2	16.2	85-88	
Hydrogen	13.5	13.5	12-15	
Oxygen	21.6	21.6	0-4	
Density (g/cm3) at 15deg C	0.81	0.801	0.69-0.79	
Vapor Pressure (kPa)	18.6 [j]	1.07	48-103 at 38C	
Boiling Point (degC)	117.7	108	27-225	
Flash Point (degC)	28.9	28	-43	*Higher flashpoint*
Freezing Point (degC)	-90 [c]	-108	-40	
High Heating Value (MJ/L)	37.3 [h]		35	
Low Heating Value (MJ/L)	34.4 [h]		30-33	
Water Solubility at 21 degC: Water in fuel (mg/L)	76700 [b]		Negligible	
Fuel Miscibility	Complete [g]			
Dielectric constant (> 15 indicates polar solvent)	17.8 [f]			
Flammability Limits (Vol%)				
Lower	1.4	1.7	1.4	
Higher	11.2	10.6	7.6	
Research Octane Number	113 [e]		88-100	
Viscosity (mPa-s) at 20 degC	3 [d]	4	0.37-0.44	
Toxicity				
Acute: Rat oral LD50 (mg/kg)	4360 [b]	2460		
Acute: Rat Inhalation LD50 (ppm)		8000	101200 [a]	
Acute:LC50 for freshwater fish (ppm)	1000 [b]			
Acute:Half max effective concentration for aquatic invertebrate (ppm)	1880 [b]			
Acute:Aquatic plants - Half max effective concentration (ppm)	500 [b]			
Chronic: Rat inhalation No observable effect conc. (mg/kg)	125 [b]			
Teratogenicity: Rat inhalation No observable effect conc. (ppm)	6000 [b]		9000 [a]	
Partition coefficient (Kow)	octanol-water		octanol-water	
Log Kow at 25 degC	0.84 [b]		2.13 to 4.85 [a]	
Bioconcentration factor (L/kg)	< 3 (estimated) [c]			
Transport between Environmental Compartments				
Air/Soil	Slow to moderate volatilization [c]			
Water/Soil	May adsorb to clay, but leaches into water [c]			
Photodegradation half-life in air	2.2 days [c]			
Biodegradation in soil in 20 days	67% [c]			
Biodegradation in water in 24 hrs (Chemical oxygen demand method)	82% [c]		0.8 to 16 days [a]	
Appearance	clear liquid		Readily in aerobic cond. [a]	
Odor	Wine-like [c]		clear to amber [a]	
Odor Threshold (ppm)	7.1 ppm (in water); 0.83 ppm (in air) [c]	1.6 ppm		
Odor of incomplete combustion product, butyric acid	extremely strong and unpleasant [i]			
CAS number	71-36-3	78-83-1		

references (butanol):

Science Lab MSDS, 1-Butanol, http://www.sciencelab.com/xMSDS-1_Butanol-9927115, Nov. 6, 2008
a) Argonne National Laboratory, Biobutanol Properties, http://www.greencarcongress.com/2008/08/argonne-investi.html
b) US EPA High Production Volume Information System, Butanol Detailed Chemical Results, http://iaspub.epa.gov/oppthpv/quicksearch.display?pChem=101066
c) EPA Chemical Fact Sheet, 1-Butanol, http://www.epa.gov/chemfact/s_butano.txt
d) California Air Resources Board Solvents Database, Butanol, http://www.arb.ca.gov/db/solvents/solvent_pages/alcohols-html/butanol.htm
e) Alasfour, *Butanol - A Single Cylinder Engine Study: Engine Performance*, International Journal of Energy Research, 1997, 21, 21-30.
f) American Chemical Society, Organic Chemistry Division, Common Organic Solvents - Table of Properties, http://organicdivision.org/organic_solvents.html
g) Mariano, Tomasella, Martino, Filho, Seleghim, Contiero, deFranceschi de Angeles,*Aerobic Biodegradation of Butanol and Gasoline Blends*, **Biomass and Bioenergy**, 2009, 33, 1175-1181.
h) Pacific Northwest National Laboratory, Hydrogen Analysis Resource
http://hydrogen.pnl.gov/filedownloads/hydrogen/datasheets/lower_and_higher_heating_values.xls
i) University of California, Low Carbon Fuel Standard-Final Report 1, http://www.energy.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_1-FINAL.pdf
j) *Gautam, Martin, Combustion Characteristics of Higher Alchohol/Gasoline Blends, Proceedings of the Institution of Mechanical Engineers; Part A; Journal of Power and Energy, 2000, vol. 214, pg. 497.*

references (gasoline):

Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications
SAE Order Number R-180, 1997
Richard L. Bechtold
a) JT Baker MSDS, Gasoline, 10/14/2008, http://www.docs.citgo.com/msds_pi/UNLEAD.pdf

Gasoline Fuels

E.32. BioButanol--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
	aluminum
	copper

Compatible Materials

elastomers	metals
	steel

Advantages

Can be run in existing gasoline engines as blend or pure with little or no modification
Biodegrades easily in soil and water
Energy content closer to gasoline than ethanol
according to BP "can be transported through pipelines…can be blended at refineries"
"a commercial fuels trial confimed the compatibility of butanol with existing fuel infrastructure"

Disadvantages

Highly flammable
miscible with water

Environmental/Health concerns

Biodegrades easily in soil and water
Flammable

Compatibility/Fungibility issues

Miscible with water
Requires private track for transport by rail
Can be run in existing gasoline engines as blend or pure with little or no modification

references: Acros Organics, "1-Butanol Material Data Safety Sheet", www.acros.com, 12/09
BP, "Biobutanol Fact Sheet", www.bp.com, 2009

Gasoline Fuels

E.33. Methanol--Properties

Properties	Methanol	M85	Gasoline	*Comments*
Molecular Formula	CH3OH		C4 to C12	
Molecular Weight (g/mol)	32.04		100-105	
Elemental Composition (mass%)				
Carbon	37.5	43-45	85-88	
Hydrogen	12.6	40160.0	12-15	
Oxygen	49.9	43-44	0-4	
Density (g/cm3) at 15deg C	0.796	0.79-0.80	0.69-0.79	
Vapor Pressure at 38 degC (kPa)	32	48-103	48-103	
Boiling Point (degC)	65	49-66	27-225	
Flash Point (degC)	11	slightly higher than gasoline	-43	*Higher flashpoint*
Pour Point (degC)				
Cloud Point				
Freezing Point (degC)	-97.5		-40	
High Heating Value (MJ/L)	18 [a]		35	
Low Heating Value (MJ/L)	15.8	17.9-18.3	30-33	*Lower energy content*
Water Solubility at 21 degC				
Water in fuel (Vol%)	100	100	Negligible	
Fuel Miscibility				
Solvation Potential				
Flammability Limits (Vol%)				
Lower	7.3	wider than	1.4	
Higher	36	gasoline	7.6	
Acid Number				
Research Octane Number	109	108	88-100	
Viscosity (mPa-s) at 20 degC	0.57 [d]	1.07-1.08	0.37-0.44	
Lubricity (um)				
Toxicity				
Acute: Mouse oral LD50 (mg/kg)	5628 [b]			
Acute: Mouse Inhalation LD50 (ppm)			101200 [a]	
Acute:LC50 for freshwater fish (Lepomis macrochirus) (mg/L)	15400 [b]			
Acute:Half max effective concentration for aquatic invertebrate (daphnia) (mg/L)	10000 [b]			
Acute:Aquatic plants - Half max effective concentration (mg/L)	28440 [b]			
Chronic: Rat inhalation Lowest observable effect conc. (ppm)	5000 [b]			
Teratogenicity: Rat inhalation Lowest (Gaso:No) observable effect conc. (ppm)	2000 [b]		9000 [a]	
Partition coefficient (Kow)	octanol-water		octanol-water	
Log Kow at 25 degC	-0.77 [b]		2.13 to 4.85 [a]	
Bioconcentration factor (L/kg)	Low based on Kow			
Transport between Environmental Compartments				
Soil/Water Environment - low organic carbon in soil	Preferentially in water [b]			
Soil/Water Environment - 10% organic carbon in soil	Equal amounts in soil & water [b]			
Half-life in water at typical env. conditions	2.6 days to volatilize from a pond [b]			
Half-life in atmosphere				
Photodegradation half-life in air	17.8 days [b]		0.8 to 16 days [a]	
Biodegradation in activated sludge for 6 days	80% [b]		Readily in aerobic cond. [a]	
Appearance	clear liquid		clear to amber [a]	
Odor Threshold (ppm)	160 detectable, 690 recognizable [c]			
CAS number	67-56-1			

References: Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications
Gasoline SAE Order Number R-180, 1997
Richard L. Bechtold
a) JT Baker MSDS, Gasoline, 10/14/2008, http://www.docs.citgo.com/msds_pi/UNLEAD.pdf

References: a) NIST Chemistry WebBook
Methanol b) US EPA High Production Volume Information System, Methanol Detailed Chemical Results, http://iaspub.epa.gov/oppthpv/quicksearch.display?pChem=100296
c) Methanex MSDS, Methanol, http://www.methanex.com/products/documents/MSDS_USenglish.pdf, Oct. 13, 2005
d) Assael and Polimatidou, *Measurements of the Viscosity of Alcohols in the Temperature Range 290-340 K at Pressures up to 30 Mpa*, **International Journal of Thermophysics**, 1994, 15, 95-107.

c) Ren, Huang, Miao, Jiang, Liu, Wang, *Effect of the Addition of Diglyme in Diesel Fuel on Combustion and Emissions in a Compression-Ignition Engine*, **Energy and Fuels**, 2007, 21, 2573-2583.

Gasoline Fuels

E.34. Methanol--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
	lead
	magnesium
	platinum
	oxidizing materials

Compatible Materials

elastomers	metals
nitrile	mild steel
neoprene	
ethylene propylene	
Teflon	
natural rubber	

Vehicle Compatibility
Incompatible with terne-coated steel, commonly used for fuel tanks in older vehicles
Compatible with nitrile and natural rubber, commonly used for hoses
Low freezing point, suitable for use in cold climates

Advantages
Can be converted to hydrogen at relatively low temps
Widely distributed currently
Biodegrades easily in soil and water

Disadvantages
Highly flammable
Miscible in water
Existing engines would require modifcation

Environmental/Health concerns
Biodegrades easily in soil and water
Flammable
Short term harmful effects on aquatic life in spill zone

Compatibility/Fungibility issues
Miscible with water
Requires private track for transport by rail
Engine modification required for use in engines

Current production
2004 US methanol production capacity: 2.6 billion gallons

references:
Methanex, "Technical Information and Safe Handling Guide for Methanol: Version 3.0", 9/2006
Sax and Lewis, “Dangerous Properties of Industrial Materials: 9th Ed.”, 1995
“Hawley’s Condensed Chemical Dictionary: 11th Ed.”, 1987
Institute for the Analysis of Global Security, "Sources of Methanol", www.iags.org, 2004
Columbia Engineered Rubber, Inc., www.columbiaerd.com, 2010
Alvarado, Peter J., "Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks", JOM 48 (7) pp. 22-25, 1996

Gasoline Fuels

E.35. Propanol--Properties

Properties

	1-Propanol	Gasoline	*Comments*
Molecular Formula	C3H8O	C4 to C12	
Molecular Weight (g/mol)	60.095	100-105	
Elemental Composition (mass%)			
Carbon	59.96	85-88	
Hydrogen	13.42	12-15	
Oxygen	26.62	0-4	
Density (g/cm3)	0.8 at 25 deg C	0.69-0.79 at 15 deg C	
Reid Vapor Pressure (kPa)	9.0 at 25 deg C	48-103 at 38 deg C	
Boiling Point (degC)	82.2	27-225	
Flash Point (degC)	23	-43	*Higher flashpoint*
Pour Point (degC)			
Cloud Point			
Freezing Point (degC)	-126.1	-40	
High Heating Value (MJ/L)	27 [f]	35	
Low Heating Value (MJ/L)	24 [d]	30-33	*Lower energy content*
Water Solubility at 21 degC			
Water in fuel (Vol%)	100	Negligible	
Fuel Miscibility			
Solvation Potential			
Flammability Limits (Vol%)			
Lower	2.2 [b]	1.4	
Higher	13.7 [b]	7.6	
Acid Number			
Research Octane Number	112 [a]	88-100	
Viscosity (mPa-s) at 25 degC	1.94	0.37-0.44	
Lubricity (um)			
Toxicity			
Acute: Rat oral LD50 (mg/kg)	1870 [c]		
Acute: Mouse Inhalation LD50 (ppm)	18 [c]	101200 [a]	
Acute: Rabbit eye irritation (mg)	4 [c]		
Acute: Rabbit dermal (mg)	580 [c]		
Acute:LC50 for fish 96-hour values(ppm)	0.3 to 3 [c]	2 to 8 [a]	
Acute:Half max effective concentration for aquatic invertebrate (daphnia) (mg/L)			
Acute:Aquatic plants - Half max effective concentration (mg/L)			
Chronic: Rat inhalation Lowest observable effect conc. (ppm)			
Teratogenicity: Rat inhalation No observable effect conc. (ppm)		9000 [a]	
Partition coefficient (Kow)	octanol-water	octanol-water	
Log Kow at 25 degC	0.32 [e]	2.13 to 4.85 [a]	
Bioconcentration factor (L/kg)	0.7 [e]		
Transport between Environmental Compartments			
Soil/Air	Evaporates [e]		
Soil/Water	Can leach into groundwater [c]		
Air/Water	Evaporates [e]		
Half-life in water at typical env. conditions	2.6 days to volatilize from a pond [b]		
Half-life in atmosphere	short-lived: reaction with hydroxyl [e]		
Photodegradation half-life in air		0.8 to 16 days [a]	
Biodegradation	Readily biodegradable [e]	Readily in aerobic cond. [a]	
Appearance	clear liquid	clear to amber [a]	
Odor Threshold (ppm)	0.13 recognizable [b]		
CAS number	71-23-8		

references:
1-propanol

California Air Resources Board, Solvents Database, 1-propanol, http://www.arb.ca.gov/db/solvents/solvent_pages/Alcohols-HTML/propanol.htm
a) Gautam, Martin, Combustion Characteristics of Higher Alchohol/Gasoline Blends, Proceedings of the Institution of Mechanical Engineers; Part A; Journal of Power and Energy, 2000, vol. 214, pg. 497.
b) Air Liquide, 1-Propanol MSDS, http://www.scottecatalog.com/msds.nsf/MSDSNo/71-23-8?OpenDocument
c) JT Baker MSDS, 1-Propanol, http://www.jtbaker.com/msds/englishhtml/P6390.htm
d) Sevon, Cooper, Modeling Combustion Efficiency in a Circulating Fluid Bed Liquid Incinerator, Chemical Engineering Science, 1991, Vol. 46, pp. 2983-2996.
e) International Program on Chemical Samety, INCHEM, 1-Propanol, http://www.inchem.org/documents/ehc/ehc/ehc102.htm#SectionNumber:1.3
f) Chao, Rossini, Heats of Combustion, Formation, and Isomerization of Nineteen Alkanols, Journal of Chemical Engineering Data, 1965, Vol. 10, pp. 374-379.

references:
gasoline

Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications
SAE Order Number R-180, 1997
Richard L. Bechtold
a) JT Baker MSDS, Gasoline, 10/14/2008, http://www.docs.citgo.com/msds_pi/UNLEAD.pdf

Gasoline Fuels

E.36. Propanol--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
	alkali metals

Compatible Materials

elastomers	metals
	steel

Advantages

Biodegrades easily

Disadvantages

Highly flammable

Environmental/Health concerns

Biodegrades easily in soil and water
Flammable

Compatibility/Fungibility issues

Requires private track for transport by rail

references:

Cameo Chemicals, "n-Propanol Chemical Data Sheet", www.cameochemicals.noaa.gov, 12/09
Dow Chemicals, "Dow n-Propanol Product Safety Assessment", www.dow.com, 6/18/09

Gasoline Fuels

E.37. Higher Carbon Alcohols--Properties

Higher carbon alcohols have greater energy density, lower miscibility with water, and lower vapor pressure than lower carbon alcohols like ethanol and methanol. [a]
Recent developments by Atsumi, Hanai, Liao (2008) enabled biosynthesis of branched higher alcohols (in table below) which are not natural fermenation products. [b]
2-methyl-1butanol and 3-methyl-1-butanol may be superior fuels to both ethanol and n-butanol. [c]
References:
a) Kreame, N., Gross, C., Univeristy of Minnesota Biofuels Database, Branched Chain Alcohol Pathway, https://www.biofuelsdatabase.org/wiki/index.php5/Branched-Chain_Alcohol_Pathway
b) Atsumi, S., Hanai, T., Liao, J. C. (2008) Non-fermentative Pathways for Synthesis of Branched-Chain Higher Alcohols as Biofuels, Nature, Vol. 451, doi:10.1038/nature06450.
c) Wackett, L.P. (2010) Biofuels (Butanol-Ethanol Production), page 2805, In: Handbook of Hydrocarbon and Lipid Microbiology, Editor: K. N. Timmis, Springer.

Properties	2-methyl-1-butanol	3-methyl-1-butanol	Gasoline
Molecular Formula	$C_5H_{12}O$	$C_5H_{12}O$	C4 to C12
Molecular Weight (g/mol)	88.15	88.15	100-105
Elemental Composition (mass%)			
Carbon	13.72	13.72	85-88
Hydrogen	68.13	68.13	12-15
Oxygen	18.15	18.15	0-4
Density (g/cm3)	0.815	0.8	0.69-0.79 at 15 deg C
Vapor Pressure (kPa)	0.4	0.32	48-103 at 38 deg C
Boiling Point (degC)	130		27-225
Flash Point (degC)	43	43	-43
Pour Point (degC)			
Cloud Point			
Freezing Point (degC)	-70	-117	-40
High Heating Value (MJ/L)	30.75 [a]	30.18 [a]	35
Low Heating Value (MJ/L)			30-33
Water Solubility			
Water in fuel (grams per 100 ml water)	3.6	2	Negligible
Fuel Miscibility			
Solvation Potential			
Flammability Limits (Vol%)			
Lower	1.1	1.2	1.4
Higher	9.3	9	7.6
Acid Number			
Research Octane Number			88-100
Viscosity (mPa-s) at 20 degC	5.1	4.37	0.37-0.44
Lubricity (um)			
Toxicity			
Acute: Rat oral LD50 (mg/kg)		1300	
Acute: Mouse Inhalation LD50 (ppm)			101200 [a]
Acute: Rabbit eye irritation (mg)		20	
Acute: Rabbit dermal LD50 (mL/kg)	3.54	3.97	
Acute:Lethal for fish 82-hour values (ppm)		100	
Acute:Half max effective concentration for aquatic invertebrate (daphnia) (mg/L)			
Acute:Aquatic plants - Half max effective concentration (mg/L)			
Chronic: Rat inhalation Lowest observable effect conc. (ppm)			
Teratogenicity: Rat inhalation No observable effect conc. (ppm)			9000 [a]
Partition coefficient (Kow)			octanol-water
Log Kow at 25 degC			2.13 to 4.85 [a]
Bioconcentration factor (L/kg)		Not expected to bioconcentrate	
Transport between Environmental Compartments			
Soil/Air			
Soil/Water		Leaches into groundwater	
Air/Water		Volatilizes	
Half-life in water at typical env. conditions			
Half-life in atmosphere			
Photodegradation half-life in air		Rapid	0.8 to 16 days [a]
Biodegradation		Readily biodegrades	Readily in aerobic cond. [a]
Appearance	Clear, colorless, liquid	Clear, colorless, liquid	clear to amber [a]
Odor	Stench	Disagreeable	
Odor Threshold (ppm)			
CAS number	137-32-6	123-51-3	

references:
2-methyl-1-butanol
Fisher Scientific MSDS, DL-2-Methyl-1Butanol, 98%, 11/20/2008, https://fscimage.fishersci.com/msds/52450.htm
a) Chao, Rossini, Heats of Combustion, Formation, and Isomerization of Nineteen Alkanols, Journal of Chemical Engineering Data, 1965, Vol. 10, pp. 374-379.

references:
3-methyl-1-butanol
Fisher Scientific MSDS, 3-Methyl-1Butanol, 9/30/2002, https://fscimage.fishersci.com/msds/00798.htm
a) Chao, Rossini, Heats of Combustion, Formation, and Isomerization of Nineteen Alkanols, Journal of Chemical Engineering Data, 1965, Vol. 10, pp. 374-379.

references:
gasoline
Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications
SAE Order Number R-180, 1997
Richard L. Bechtold
a) JT Baker MSDS, Gasoline, 10/14/2008, http://www.docs.citgo.com/msds_pi/UNLEAD.pdf

Gasoline Fuels

E.38. Higher Carbon Alcohols--Compatibility and Environmental Issues

Advantages
Low freezing point

Disadvantages
Moderate flammability
Moderate toxicity
High oxygen content
Low vapor pressure
Somewhat soluble in water

references:
Fisher Scientific MSDS, DL-2-Methyl-1Butanol, 98%, 11/20/2008, https://fscimage.fishersci.com/msds/52450.htm
Fisher Scientific MSDS, 3-Methyl-1Butanol, 9/30/2002, https://fscimage.fishersci.com/msds/00798.htm

Biocrude and Intermediates

E.39. Pyrolysis Oil--Properties

Properties	NREL Oil *	Ensyn Oil**	MFR Specifications***	Fast Pyrolysis Bio-oil	Hydrothermal Bio-oil	Heavy Petroleum Fuel	
Molecular Formula							
Molecular Weight (g/mol)	370	550					
Elemental Composition (mass%)							
Carbon	58.25	57.95		39.5 - 55.8	72.6 - 74.8	85.2	
Hydrogen	7.4	7.23		7.5 - 6.1	8.0	11.1	
Oxygen	32.83	33.19		37.9 - 52.6			
Nitrogen	1.52	1.64		< 0.1	< 0.1	0.3	
Sulfur	1.2	1.22		< 0.05	< 0.05	2.3	*Lower sulfur content*
Density (g/cm3)				1.23	1.1	0.94	
Vapor Pressure kPa							
Boiling Point (degC)							
Flash Point (degC)		55 [a]					
Pour Point (degC)		-25 [a]					
Cloud Point (degC)							
High Heating Value (MJ/kg)		17.6 [a]	min. 18 [a]	16.5 - 17.5		40	*Lower energy content*
Low Heating Value (MJ/kg)	17	16.3	min. 16 [a]				
Water Content (mass%)	16.9	26.3	max. 26 [a]	15 - 25	3 - 5	0.1	
Water Solubility at 21 degC							
Water in fuel (ppm)							
Fuel Miscibility							
Solvation Potential							
Flammability Limits (Vol%)							
Lower							
Higher							
pH		2.5					
Cetane Number							
Viscosity (mPa-s)		59 [a]		10 - 150 at 50 degC	3000 - 17000 at 60 degC	180 at 50 degC	*Lower viscosity*
Lubricity (um)							

* National Renewable Energy Laboratory wood-derived flash pyrolysis oil produced by ablative vortex reactor

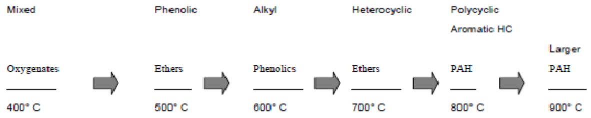
** Ensyn Corporation wood-derived flash pyrolysis oil produced in a tubular transport reactor

*** Manufacturer Specifications Set by Ensyn (US/Canada), Wartsila (Finland), and Birka (Sweden) in the 1990s [a]

Information below for various pyrolysis oils: not only NREL Oil

Toxicity	
Acute: Animal Aerosol Inhalation LD50 (mg/m3)	3100 [b]
Acute: Rabbit Dermal No observable effect concentration (mg/kg)	2000 [b]
Acute: Rabbit Eye Corneal Damage (mL)	0.1 [b]
Acute: Oral (mg/kg)	700 [b]
Acute:Fish LC50 and bacteria EC50 (mg/L)	
Chronic: Rat and Mouse oral (mg/m3)	
Mutagenicity	Conflicting studies [b]
Partition coefficient (Kow)	
Log Kow at 25 degC	
Bioconcentration factor (L/kg) [j]	
Soil adsorption	
Half-life in water at typical env. conditions	
Half-life in atmosphere	
Biodegradation: Aerobic in freshwater, 28 days	41% - 50% [d]
Appearance	
Odor	Strong Smoky [c]
Odor threshold (mg/m3)	
Odor threshold (ppm)	

Biomass pyrolysis products formed at higher temperature have greater toxicity (see blow) [c]



References:	Shihadeh, Hochgreb, Energy and Fuels, 2002, 16, 552-561.
NREL oil, Ensyn oil, and MFR specifications	a) Oasmaa, Peacocke, Gust, Meier, McLellan, Norms and Standards for Pyrolysis Liquids. End-User Requirements and Specifications, Energy and Fuels C, http://www.combio-project.com/download/PDF/COMBIO_WP2_specification.pdf
	b) Diebold, A review of the toxicity of biomass pyrolysis liquids formed at low temperatures. National Renewable Energy Laboratory, NREL/TP-430-22739, 1997.
	c) Ringer, Putsche, Scahill, Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis, National Renewable Energy Laboratory, NREL/TP-510-37779, November 2006.
	d) Blin, Volle, Girard, Bridgwater, Meier, Biodegradability of biomass pyrolysis oils: Comparison to conventional petroleum fuels and alternatives fuels in current use, 2007, Fuel, 86, 2679-2686

References:	Douglas C. Elliott, Staff Scientist, U.S. Department of Energy, Pacific Northwest National Laboratory, Richland, WA
fast pyrolysis, hydrothermal, and	Hydroprocessing of Pyrolysis Bio-oil to Fuels and Chemicals, Bioenergy & Wood Products, Smallwood, May 14, 2008
heavy petroleum	http://www.forestprod.org/smallwood08powerpoints.html

Biocrude and Intermediates

E.40. Pyrolysis Oil--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
	aluminum
	mild steel
	nickel
	impure copper

Compatible Materials

elastomers	metals
polyethylene	stainless steel
polypropylene	cobalt
polyester resins	brass

Advantages

Biodegrades quickly
Less toxic than petroleum fuels

Disadvantages

corrosive
high viscosity
instability
temperature sensitivity
high char and solids content
contains alkali metals, leading to deposits in filters, boilers, engines, etc.
suspended char particles can contribute to phase separation

Environmental/Health Concerns

Biodegrades quickly
Less toxic than petroleum fuels

Compatibility/Fungibility Issues

Generally not soluble in water
Can phase separate
High oxygen content leads to polarity, can cling to pipe/vessel walls

references:

Hydroprocessing of Pyrolysis Bio-oil to Fuels and Chemicals, Bioenergy & Wood Products, Smallwood, May 14, 2008, http://www.forestprod.org/smallwood08powerpoints.html
Qiang, Lu, Wen-Zhi, Li, Xi-Feng, Zhu, Overview of Fuel Properties of Biomass Fast Pyrolysis Oils, Journal of Energy Conversion and Management vol 50, 2009
Cirad-Foret, "MSDS: Bio-Oil", 5/06

Biocrude and Intermediates

E.41. Syngas--Properties

Properties

	FERCO* Bio-Syngas	Coal-derived Syngas	Landfill Gas	Typical Natural Gas
Molecular Formula				
Molecular Weight (g/mol)				
Gas Composition				
Hydrogen Molecule	26.2	45		Trace
Carbon Monoxide	38.2	49		
Carbon Dioxide	15.1	2.9	37.5	0.7
Nitrogen Molecule	2	2.2	7	1.3
Methane	14.9	0.9	54.5	95.2
Gaseous Compounds with more than two Carbon Atoms	4			3.6
Density (g/cm3)				0.58
Vapor Pressure kPa at 38 degC				
Boiling Point				
Flash Point (degC)				
Wobbe Index (BTU/scf)	499 [a]	450	639	1367 [a]
High Heating Value (MJ/m^3)	16.30			37.8
Low Heating Value (MJ/m^3)				
Water Solubility at 21 degC				
Water in fuel (%mass)				
Water content in fuel (mg/m^3)				16 to 32
Fuel Miscibility				
Solvation Potential				
Flammability Limits (Vol%)				4 to 16
Lower	4 [b]			
Higher	75 [b]			
Acid Number				
Cetane Number				
Viscosity (mPa-s)				
Kinematic viscosity (mm^2/s)				

Toxicity based on Carbon Monoxide Content [b]

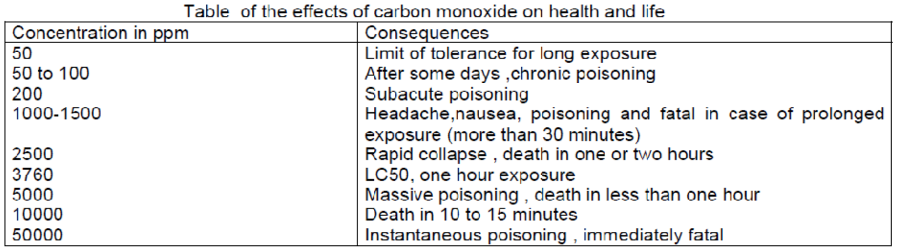


Table of the effects of carbon monoxide on health and life

Concentration in ppm	Consequences
50	Limit of tolerance for long exposure
50 to 100	After some days ,chronic poisoning
200	Subacute poisoning
1000-1500	Headache,nausea, poisoning and fatal in case of prolonged exposure (more than 30 minutes)
2500	Rapid collapse , death in one or two hours
3760	LC50, one hour exposure
5000	Massive poisoning , death in less than one hour
10000	Death in 10 to 15 minutes
50000	Instantaneous poisoning , immediately fatal

Appearance
Odor
Odor threshold (mg/m3)
Odor threshold (ppm)

*Future Energy Resources Company (FERCO), 950 E. Paces Ferry Road, NE, Suite 810, Atlanta, GA 30326

References: FERCO Bio-syngas	Richard L. Bain, An Introduction to Biomass Thermochemical Conversion, DOE/NASLUGC Biomass and Solar Energy Workshops, August 3-4, 2004. a) Paisley, Farris, Black, Irving, Overend, Preliminary Operating Results from the Battelle/FERCO Gasification Demonstration Plant in Burlington, Vermont, U.S.A., http://www.silvagas.com/downloads/seville.pdf b) European Industrial Gases Association, Carbon Monoxide and Syngas Pipeline Systems, IGC Doc 120/04/E,
References: Natural Gas	Union Gas Limited, Chemical Composition of Natural Gas, http://www.uniongas.com/aboutus/aboutng/composition.asp, February 2010. a) Ferguson, Straub, Richards, Robey, Impact of Fuel Variability on Dynamic Instabilities in Gas Turbine Combustion, 5th US Combustion Meeting, Organized by the Western States Section of the Combustion Institute and Hosted by the University of San Diego, March 25-28, 2007.
References: Coal-derived Syngas and Landfill Gas	Ferguson, Straub, Richards, Robey, Impact of Fuel Variability on Dynamic Instabilities in Gas Turbine Combustion, 5th US Combustion Meeting, Organized by the Western States Section of the Combustion Institute and Hosted by the University of San Diego, March 25-28, 2007.

Biocrude and Intermediates

E.42. Syngas--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
Buna N	some grades of carbon steel
Neoprene	low-alloy steel
Natural rubber	high strength steel
Butyl rubber	stainless steel
	nickel alloy

Compatible Materials

elastomers	metals
Viton	low strength, high toughness carbon steel
Teflon	microalloyed steel

Environmental/Health Concerns

Flammable
CO component is highly toxic

Transportation Precautions

Pipeline must be free of water to prevent serious corrosion when syngas is introduced
H_2 component highly prone to leaks

references: European Industrial Gases Association, Carbon Monoxide and Syngas Pipeline Systems, www.eiga.org, 2004

Biocrude and Intermediates

E.43. Lignin Liquids--Properties

Properties	Black Liquor Eucalyptus	Black Liquor Bamboo	Heavy Petroleum Fuel	
Molecular Formula				
Molecular Weight (g/mol)				
Elemental Composition (mass% per dry solids for liquor)				
Carbon	30.8	35.4	85.2	
Hydrogen	3.6	3.6	11.1	
Oxygen				
Nitrogen	0.01	0.3	0.3	
Sodium	21.8	13.3		*High Group 1 metals*
Potassium	1.8	3.3		
Sulfur	3.7	0.2	2.3	
Chlorine	4.5	1.3		
Silicon	0.1	3.8		
Lignin Concentration (% mass per mass dry solids)	42.3	45.3		
Density (g/cm3) at 26 - 30 degC for liquors	1.005	0.947	0.94	
Vapor Pressure kPa at 38 degC				
Boiling Point				
Flash Point (degC)				
Pour Point (degC)				
Cloud Point (degC)				
High Heating Value (MJ/L)	14.67	13.90	40	*Lower energy content*
Low Heating Value (MJ/L)				
Water Solubility at 21 degC				
Water in fuel (%mass)			0.1	
Water content in fuel (mg/kg)				
Fuel Miscibility				
Solvation Potential				
Flammability Limits (Vol%)				
Lower				
Higher				
Acid Number				
Cetane Number				
Viscosity (mPa-s)	30000*	50*	180 at 50 degC	*Higher viscosity for Eucalyptus*
Kinematic viscosity (mm^2/s)				
Lubricity (um)				
Toxicity				
Acute: Animal Aerosol Inhalation LD50 (mg/m3)				
Acute: Rabbit Dermal No observable effect concentration (mg/kg)				
Acute: Rabbit Eye Corneal Damage (mL)				
Acute: Oral (mg/kg)				
Acute:Fish LC50 and bacteria EC50 (mg/L)				
Chronic: Rat and Mouse oral (mg/m3)				
Mutagenicity				
Partition coefficient (Kow)				
Log Kow at 25 degC				
Bioconcentration factor (L/kg) [j]				
Soil adsorption				
Half-life in water at typical env. conditions				
Half-life in atmosphere				
Biodegradation: Aerobic in freshwater, 28 days				
Appearance				
Odor				
Odor threshold (mg/m3)				
Odor threshold (ppm)				

* The liquor viscosity depends on sheer rate, temperature and lignin concentration; the values reported are for 10/s sheer rate, ~40.5 % mass lignin per dry mass solids, and 30.1 - 31.5 degC (Cardoso et al., 2009).

Black Liquor References

Cardoso, Domingos, Oliveira, Passos, *Chemical Composition and Physical Properties of Black Liquors and Their Effects on Liquor Recovery Operation in Brazilian Pulp Mills*, Fuel, 2009, 88, 756-763.

FAME Specification Reference

Hannu Jaaskelainen, Biodiesel Fuel Standards, http://www.dieselnet.com/tech/fuel_biodiesel_std.html

Diesel References

Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications
SAE Order Number R-180, 1997
Richard L. Bechtold

a) Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels
SwRI 7507, November 1996
Christopher A. Sharp

b) Hess, Boehman, Tijm, Waller, *Experimental Studies of the Impact of CETANER on Diesel Combustion and Emissions*, SAE Technical Paper 2000-01-2886

Biocrude and Intermediates

E.44. Lignin Liquids--Compatibility and Environmental Issues

Advantages
Can be refined into a number of different fuels including DME, ethanol, methanol, FT diesel, and biogas
Estimated US annual black liquor yield is 28 million tons
High land-use efficiency when processed to produce DME or methanol

Disadvantages
Low diesel yield compared to DME/methanol/etc. yields
Black liquor generation also produces highly corrosive Na2CO2 and Na2S smelts that can damage a recovery boiler

references:
LeBlanc, Richard J., "Black Liquor Gasification Can Help Sustain Forests, Generate Ultra-Clean Biofuels", Biomass Magazine, 7/09
Ekbom, T., "High Efficienct Motor Fuel Production From Biomass Via Black Liquor Gasification", ISAF XV International Symposium on Alcohol Fuels, 9/05
Hubbard, C. R., Peascoe, R. A., Keiser, J. R., "Pulp and Paper Plant Materials Issues Addressed by X-Ray and Neutron Diffraction Methods", International Center for Diffraction Data, Advances in X-Ray Analysis Vol. 46, 2003
European Project BioDME, "Production of DME from Biomass and Utilisation as Fuel for Transport and for Industrial Use", 7th Framework Program, 2009

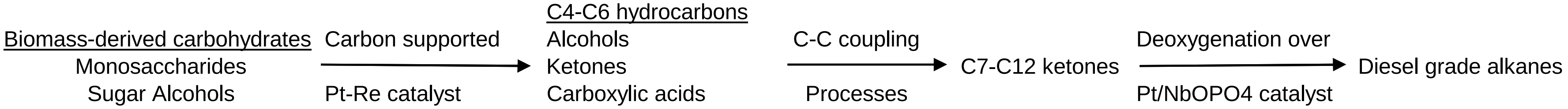
Biocrude and Intermediates

E.45. Sugar and Alcohols--Properties

NO PUBLISHED DATA WAS FOUND FOR PROPERTIES OR CHEMISTRY OF MIXED SUGAR AND CARBOHYDRATE FEEDSTOCKS FOR FUEL PRODUCTION
ALCOHOL BASED FEEDSTOCKS WOULD BE EXPECTED TO HAVE SIMILAR PROPERTIES AND CHEMISTRY TO ALCOHOLS LISTED IN THE FUELS SECTIONS

Fungible Fuels Composed of Gasoline- and Diesel-like Hydrocarbons Produced from Sugar and Alcohols

Process developed by group of J. A. Dumesic at the University of Wisconsin-Madison:

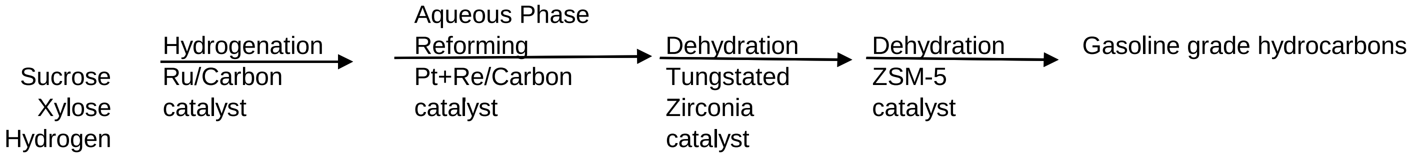


References:

Gurbuz, Kunkes, Simonetti, West, Serrano-Ruiz, Gaertner, Dumesic (2009) Catalytic Production and Upgrading of Biomass Derived Monofunctional Hydrocarbons, Proceedings of the American Institute of Chemical Engineers Annual Meeting, November 2009, Nashville, TN.

Kunkes, Simonetti, West, Serrano-Ruiz, Gartner, Dumesic (2008) Catalytic Conversion of Biomass to Monofunctional Hydrocarbons and Targeted Liquid-fuel Classes, Science, Vol. 322, pp. 417-421.

Process developed by Virent Energy Systems, Inc., Madison, Wisconsin.



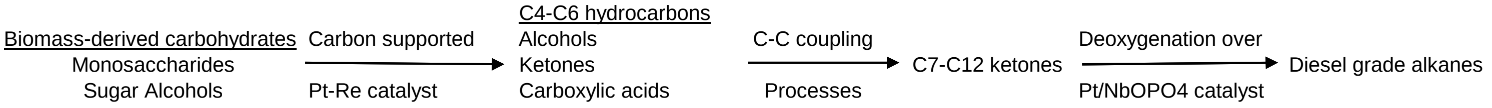
	Virent sugar-derived aviation fuel	
		Limit
	1.1	25 max
Aromatics (vol %)	< 0.001	0.3 max
Sulfur	.775 - .84	0.7398
Density (g/cm3)	< -70	-40 max
Freezing Point (deg C)	240.7	300 max
Boiling Point	33	38 min
Flash Point (degC)	44.21	42.8
Specific Energy (MJ/kg)	2.74	8 max
Viscosity at -20C (cSt)		

Biocrude and Intermediates
E.46. Sugar and Alcohols--Compatibility and Environmental Issues

NO PUBLISHED DATA WAS FOUND FOR COMPATABILITY OR ENVIRONMENTAL INFORMATION RELATED TO MIXED SUGAR AND CARBOHYDRATE FEEDSTOCKS FOR FUEL PRODUCTION ALCOHOL BASED FEEDSTOCKS WOULD BE EXPECTED TO HAVE SIMILAR COMPATABILITY AND ENVIRONMENTAL CHARACTERISTICS TO ALCOHOLS LISTED IN THE FUELS SECTIONS

Fungible Fuels Composed of Gasoline- and Diesel-like Hydrocarbons Produced from Sugar and Alcohols

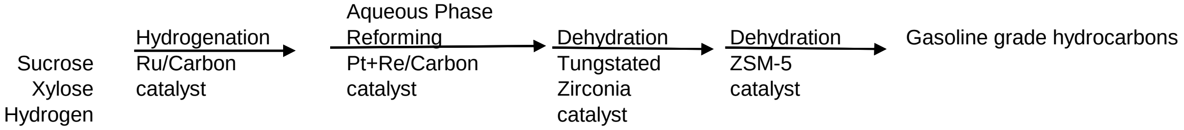
Process developed by group of J. A. Dumesic at the University of Wisconsin-Madison:



References:
Gurbuz, Kunkes, Simonetti, West, Serrano-Ruiz, Gaertner, Dumesic (2009) Catalytic Production and Upgrading of Biomass Derived Monofunctional Hydrocarbons, Proceedings of the American Institute of Chemical Engineers Annual Meeting, November 2009, Nashville, TN.

Kunkes, Simonetti, West, Serrano-Ruiz, Gartner, Dumesic (2008) Catalytic Conversion of Biomass to Monofunctional Hydrocarbons and Targeted Liquid-fuel Classes, Science, Vol. 322, pp. 417-421.

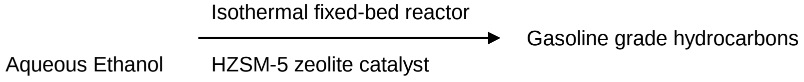
Process developed by Virent Energy Systems, Inc., Madison, Wisconsin.



	Virent sugar-derived aviation fuel	Limit
	1.1	25 max
Aromatics (vol %)	< 0.001	0.3 max
Sulfur	.775 - .84	0.7398
Density (g/cm3)	< -70	-40 max
Freezing Point (deg C)	240.7	300 max
Boiling Point	33	38 min
Flash Point (degC)	44.21	42.8
Specific Energy (MJ/kg)	2.74	8 max
Viscosity at -20C (cSt)		

Reference:
Blommel, Cortright of Virent Energy Systems, Inc., Production of Conventional Liquid Fuels from Sugars, White Paper, August 25, 2008.

Process developed by Aguayo et al. (2002) at the Universidad del Pais Vasco, Spain



Reference:
Aguayo, Gayubo, Tarrio, Atutxa, Bilbao (2002) Study of Operating Variables in the Transformation of Aqueous Ethanol into Hydrocarbons on a HZSM-5 Zeolite, Journal of Chemical Technology and Biotechnology, Vol. 77, pp. 211-216.

Biocrude and Intermediates

E.47. Terpenes--Properties

An advantage of terpenes is water insolubility, however,
"Strains and processes capable of converting sugars to terpenoids at yields similar to the ethanol process have not yet been reported in the scientific literature."
Reference:
Fisher, Kein-Marcuschamer, Stephanopoulos, Selection and Optimization of Microbial Hosts for Biofuels Production, Metabolic Engineering, 2008, Vol. 10, pp. 295-304.

"Orange oil is a biomass-derived fuel obtained from orange skin, which has ~90% D-limonene and can be used for many applications."
"In addition, orange oil can also be used as an alternative to gasoline either partially in the form of a blend or as a total replacement."
"India has a huge potential of producing orange peel oil of ~27,600 ton (based on 0.6% recovery of oil from 46 lakhs ton fruits by cold press process) from the orange fruits. Presently, 2–3 tons of orange oil are produced for food and cosmetic industries. There is no other demand for orange oil."
Reference:
Purushothaman, Nagarajan (2009) Experimental Investigation on a C.I. Engine Using Orange Oil and Orange Oil with DEE, Fuel, Vol. 88, pp. 1732-1740.

Properties

	d-Limonene	Gasoline
Molecular Formula	$C_{10}H_{16}$	C4 to C12
Molecular Weight (g/mol)	136.23	100-105
Elemental Composition (mass%)		
Carbon	88	85-88
Hydrogen	12	12-15
Oxygen		0-4
Density (g/cm3)	0.8402	0.69-0.79 at 15 deg C
Vapor Pressure (kPa)	0.2	48-103 at 38 deg C
Boiling Point (degC)	175	27-225
Flash Point (degC)	45	-43
Pour Point (degC)		
Cloud Point		
Freezing Point (degC)	-40	-40
High Heating Value (MJ/L)	37.96 [a]	35
Low Heating Value (MJ/L)		30-33
Water Solubility at 21 degC		
Water in fuel (Vol%)	Negligible [b]	Negligible
Fuel Miscibility		
Solvation Potential		
Flammability Limits (Vol%)		
Lower	0.7	1.4
Higher	6.1	7.6
Acid Number		
Research Octane Number		88-100
Viscosity (mPa-s) at 25 degC	1.08 [b]	0.37-0.44
Lubricity (um)		
Toxicity	Sensitizer, skin & lung irritant	
Acute: Rat oral LD50 (mg/kg)	4400	
Acute: Mouse Inhalation LD50 (ppm)		101200 [a]
Acute: Rabbit eye irritation (mg)		
Acute: Rabbit dermal (mgkg)	> 5000	
Acute:LC50 for fish 96-hour values(ppm)		
Acute:Half max effective concentration for aquatic invertebrate (daphnia) (mg/L)		
Acute:Aquatic plants - Half max effective concentration (mg/L)		
Chronic: Rat inhalation Lowest observable effect conc. (ppm)		
Teratogenicity: Rat inhalation No observable effect conc. (ppm)	May cause birth defects	9000 [a]
Partition coefficient (Kow)		octanol-water
Log Kow at 25 degC		2.13 to 4.85 [a]
Bioconcentration factor (L/kg)		
Transport between Environmental Compartments		
Soil/Air		
Soil/Water		
Air/Water		
Half-life in water at typical env. conditions		
Half-life in atmosphere		
Photodegradation half-life in air	1 hour [b]	0.8 to 16 days [a]
Biodegradation	100% in 28 days	Readily in aerobic cond. [a]
Appearance	clear, almost colorless	clear to amber [a]
Odor	citrus	
Odor Threshold (ppm)		
CAS number	5989-27-5	

references:
d-Limonene
Science Lab MSDS, d-Limonene, 11/06/2008, http://www.sciencelab.com/xMSDS-DLimonene-9924496
a) Hawkins, Eriksen, Physical and Thermodynamic Properties of Terpenes. II. The Heats of Combustion of Some Terpene Hydrocarbons, Journal of the American Chemical Society, 1954, Vol. 76, pp. 2669-2671.
b) PDM, Inc., MSDS d-limonene, http://www.pdmchemicals.com/MSDS/MSDS-d-Limonene.doc

references:
gasoline
Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications
SAE Order Number R-180, 1997
Richard L. Bechtold
a) JT Baker MSDS, Gasoline, 10/14/2008, http://www.docs.citgo.com/msds_pi/UNLEAD.pdf

Biocrude and Intermediates

E.48. Terpenes--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals
PVC	ferrous metals*
nitrile	
silicone	
Tygon	
natural rubber	
latex rubber	
neoprene	

Compatible Materials

elastomers	metals
Teflon	non-ferrous metals*
polypropylene	stainless steel
epoxy	
Viton	
nylon	

Vehicle Compatibility

Compatible with terne-coated steel, commonly used for fuel tanks
Hoses made of nitrile or natural rubber must be replaced with Viton, etc.

Advantages

Negligibly miscible in water

Disadvantages

notes: *non-corrosive to metals but can
become discolored by rust from ferrous metals

references: T2 Laboratories Inc., "Information Bulletin: Material Compatability with Terpene Chemicals", www.t2labs.com, 1995

Biocrude and Intermediates

E.49. Isoprenes--Properties

"...ethanol has a lower energy density and must be distilled from the fermentation broth, requiring significant energy. Isoprene could be made instead and collected from the gas phase of the fermentor, eliminating the need for distillation. Isoprene has a higher energy density than ethanol and does not absorb water and so should be less corrosive when used in automobiles. Isoprene could be made from the same inputs currently used to make ethanol. Starch from Zea mays grain is currently a major starting point in the ethanol industry in the US and this is generally considered unsustainable. As alternate inputs are developed there is no reason that those inputs could not be converted to isoprene instead of ethanol. On the other hand, isoprene emission is closely associated with photosynthesis so photosynthetic organisms engineered to make high levels of isoprene can also be envisioned for the future."

Reference:
Sharkey (2009) The Future of Isoprene Research, Bulletin of the Georgian National Academy of Sciences, Vol. 3, No. 3.

Properties

	Isoprene	Gasoline	*Comments*
Molecular Formula	C5H8	C4 to C12	
Molecular Weight (g/mol)	68.12	100-105	
Elemental Composition (mass%)			
Carbon	88	85-88	
Hydrogen	12	12-15	
Oxygen	0	0-4	
Density (g/cm3) at 20deg C	0.68	0.69-0.79	
Reid Vapor Pressure (kPa)	103.4	48-103	
Boiling Point (degC)	34.1	27-225	
Flash Point (degC)	-54	-43	*Lower flashpoint*
Pour Point (degC)			
Cloud Point			
Freezing Point (degC)	-146		
High Heating Value (MJ/L)	30	35	
Low Heating Value (MJ/L)		30-33	
Water Solubility at 21 degC			
Water in fuel (ppm)		<50	
Fuel Miscibility			
Solvation Potential			
Flammability Limits (Vol%)			
Lower	1.5	1.4	
Higher	9.7	7.6	
Acid Number			
Research Octane Number		88-100	
Viscosity (mPa-s)		0.37-0.44	
Lubricity (um)			
Toxicity	Risk damage eyes, respir.		
Acute: Rat oral LD50 (mg/kg)	5240		
Acute: Mouse Inhalation LD50 (ppm)	35278	101200 [a]	
Acute: Rabbit eye irritation (mg)			
Acute: Rabbit dermal (mgkg)	8900		
Acute:LC50 for fish 96-hour values(ppm)			
Acute:Half max effective concentration for aquatic invertebrate (daphnia) (mg/L)			
Acute:Aquatic plants - Half max effective concentration (mg/L)			
Chronic: Rat inhalation Lowest observable effect conc. (ppm)			
Carcinogenicity	Carcinogenic		
Teratogenicity: Rat inhalation No observable effect conc. (ppm)		9000 [a]	
Partition coefficient (Kow)		octanol-water	
Log Kow at 25 degC		2.13 to 4.85 [a]	
Bioconcentration factor (L/kg)			
Transport between Environmental Compartments			
Soil/Air			
Soil/Water			
Air/Water			
Half-life in water at typical env. conditions			
Half-life in atmosphere			
Photodegradation half-life in air		0.8 to 16 days [a]	
Biodegradation	Products of biodeg. toxic	Readily in aerobic cond. [a]	
Appearance	liquid	clear to amber [a]	
Odor			
Odor Threshold (ppm)			
CAS number	7879-5		

Reference: Science Lab MSDS, 11/06/2008, http://www.sciencelab.com/xMSDS-Isoprene-9924409
isoprene

references: Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications
gasoline SAE Order Number R-180, 1997
Richard L. Bechtold
a) JT Baker MSDS, Gasoline, 10/14/2008, http://www.docs.citgo.com/msds_pi/UNLEAD.pdf

Biocrude and Intermediates

E.50. Isoprenes--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals

Compatible Materials

elastomers	metals

Advantages

Water insoluble

Disadvantages

Highly flammable
Harmful to aquatic life in very low doses
Highly volatile

Environmental/Health concerns

Water insoluble
Flammable
Harmful to aquatic life in very low doses

Compatibility/Fungibility issues

Requires private track for transport by rail

Production

1996 US isoprene production capacity: 598 million lbs.

references:
Cameo Chemicals Inc., "Isoprene", www.cameochemicals.noaa.gov, 6/1999
ExxonMobil Chemical, "Isoprene Product Safety Summary", www.exxonmobilchemical.com, 6/2009
National Institute of Health, "Substance Profiles: Isoprene", www.ntp.niehs.nih.gov, 2000

Other

E.51. Methane--Properties

"When fitted according to approved standards, the use of biomethane in vehicles can be safer than petrol.
This is due to the higher flammability limits, higher diffusion coefficient and auto-ignition temperature of biomethane (Cenex, 2009)."
Reference:
Renewable Energy, Landfill Gas and EfW: Now, Next and Future
K A Adu-Gyamfi, R Villa and F Coulon
http://www.geotech.co.uk/press_releases/Geotech%20sponsored%20paper.pdf

Motor vehicle fuel standard in Sweden for biomethane

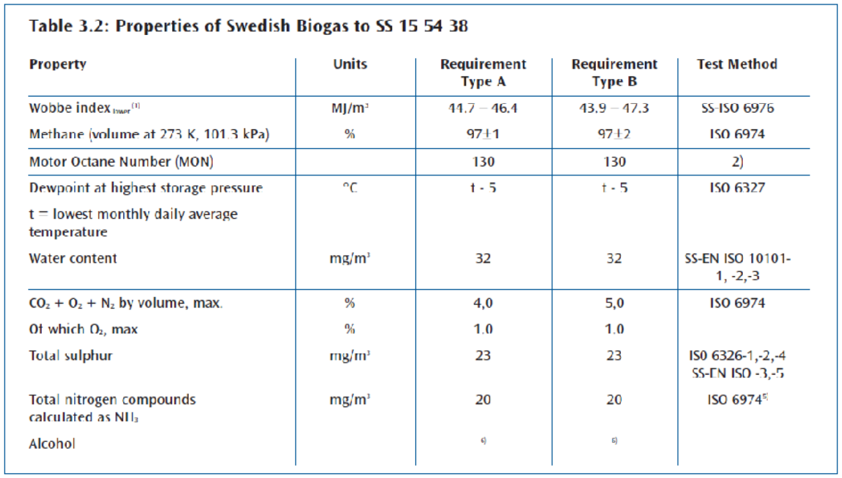


Table 3.2: Properties of Swedish Biogas to SS 15 54 38

Property	Units	Requirement Type A	Requirement Type B	Test Method
Wobbe index$_{lower}$ (1)	MJ/m^3	44.7 – 46.4	43.9 – 47.3	SS-ISO 6976
Methane (volume at 273 K, 101.3 kPa)	%	97±1	97±2	ISO 6974
Motor Octane Number (MON)		130	130	2)
Dewpoint at highest storage pressure	°C	t - 5	t - 5	ISO 6327
t = lowest monthly daily average temperature				
Water content	mg/m^3	32	32	SS-EN ISO 10101-1, -2,-3
$CO_2 + O_2 + N_2$ by volume, max.	%	4,0	5,0	ISO 6974
Of which O_2, max	%	1.0	1.0	
Total sulphur	mg/m^3	23	23	ISO 6326-1,-2,-4 SS-EN ISO -3,-5
Total nitrogen compounds calculated as NH_3	mg/m^3	20	20	ISO 6974[5]
Alcohol		6)	6)	

Reference:
EPUK (2006) Biogas as a Road Transport Fuel, National Society for Clean Air and
Environmental Protection (now Environmental Protection UK), June 2006.
http://www.environmentalprotection.org.uk/assets/library/documents/biogas_as_transport_fuel_june06.pdf

Motor vehicle fuel standard in Austria (BGBL 417/04) and Europe (DIN 51624) for biomethane
In comparison to upgraded biogas (methaPUR) and raw biogas

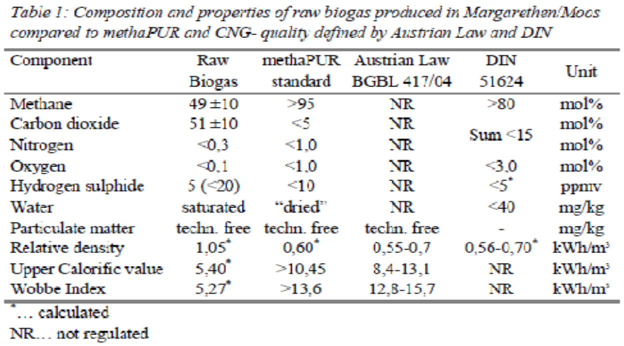


Table 1: Composition and properties of raw biogas produced in Margarethen/Moos compared to methaPUR and CNG- quality defined by Austrian Law and DIN

Component	Raw Biogas	methaPUR standard	Austrian Law BGBL 417/04	DIN 51624	Unit
Methane	49 ±10	>95	NR	>80	mol%
Carbon dioxide	51 ±10	<5	NR	Sum <15	mol%
Nitrogen	<0,3	<1,0	NR		mol%
Oxygen	<0,1	<1,0	NR	<3,0	mol%
Hydrogen sulphide	5 (<20)	<10	NR	<5*	ppmv
Water	saturated	"dried"	NR	<40	mg/kg
Particulate matter	techn. free	techn. free	techn. free	-	mg/kg
Relative density	1,05*	0,60*	0,55-0,7	0,56-0,70*	kWh/m^3
Upper Calorific value	5,40*	>10,45	8,4-13,1	NR	kWh/m^3
Wobbe Index	5,27*	>13,6	12,8-15,7	NR	kWh/m^3

*… calculated
NR… not regulated

"In order to produce fuel for the Austrian market, the product has to fulfill the Austrian law "Kraftstoffverordnung" BGBL 417/04, while in Germany and many other European countries DIN 51624 is applicable. It is planned to merchandize upgraded biogas on several locations in Austria and abroad; therefore a new fuel brand called "methaPUR" has been established, unifying the numerous quality parameters in one standard. The definition of the methaPUR standard is compared to the composition of gaseous fuels (CNG – compressed natural gas) prescribed in the aforementioned laws and to the raw biogas in Table 1. It has to be mentioned, that the hydrogen sulphide content of the raw biogas is extremely low due to effective in-situ-desulphurization using commercially available liquid mixtures of metal salts and due to the favorable local substrate mixture (high content of energy crops together with liquid pig manure).
It can be easily seen that in order to upgrade biogas to accepted fuel qualities, several steps must be performed. The most important of them are the separation of malicious substances, drying and separation of carbon dioxide, nitrogen and oxygen, which results in the increase of the calorific value and the Wobbe Index."

Reference:
Biogas upgrading for transportation purposes – Operational Experiences with Austria's first Bio-CNG fuelling station
Martin Miltner, Aleksander Makaruk, Harald Bala, Michael Harasek
http://www.aidic.it/pres09/webpapers/134Miltner.pdf
Chem Eng Trans, 2009

Other

E.52. Methane--Compatibility and Environmental Issues

Incompatibility

elastomers	metals

Compatibility

elastomers	metals

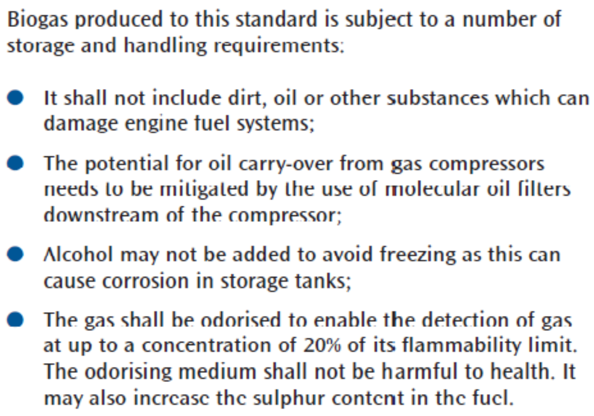
Advantages
Non-toxic
Can produce significant reductions in CO2, CO, NOx, and PM emissions

Disadvantages
Must be compressed to a liquid for ease of transport
Highly flammable
Can produce significant increases in HC emissions (20x that of gasoline vehicles in Sweden)
Can produce significant increases in fuel consumption versus comparable diesel engines

Environmental/Health concerns
Non-toxic
Flammable

Compatibility/Fungibility issues
Must be compressed to a liquid for ease of transport
Trucks carrying methane not permitted in tunnels

Motor vehicle fuel standard in Sweden for biomethane



Biogas produced to this standard is subject to a number of storage and handling requirements:

- It shall not include dirt, oil or other substances which can damage engine fuel systems;
- The potential for oil carry-over from gas compressors needs to be mitigated by the use of molecular oil filters downstream of the compressor;
- Alcohol may not be added to avoid freezing as this can cause corrosion in storage tanks;
- The gas shall be odorised to enable the detection of gas at up to a concentration of 20% of its flammability limit. The odorising medium shall not be harmful to health. It may also increase the sulphur content in the fuel.

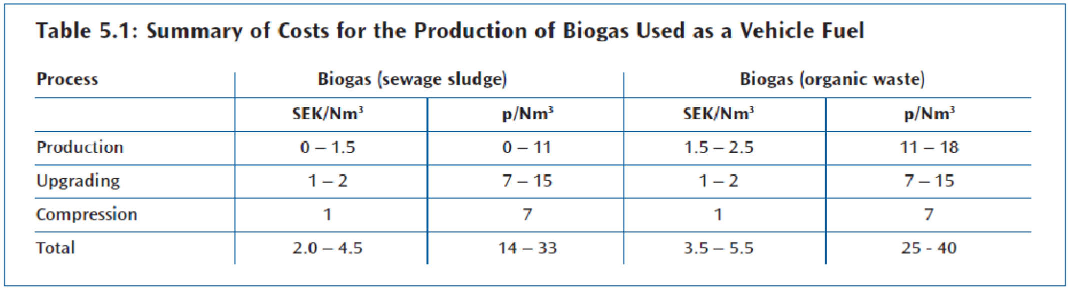


Table 5.1: Summary of Costs for the Production of Biogas Used as a Vehicle Fuel

Process	Biogas (sewage sludge)		Biogas (organic waste)	
	SEK/Nm³	p/Nm³	SEK/Nm³	p/Nm³
Production	0 – 1.5	0 – 11	1.5 – 2.5	11 – 18
Upgrading	1 – 2	7 – 15	1 – 2	7 – 15
Compression	1	7	1	7
Total	2.0 – 4.5	14 – 33	3.5 – 5.5	25 - 40

references:
EPUK, "Biogas as a Road Transport Fuel, National Society for Clean Air and Environmental Protection", www.environmentalprotection.org/uk, 6/06
iSOC Technology, "MSDS: Methane", www.isocinfo.com, 12/09
Feasibility Study for a Large Scale Regional Anaerobic Digestion Facility", 2009

Properties

Hydrogen is an asphyxiant and highly flammable.

Production of bio-hydrogen is in research phase

"Researchers at The National Renewable Energy Laboratory (NREL) are developing advanced processes to produce hydrogen economically from sustainable resources. These R&D efforts include:
Fermentation
Biological Water Splitting
Photoelectrochemical Water Splitting
Conversion of Biomass and Wastes
Solar Thermal Water Splitting
Renewable Electrolysis."
Reference:
http://www.nrel.gov/hydrogen/proj_production_delivery.html#water

"Currently most hydrogen is produced from fossil fuels (e.g. steam reforming of natural gas). Prototype hydrogen vehicles have been developed, but there is currently no significant infrastructure for distributing hydrogen as a transport fuel, and in-vehicle storage capacity is still an issue. In addition, hydrogen fuel cells are expensive to produce and fragile, and have a relatively short service life."
"Extensive research is being carried out on chemical storage of hydrogen"
Reference:
European Biofuels Technology Platform, funded by the EC under Grant Agreement 241269,
Last updated February 23, 2010
http://www.biofuelstp.eu/hydrogen.html

Chemical Hydrogen Storage R&D

"DOE's chemical hydrogen storage R&D is focused on developing low-cost energy-efficient regeneration systems for these irreversible hydrogen storage systems. Significant technical issues remain regarding the regeneration of the spent material and whether regeneration can be accomplished on-board. In addition, life cycle cost analysis is needed to assess the costs of regeneration. Currently, borohydride-water systems, magnesium-hydride slurries, and innovation beyond boron are under investigation."
"Research is carried out through DOE's Chemical Hydrogen Storage Center of Excellence and Independent Projects overseen by the Fuel Cell Technologies Program."
Reference:
DOE Fuel Cell Technologies Program
http://www1.eere.energy.gov/hydrogenandfuelcells/storage/hydro_storage.html

Hydrogen Infrastructure

"Germany to Launch Nationwide Hydrogen Fuel Network by 2015
Signs a memorandum of understanding with eight industrial partners, including Daimler, Shell, and Total."
Reference:
http://www.nacsonline.com/NACS/News/Daily/Pages/ND0917097.aspx

Other

E.54. Hydrogen--Compatibility and Environmental Issues

Incompatible Materials

elastomers	metals*
	cast iron
	nickel steel

Compatible Materials

elastomers	metals*
	stainless steel
	carbon steel
	aluminum
	copper titanium alloy

Advantages

Disadvantages

Highly flammable
Must be compressed to a liquid for ease of transport

Environmental/Health concerns

Flammable

Compatibility/Fungibility issues

Must be compressed to a liquid for ease of transport
Trucks carrying hydrogen not permitted in tunnels

notes: *high strength steels (above 100ksi) are more suscpetible to hydrogen embrittlement, therefore low strength steels are recommended for hydrogen pipelines

references:
BOC Gases, "MSDS: Hydrogen", www.fergusongases.com, 6/7/1996
Gillette and Kolpa, Argonne National Laboratories, "Overview of Interstate Hydrogen Pipeline Systems", www.corridoreis.anl.gov, 11/07