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COAL AND NATURAL GAS TO LIQUID ALKANES BY HYBRID PROCESSING

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Abstract

This report describes a process to convert coal and natural gas to a mixture of liquid hydrocarbons, which is intended to be sold as a feedstock for a refinery. Given that the region has a large amount of coal production and sits atop the Marcellus shale with its expanding natural gas production, as well as the proximity to refineries in Ohio, southwestern Pennsylvania is a natural location for such a venture.

2600 tons per day of coal and 66 million standard cubic feet per day of natural gas are converted to syngas in separate, parallel process trains. The hydrogen rich natural gas syngas is mixed with the hydrogen lean coal syngas to give the desired syngas composition. Fischer-Tropsch chemistry is used to convert syngas with a 2 to 1 H_2:CO molar ratio to a distribution of alkanes. The alkanes are separated to give 15,500 barrels per day of liquid product.

The total capital investment of the project was estimated to be $1,308 million. Using the EIA baseline projection for the price of oil and a 15% discount rate, the project is expected to have a net present value of -$258 million, with an internal rate of return of 11%. The profitability of the project is especially dependent on the price of oil and the total capital investment.

Department of Chemical and Biomolecular Engineering
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Senior Design Report, 2012

Coal and Natural Gas to Liquid Alkanes by Hybrid Processing

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John A. Wismer

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April 3, 2012

Dear Professor Seider, Professor Fabiano, and Mr. Wismer,

The following is our report for our senior design project, “Coal and Natural Gas to Liquid Alkanes by Hybrid Processing,” proposed by Mr. John Wismer. The project called for the design of a process that can convert both Coal and Natural gas into a liquid hydrocarbon stream. The products can be shipped to nearby refineries in Ohio for further refining and processing into fuel.

The report primarily focuses on a preliminary plant design and profitability analysis. The plant has an estimated life of 30 years and utilizes 66 million standard cubic feet per day of Marcellus shale gas and 2,600 tons per day of Pennsylvania bituminous coal. The liquid product would be 15,500 barrels per day of liquid alkanes. The plant would require a total capital investment of $1,309 million. Using the Energy Information Administration’s Annual Energy Outlook for 2012 baseline oil price projections and a discount rate of 15%, the project has a net present value of -$285 million, with an internal rate of return of 11%.

While the process is not profitable under the baseline assumptions and discount rate, further analysis of the costs, price projections, and the capital position of interested companies may make it worthwhile to proceed.

Sincerely,

Patrick Driscoll	Igor Gonzales
Bill Matczak	Tommy Puckette

Table of Contents

Section 1 - Abstract

This report describes a process to convert coal and natural gas to a mixture of liquid hydrocarbons, which is intended to be sold as a feedstock for a refinery. Given that the region has a large amount of coal production and sits atop the Marcellus shale with its expanding natural gas production, as well as the proximity to refineries in Ohio, southwestern Pennsylvania is a natural location for such a venture.

2600 tons per day of coal and 66 million standard cubic feet per day of natural gas are converted to syngas in separate, parallel process trains. The hydrogen rich natural gas syngas is mixed with the hydrogen lean coal syngas to give the desired syngas composition. Fischer-Tropsch chemistry is used to convert syngas with a 2 to 1 H_2:CO molar ratio to a distribution of alkanes. The alkanes are separated to give 15,500 barrels per day of liquid product.

The total capital investment of the project was estimated to be $1,308 million. Using the EIA baseline projection for the price of oil and a 15% discount rate, the project is expected to have a net present value of -$258 million, with an internal rate of return of 11%. The profitability of the project is especially dependent on the price of oil and the total capital investment.

Section 2 - Introduction

Conversion of coal to liquid hydrocarbons (CTL) and natural gas to liquid hydrocarbons (GTL) have each been successfully implemented on a commercial scale as individual operations. Rising oil prices have made these technologies an attractive proposition. To date, no commercial project makes use of a hybrid coal and natural gas to liquids process.

In order to achieve this conversion, the natural resources must first be converted to synthesis gas (syngas). For natural gas this is generally achieved through catalyzed steam methane reforming. The overall chemical equation for this process is:

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

Syngas produced from coal utilizes the process known as coal gasification. It is the equivalent of steam methane reforming for coal. The reaction for this process is:

$$CH_x + H_2O \rightarrow (1+0.5x)H_2 + CO \qquad 0.35 < x < 0.85$$

Syngas is a mixture of hydrogen and carbon monoxide which can then be put through a Fischer-Tropsch reactor and converted to a distribution of hydrocarbons. An important note is that a side reaction, known as the water gas shift reaction, also occurs during the reforming and gasification process. This equilibrium reaction:

$$H_2O + CO \leftrightarrow H_2 + CO_2$$

is an unwanted side reaction in this process because carbon is lost as carbon dioxide rather than converted to alkanes.

Syngas can be converted to linear hydrocarbon chains using Fischer-Tropsch chemistry:

$$(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O$$

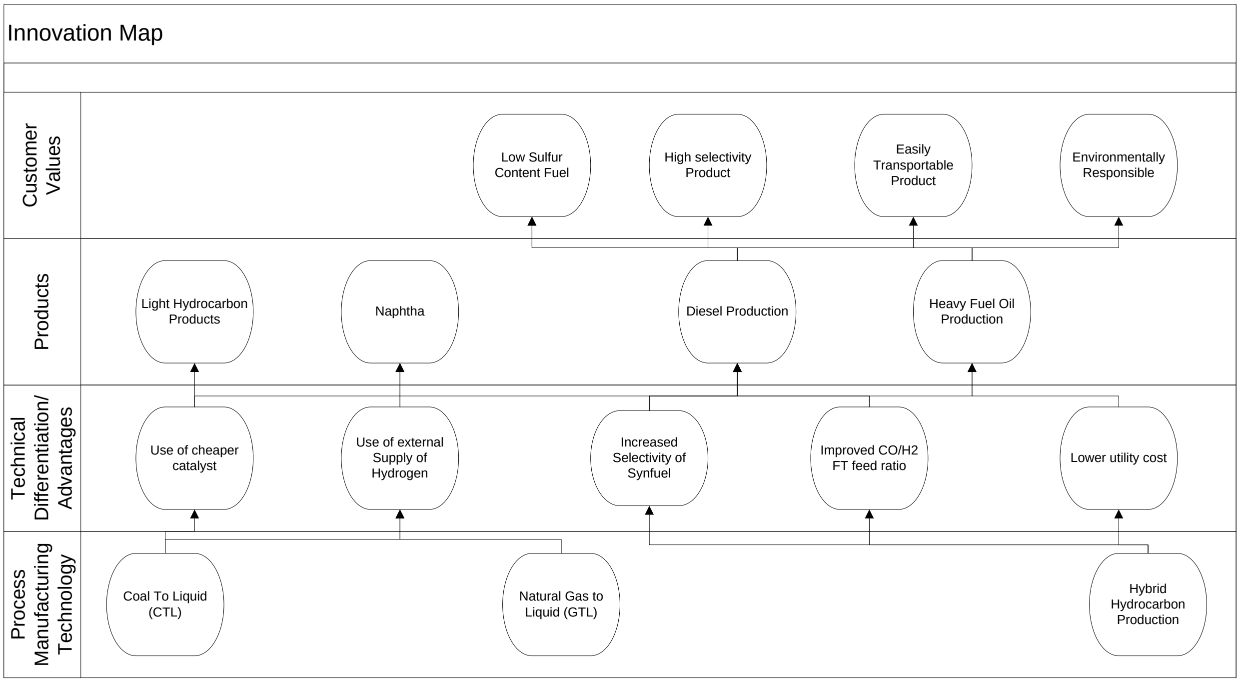
This chemistry produces a distribution of linear alkanes with varying chain lengths. The distribution depends on the operating conditions and the composition of the syngas. The desired reactant ratio of hydrogen to carbon monoxide is two to one.

One of the main issues associated with producing crude oil from either natural gas or coal is that the syngas produced is too rich or too lean in hydrogen gas respectively. For a system that strictly utilizes coal as the feed material, the water gas shift reaction is often used to provide additional hydrogen.

Pennsylvania and West Virginia present a unique opportunity because they possess both coal reserves and natural gas reserves through Marcellus shale. These resources are also located relatively close to Ohio refineries. This creates the prospect to implement a hybrid system that utilizes both coal and natural gas as a feed stock. The goal of the hybrid process is to produce synthesis gas with a CO to H_2 ratio of two to one. Although the Fischer-Tropsch reactor produces a spread of different hydrocarbons, the desired products include diesel fuel (molecules ranging from approximately $C_{12}H_{26}$ to $C_{18}H_{38}$), gasoline (ranging from C_5H_{12} to $C_{11}H_{24}$), and waxes ($C_{19}H_{40}$ and longer). The final product of this 15,500 barrel per day facility can be sold to a refinery for further processing through the use of nearby railroad lines.

This report details the design and economics of the coal and natural gas to liquid alkane’s process, a hybrid synthetic fuel production process. The feasibility of such a process is then evaluated.

Section 3 - Innovation Map



Producing high quality synthetic fuel traditionally means utilizing one feed stock source. Coal to Liquid (CTL) distinguishes itself by utilizing strictly a coal-based feedstock, while Gas to Liquid utilizes only natural gas as a feed. The hybrid system is unique in that it uses both coal and natural gas as feed to the process. All three processes can produce a similar array of products, but the hybrid system possesses significant advantages over traditional approaches. This combined system allows for an improved feed ratio to the Fischer-Tropsch reactor. Additionally, the system minimizes the amount of heat utility required throughout the process by utilizing heat produced in the coal gasifier to heat sections of the steam methane reformer. The process also utilizes excess heat to produce steam and power for the entire process. The hybrid system also implements a new technology, a micro-channel Fischer-Tropsch reactor, which allows for increased product selectivity. All of this leads to a product with low sulfur content that can be easily sold to a refinery.

Section 4 - Market and Competitive Analysis

In 2010, 9,443,000 barrels per day of crude were produced in the United States, about half of the total U.S. consumption of 19,157,000 barrels per day. Oil prices have risen significantly in recent years from $27.72 per barrel in 2000 to $102.67 per barrel in 2011. The market for crude oil is therefore very large and lucrative.

Pennsylvania is currently a major producer of coal, and recent gas discoveries and advances in drilling technology are expected to result in expanding natural gas production. In 2010, Pennsylvania produced over 58 million tons of coal, making it the second largest producer of coal in the country. Almost all of that coal was produced in counties in the southwestern corner of the state. Additionally, in 2009, the Department of Energy estimated that there is 262 trillion cubic feet of recoverable gas in the Marcellus Shale, a huge upward revision of the amount of gas. Advances in directional drilling and hydraulic fracturing, developed while drilling the Barnett Shale in northern Texas, have made wells more productive and economical.

Currently, the US has a refining capacity of around 17 million barrels per day, with over 500,000 barrels per day in nearby Ohio. It is expected that these refineries can easily handle the output from this small 15,000 barrel per day project.

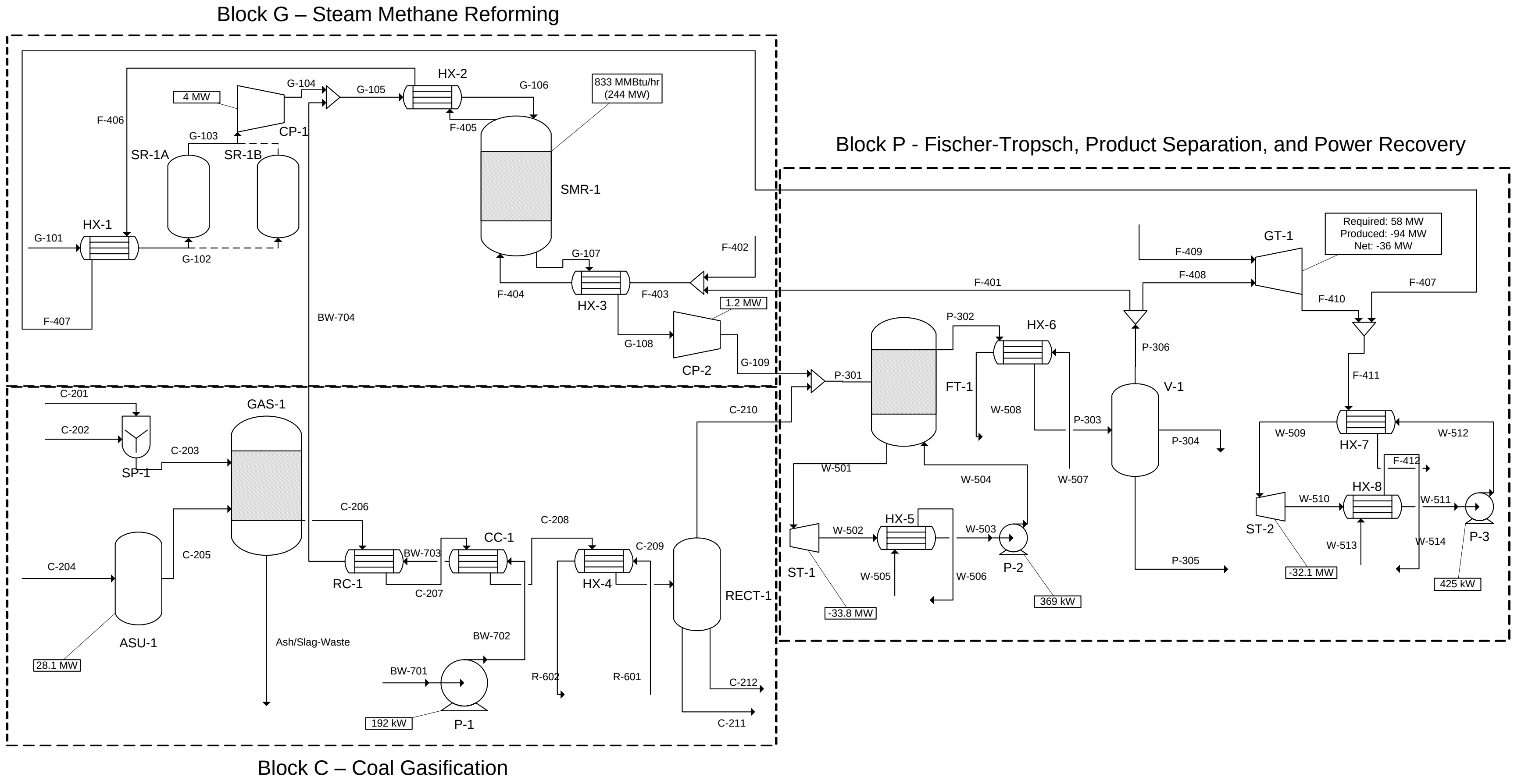
While there are currently no hybrid Coal and Natural Gas to Liquids projects on the commercial scale, there are several Coal to Liquids and Natural Gas to Liquids plants that are in operation. These projects make use of the same Fischer-Tropsch chemistry used in this design.

The largest CTL undertaking is run by Sasol in South Africa. This operation, which was originally commissioned in 1955 and is still in operation, produces more than 150,000 barrels per day of synthetic petroleum products.

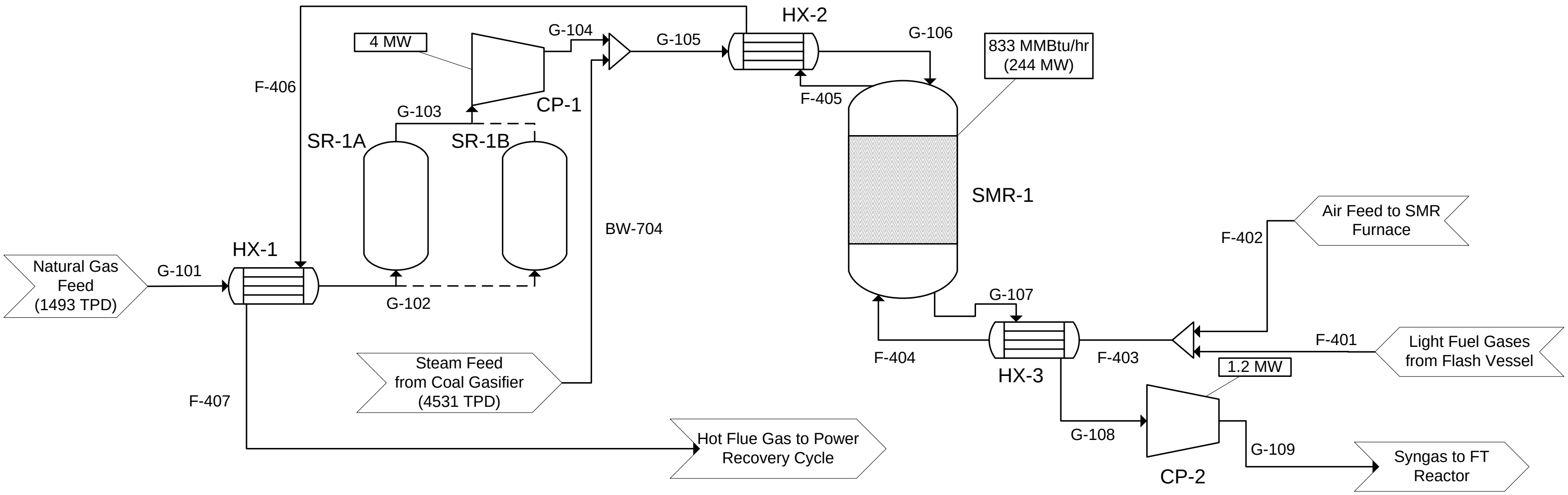
Oryx GTL, joint venture between Sasol and Qatar Petroleum, produces 34,000 barrels per day of liquids from natural gas. PetroSA operates a 35,000 barrel per day GTL plant in Mossel Bay, South Africa.

Section 5 - Process Flow Diagrams and Material Balances

Overall Process



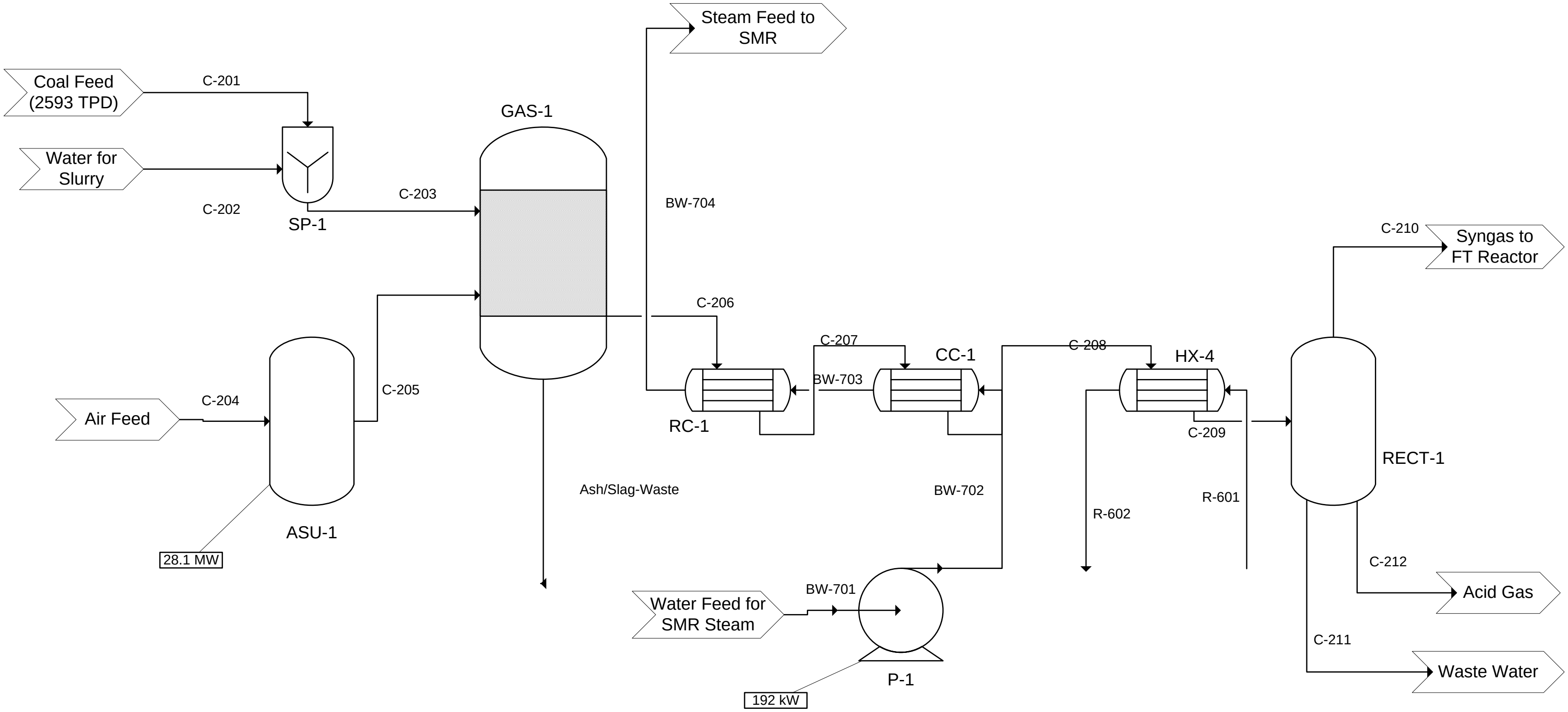
Block G • Natural Gas Reforming



Block G

Stream	G-101	G-102	G-103	G-104	G-105	G-106	G-107	G-108	G-109	F-401	F-402	F-403	F-404	F-405	F-406	F-407	BW-704
Temperature (°F)	70	700	700	834	403	1200	1800	594	607	81	77	77	1581	2000	1186	1007	434
Pressure (psia)	218	213	213	368	363	358	356	351	363	218	44	44	39	39	34	29	363
Mole Flow (lbmol/hr)																	
CO_2	3	3	3	3	3	3	1776	1776	1776	1238	0	1238	1238	4202	4202	4202	0
CO	0	0	0	0	0	0	4864	4864	4864	1794	0	1794	1794	0	0	0	0
N_2	225	225	225	225	225	225	225	225	225	182	22444	22626	22626	22626	22626	22626	0
H_2O	0	0	0	0	20959	20959	12549	12549	12549	17	0	17	17	5384	5384	5384	20958
H_2	0	0	0	0	0	0	21684	21684	21684	3595	0	3595	3595	0	0	0	0
O_2	0	0	0	0	0	0	0	0	0	0	5966	5966	5966	1215	1215	1215	0
H_2S	0.03	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CH_4	6986	6986	6986	6986	6986	6986	349	349	349	300	0	300	300	0	0	0	0
C_2H_6-C_5H_{12}	189	189	189	189	189	189	189	189	189	287	0	287	287	0	0	0	0
C_6H_{14}-$C_{11}H_{24}$	0	0	0	0	0	0	0	0	0	15	0	15	15	0	0	0	0
$C_{12}H_{26}$-$C_{20}H_{42}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$C_{21}H_{44}$+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Flow (lbmol/hr)	7404	7404	7404	7404	28363	28363	41637	41637	41637	7428	28411	35838	35838	33428	33428	33428	20958
Total Flow (lb/hr)	124451	124451	124450	124450	502028	502028	502028	502028	502028	135006	819659	954665	954665	954665	954665	954665	377569
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.84
Liquid Frac	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16
Density (lb/cuft)	0.666	0.286	0.286	0.442	0.759	0.357	0.176	0.375	0.383	0.689	0.218	0.202	0.047	0.042	0.054	0.052	0.906

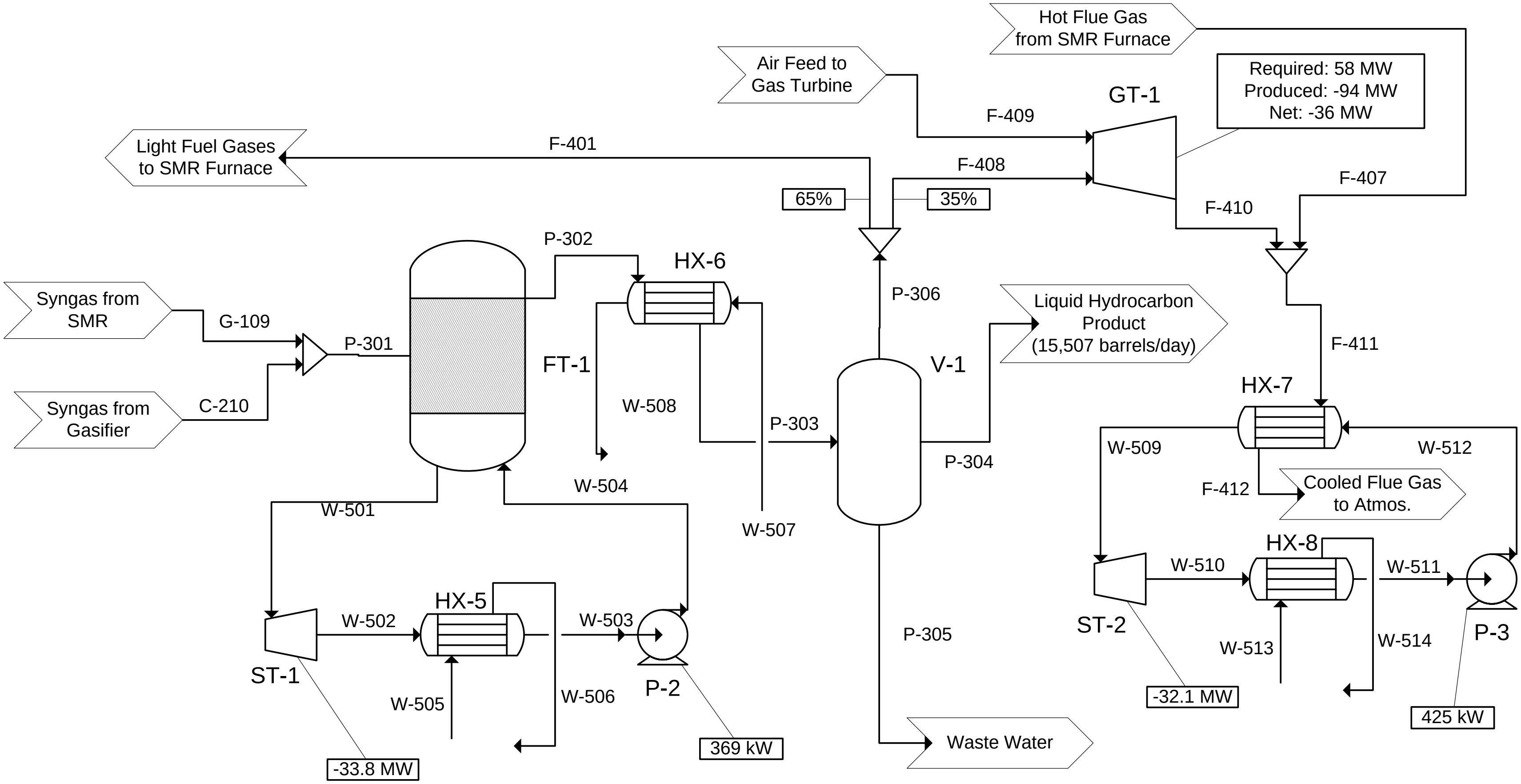
Block C • Coal Gasification



Block C

Stream	**C-201**	**C-202**	**C-203**	**C-204**	**C-205**	**C-206**	**C-207**	**C-208**	**C-209**	**C-210**	**C-211**	**C-212**	**BW-701**	**BW-702**	**BW-703**	**BW-704**
Temperature (°F)	450	794	77	77	77	2400	1250	212	32	32	32	32	77	78	434	434
Pressure (psia)	353	353	353	15	353	377	372	367	362	362	362	362	15	363	363	363
Mole Flow (lbmol/hr)																
CO_2	0	0	0	0	0	1144	1144	1144	1144	172	0	972	0	0	0	0
CO	0	0	0	0	0	8947	8947	8947	8947	8947	0	0	0	0	0	0
N_2	0	0	0	21996	0	55	55	55	55	55	0	0	0	0	0	0
H_2O	0	2890	2890	0	0	3552	3552	3552	5	5	3547	0	20958	20958	20958	20958
H_2	0	0	0	0	0	5942	5942	5942	5942	5942	0	0	0	0	0	0
O_2	0	0	0	5847	5847	0	0	0	0	0	0	0	0	0	0	0
H_2S	0	0	0	0	0	71	71	71	71	0	0	71	0	0	0	0
CH_4	0	0	0	0	0	17	17	17	17	17	0	0	0	0	0	0
C_2H_6-C_5H_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_6H_{14}-$C_{11}H_{24}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$C_{12}H_{26}$-$C_{20}H_{42}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$C_{21}H_{44}$+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal Mass Flow (lb/hr)	216053	0	216053	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Flow (lbmol/hr)	-	2890	2890	27843	5847	19728	19728	19728	16181	15138	3547	1043	20958	20958	20958	20958
Total Flow (lb/hr)	216053	52069	268122		187102	381133	381133	381133	317235	272030	63898	45205	377569	377569	377569	377569
Vapor Frac	0	1	0.00	1	1	1	1	0.9	1	1	0	1	0	0	0.19	0.84
Liquid Frac	0	0	0.19	0	0	0	0	0.1	0	0	1	0	1	1	0.81	0.16
Density (lb/cuft)	82.652	0.486	66.696		1.986	0	0	1	1	1	62	4	53	53	4	1

Block P • Fischer-Tropsch, Product Separation, and Power Recovery



Block P

Stream	G-109	C-210	P-301	P-302	P-303	P-304	P-305	P-306	F-401	F-408	F-409	F-410	F-411	F-412
Temperature (°F)	607	32	464	464	81	81	81	81	81	81	77	1477	1251	320
Pressure (psia)	363	362	362	362	357	218	218	218	218	218	15	29	29	24
Mole Flow (lbmol/hr)														
CO_2	1776	172	1948	1948	1948	42	5	1901	1238	663	0	2252	6455	6455
CO	4864	8947	13811	2762	2762	6	0	2756	1794	962	0	0	0	0
N_2	225	55	280	280	280	1	0	279	182	97	27758	27855	50482	50482
H_2O	12549	5	12554	23602	23602	10	23566	26	17	9	0	2886	8270	8270
H_2	21684	5942	27626	5529	5529	7	0	5522	3595	1927	0	0	0	0
O_2	0	0	0	0	0	0	0	0	0	0	6460	3913	5128	5128
H_2S	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CH_4	349	17	367	463	463	3	0	460	300	161	0	0	0	0
C_2H_6-C_5H_{12}	189	0	189	515	515	74	0	441	287	154	0	0	0	0
C_6H_{14}-$C_{11}H_{24}$	0	0	0	300	300	277	0	22	15	8	0	0	0	0
$C_{12}H_{26}$-$C_{20}H_{42}$	0	0	0	210	210	210	0	0	0	0	0	0	0	0
$C_{21}H_{44}$+	0	0	0	141	141	141	0	0	0	0	0	0	0	0
Total Flow (lbmol/hr)	41637	15138	56774	35749	35749	770	23571	11408	7428	3981	34218	36907	70335	70335
Total Flow (lb/hr)	502028	272030	774058	773753	773753	141640	424751	207362	135006	72356	984300	1056660	2011320	2011320
Vapor Frac	1	1	1	0.994	0	0	0	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0.006	1	1	1	0	0	0	0	0	0	0
Density (lb/cuft)	0.383	1.239	0.499	0.837	4.078	39.039	52.928	0.689	0.689	0.689	0.072	0.040	0.044	0.080

Stream	W-501	W-502	W-503	W-504	W-505	W-506	W-507	W-508	W-509	W-510	W-511	W-512	W-513	W-514
Temperature (°F)	446	229	214	215	90	120	40	70	1022	402	214	216	90	120
Pressure (psia)	363	20	15	368	20	15	20	15	725	20	15	730	20	15
Mole Flow (lbmol/hr)														
CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H_2O	40076	40076	40076	40076	1236166	1236166	1084586	1084586	21196	21196	21196	21196	772135	772135
H_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H_2S	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_2H_6-C_5H_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_6H_{14}-$C_{11}H_{24}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$C_{12}H_{26}$-$C_{20}H_{42}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$C_{21}H_{44}$+	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Flow (lbmol/hr)	40076	40076	40076	40076	1236166	1236166	1084586	1084586	21196	21196	21196	21196	772135	772135
Total Flow (lb/hr)	721985	721985	721985	721985	22275719	22275719	19544244	19544244	381846	381846	381846	381846	13913866	13913866
Vapor Frac	1	1	0	0	0	0	0	0	1	1	0	0	0	0
Liquid Frac	0	0	1	1	1	1	1	1	0	0	1	1	1	1
Density (lb/cuft)	0.747	0.053	49.932	49.945	62.400	62.400	62.400	62.400	0.852	0.038	49.932	49.954	62.400	62.400

Section 6 - Process Description

Block G • Natural Gas Reforming

The principal unit in this section is the SMR reactor (SMR-1). SMR-1 is composed of a series of 24-foot long tubes arranged in a parallel fashion in order to divide the flow of natural gas and steam entering the vessel. The tubes are aligned in an inline fashion to promote better radiant heat transfer and thus provide the necessary energy for the endothermic reaction.

The natural gas first enters the heat exchanger HX-1 in order to raise the temperature up to 700°F before entering a desulfurization unit. The desulfurization units use a solid adsorbent bed to adsorb the sulfur (mainly present as H_2S). The adsorbent used is SR-110, which is almost entirely composed of ZnO. The process flow diagram shows two vessels connected in parallel with a set of valves linking the vessels to the gas stream. Once the bed is saturated, it is regenerated using hot dilute oxygen. The presence of multiple tanks allows for continuous processing of natural gas by the system. One desulfurization unit is always functioning while the other is either being regenerated or idle. It is necessary to remove the majority of the sulfur because the catalyst used in SMR-1 (nickel oxide on a calcium aluminate support) is easily poisoned by sulfur. It is susceptible to sulfur poisoning at levels above 0.5 ppm w/w sulfur.

Once exiting the desulphurization unit, the natural gas is compressed from a pressure of 218 to 368 psi. This exit pressure is slightly higher than the operating pressure of the SMR reactor. This is done in order to factor in the pressure drop across HX-2 and ensure that the natural gas feed enters the reactor at appropriate conditions. The compressed gases are mixed with steam fed from the coal gasifier (stream BW-704). The combined stream enters heat exchanger HX-2, where its temperature is raised to 1200°F before entering the SMR reactor. This is done as a way to economize the amount of heat required as an input to SMR-1 reactor. The natural gas stream is fed through the top of the reactor and passes through packed columns. After going through the reactor, the product syngas is first passed through heat exchanger HX-3 in order to both cool the products before sending them to the FT reactor, as well as preheat the incoming mixture of air and light hydrocarbons. Finally the stream is put through a compressor in order to raise the stream’s pressure from 272 to 363 psi, the operating pressure of the FT reactor. The syngas stream is then sent to the FT reactor.

Stream F-403 is preheated to 1783°F in HX-3 and is then fed to the SMR reactor via burner heads. The combustion of the light hydrocarbons provides the heat necessary for the reforming reaction. The hot flue gases then leave SMR-1. They enter HX-2 and are used to preheat stream G-105. The hot gases next enter HX-1, contributing to additional preheating of the natural gas stream. Finally the hot exhaust gases leave HX-1 in stream F-407, are mixed with the hot exhaust gases from GT-1, and are passed through a heat exchanger (HX-7) which transfers the gases' heat energy to cooling water in a cooling loop. The gases finally are released to the atmosphere at 320°F.

Block C • Coal Gasification

The major unit in this section is the coal gasifier (GAS-1) which converts coal to syngas. This section also includes the air separation unit that provides oxygen to the gasifier, the series of heat exchangers to cool the syngas, and the Rectisol unit for removing H_2S from the coal syngas prior to the Fischer-Tropsch reactor.

2600 tons per day of coal (C-201) are received and processed in unit SP-1, which represents all of the necessary solids handling equipment. The coal is mixed with 625 tons per day of water (C-202) to make the slurry. An air separation plant ASU-1 takes air and separates out oxygen for the gasifier. The compressors of this unit are a major utility cost, requiring 28 MW.

The gasifier GAS-1 takes the oxygen and the coal-water slurry and produces hot syngas in stream C-206 at 2400°F and 377 psi. Details for this unit are provided in the reactor design section of this report on page 25.

The hot syngas is cooled in two heat exchangers, producing steam for the steam methane reformer in the process. Radiant cooler RC-1 drops the temperature from 2400°F in stream C-206 to 1250°F in stream C-207. Next, the convective cooler drops the temperature down to 212°F in stream C-208, preheating the pressurized boiler water. Almost 500 tons per day of nearly saturated steam are generated in these two exchangers for the reforming process.

Prior to being treated to remove sulfur, the syngas must be cooled to near the operating temperature of the sulfur removal process. This is accomplished in HX-4, where the syngas flows counter-current to refrigerant R-134a, lowering the temperature to 32°F in stream C-209.

The final unit in this section of the process is sulfur removal in the Rectisol unit, RECT-1. This unit uses cold methanol to remove essentially all of the H_2S, in addition to some CO_2. While the refrigeration required for this type of unit makes it more expensive than some other types of sulfur removal units, it is necessary in order to remove the sulfur compounds to below the tolerance of the Fischer-Tropsch catalyst (1 ppm).

Block P • Fischer-Tropsch, Product Separation, and Power Recovery

This section converts syngas produced from Blocks G and C to liquid hydrocarbons. This section also includes two power generation units that utilize hot gases to spin turbines and to generate steam.

First, streams G-109 and C-210 are combined in order to ensure a proper H_2 to CO feed ratio of 2:1 to the FT reactor. The combined stream, P-301, is fed into the reactor. The Fischer-Tropsch reaction is exothermic and must operate under isothermal conditions in order for the distribution of products to be properly controlled. A cooling loop is used to keep the temperature of the reactor constant. Stream generated in this loop is used to drive a turbine, producing electricity. Cooling water stream W-504 enters the FT reactor at a temperature of 215°F and exits as steam at a temperature of 446°F in stream W-501. The steam in stream W-501 passes through a condensing turbine and a heat exchanger in order to produce power and ensure complete condensation of the steam. The condensed steam is then pressurized to 368 psi using pump P-2 and then circulated back to the FT reactor. Both the reactor side and cooling side run at the same pressure in order to minimize the physical strain on the F-T micro-channels. The hydrocarbon products exiting in stream P-302 pass through heat exchanger HX-6 in order to lower the temperature to that desired for flash separation. HX-6 is cooled using chilled water entering in stream W-507 at 40°F and exiting in stream W-508 at 70°F. Stream P-303 exits HX-6 at 81°F and 357 psi. Just before entering V-1, the flash vessel, the stream passes through a valve which expands the stream to 218 psi.

V-1 is a three-outlet vapor-liquid-liquid vessel where water and light hydrocarbon gases are separated from the liquid hydrocarbons and waxes. Stream P-305 contains waste water and travels from the bottom of V-1 to wastewater treatment. Stream P-304 contains the liquid product and is sent from the side of V-1 to storage tanks or railcars. The light gases leaving the top of V-1 in stream P-306 are split such that 65% is sent in stream F-401 to be combusted as fuel in SMR-1 and 35% is sent in F-408 to a gas turbine (GT-1). F-408 mixes with air in stream F-409 in GT-1. This unit first compresses the air, mixes and combusts the air and fuel, and extracts power from the resulting hot flue gas in a turbine. The exiting hot flue gas is then combined with stream F-407, which contains hot flue gas from Block G, and used to produce steam. This steam is used in a Rankine cooling cycle that is very similar to the one used to cool the FT-1. Steam is generated from water in HX-7, expanded and cooled in ST-2, condensed in HX-8 via cooling water, repressurized in P-3, and sent back to HX-7 as water. Finally, the cooled flue gas is released from HX-7 to the atmosphere.

Product Description

This process' product leaves the flash vessel (V-1) as Stream P-304. It has a mass flow rate of 141628 lb/hr, a temperature of 81 F, and a pressure of 15 bar. The composition of the product is shown in Figure 1. As shown, the product contains primarily gasoline, diesel, and waxy linear alkanes. This is a partially refined crude oil that contains little to no branched or cyclic alkanes, olefins, aromatics, other unsaturated hydrocarbons, oxygen-containing molecules, or sulfur. The lack of nonlinear unsaturated hydrocarbons is due to Fischer-Tropsch chemistry which produces solely linear hydrocarbons. The clean product produced will be much more easily processed by refineries. Local railroads will be utilized to ship the oil product in tank cars to nearby refineries.

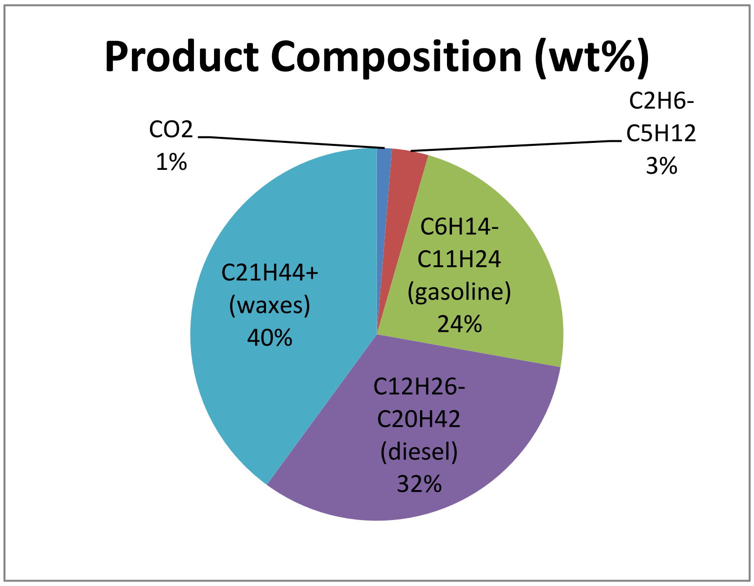


Figure 1 - Process product composition by weight. The product is a partially refined crude oil.

Section 7 - Reactor Design

Steam Methane Reformer

The steam methane reforming reaction is carried out in tubular channels packed with ReforMax 330 LDP (a nickel oxide catalyst on a calcium aluminate support). The steam methane reforming (SMR) reaction occurs endothermically as the feed of methane and steam enters the top of the reactor channels through inlet pigtails. The pigtails evenly disperse the reactants through each one of the packed tubes. The outsides of the packed vertical tubes are exposed to radiant and convective heat generated through a series of burners. The burners are located at the top of the unit. Figure 2, seen below, illustrates the general setup within the reactor facility.

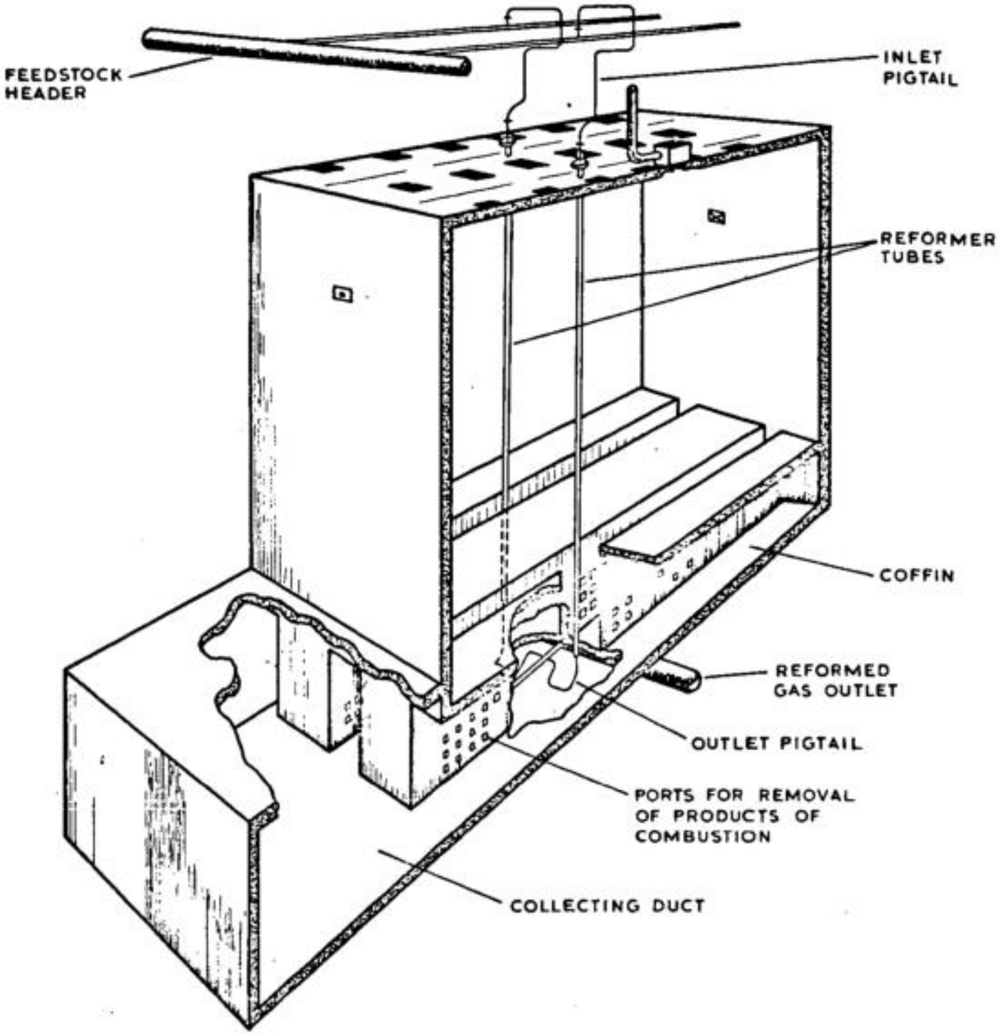


Figure 2 - Schematic of an SMR (Blythe et al.).

The calculations and kinetic model used to size the steam reformer for this process are included in the Appendix on page 97. Results from the kinetic model indicate that a reformer with 3 inch inner diameter and 24 foot long tubes must contain 1511 tubes aligned in rows. This size allows for 95 mol% conversion of methane at an operating temperature of 1800°F. Reactants are preheated to 1200°F and enter the reformer at 25 bar. The natural gas and steam are combined prior to entering the SMR. The overall process produces a molar ratio of H_2 to CO of 4.45 to 1. Some of the light hydrocarbon gases produced from the FT reactor are recycled and used as fuel in the SMR furnace burners. The effluent streams from the reactor are used to preheat the light hydrocarbon and air mixture as it enters the SMR furnace. In order to properly initiate the process (plant start-up) it will be necessary to combust some of the natural gas as a fuel source until the effluent from the SMR reactor cycles back to the furnace.

Coal Gasification Reactor

The coal gasifier selected for this process is a General Electric, slurry-fed, entrained flow gasifier. This technology was originally developed by Texaco beginning in the 1940s. A major advantage of this type of gasifier is the number of commercial sized units that have been successfully put into operation. For example there is a 2500 ton per day unit in operation as part of an integrated coal gasification combined cycle (IGCC) power plant operated by Tampa Electric, which is of similar size to the one used in this process.

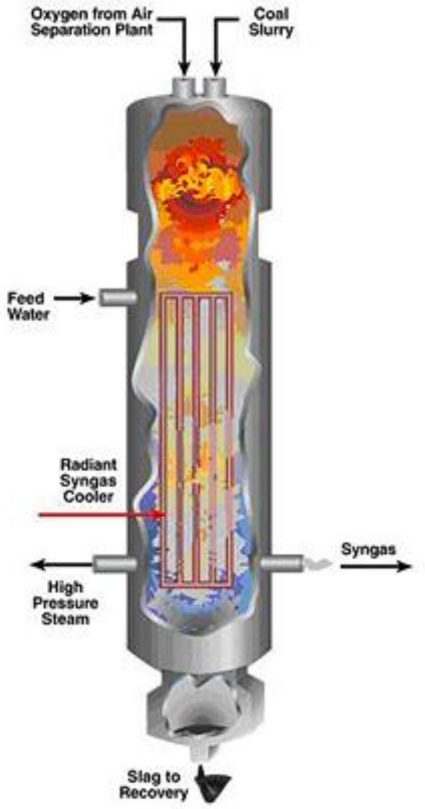


Figure 3 - GE Gasifier (netl.doe.gov).

In this type of gasifier, coal is fed into the top of the reactor as a coal and water slurry. Oxygen from an air separation unit is supplied at the top of the unit, and partial oxidation of the coal provides energy for the endothermic gasification reaction. The water from the slurry provides the steam for the gasification reactions to produce hot syngas. The reactor operates at

2400°F and 815 psi.

The GE technology allows for different modes to cool the hot syngas, ranging from simple quenching, to radiant and convective cooling of the gas for heat recovery. For this process, the gasifier will be operated with a radiant cooler that brings the syngas from 2400°F to 1250°F, raising steam for the methane reformer. A convective cooler drops the temperature further, to 212°F, preheating the feed water to be boiled in the radiant cooler. Solid waste of inert slag exits the bottom of the reactor.

The gasifier for this process handles 2600 tons per day of coal, requiring about 600 tons per day of water and 2300 tons per day of oxygen. The product syngas has a hydrogen to carbon monoxide ratio of about 0.66. The basis for this data is an Aspen model that is summarized in the Appendix on page 101.

Fischer-Tropsch Reactor

The Fischer-Tropsch reaction is carried out in a micro-channel design reactor. The FT reaction is exothermic, possessing a heat of reaction of -170kJ/mol CO. As a result, the reactor requires effective and continuous cooling in order to maintain an appropriate operating temperature of 464°F. Heat removal is accomplished utilizing cooling water that is pumped at a rate of 721900 lb/hr and a pressure of 363 psi. The water flows in a counter current arrangement in order to

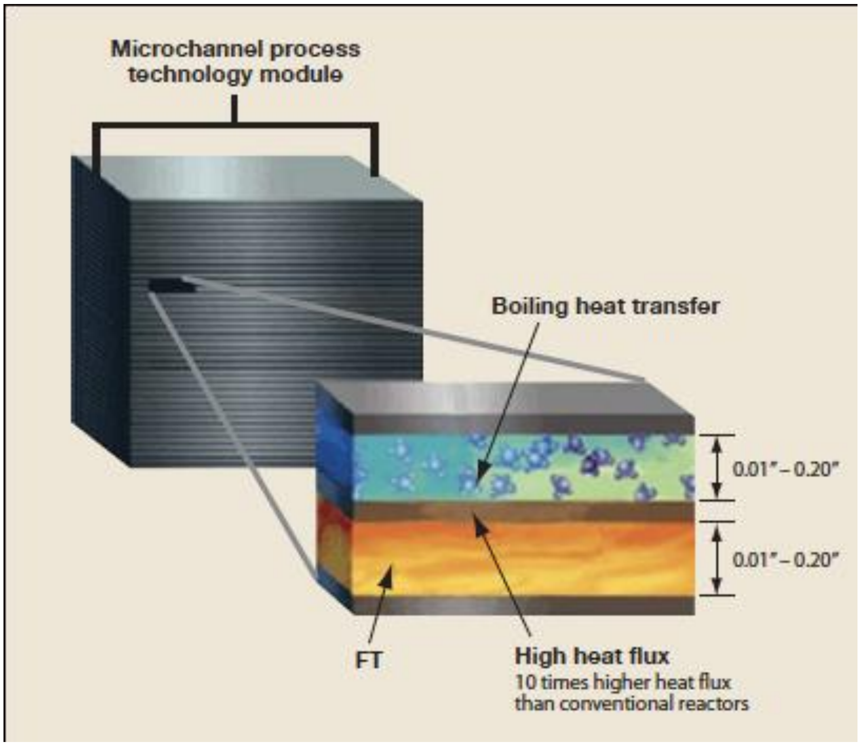


Figure 4 - FT microchannel cutaway (Atkinson and McDaniel).

maximize its cooling efficacy. The arrangement of the micro-channel reactor is shown in Figure 4. As seen in the figure, micro-channel reactors consist of a series of millimeter wide channels arranged into a module configuration. The micro-channels are formed using stacks of parallel plates with spacers in between in order to create the micro-channel. Each module consists of 19415 channels. A total of 24 modules are required in order to process the required flow rate of 774000 lb/hr syngas. The reactor module measures 1m high, 1.5 m wide, and 1.5 m long. The individual reaction channels are 0.0374 in high, 0.669 in wide and 4.593 ft long, while the cooling water channels are 0.118 in wide, 4.593 ft long, 0.0374 in high. The micro-channels are arranged in an alternating fashion within a layer. The layers are staggered such that a reactor channel is in contact with cooling channels both above and below it.

The feed to the reactor is produced by the SMR reactor (SMR-1) and the coal gasifier (GAS-1). It enters the FT reactor at a pressure of 362 psi and a temperature of 464°F. The feed to the FT reactor consists of 55700 lb/hr of hydrogen and 386800 lb/hr of carbon monoxide, this corresponds to a molar ratio of 2 to 1. This is the recommended feed ratio based on research and the reaction's stoichiometry. The reactants have an average residence time of 0.26 seconds in the reactor. This setup provides for a production of 15,500 barrels per day of hydrocarbons, of which 978 lbmol/hr of methane and other light hydrocarbons (ranging from C1 to C5) are later combusted in order to generate heat for the endothermic SMR reactor and also provide electrical energy used throughout the process.

Water is constantly circulated through the Fischer-Tropsch reactor at a rate of 721900 lb/hr in order to maintain a uniform operating temperature. The water exits at 446°F as superheated steam. The steam is then used to drive a condensing turbine (ST-1) and generate additional power for the process. The condensed steam is then pumped back through the FT reactor in order to maintain a constant cooling flow. In order to maintain a constant 464°F operating temperature, it is necessary to remove 779900 MMBtu/hr of heat.

The catalyst used in the FT reactor is a fixed bed containing Cobalt Rhenium Aluminum Oxide ($CoReAl_2O_3$) produced by the Oxford Catalyst group. The total amount of catalyst required is 20400 lb. The FT reactor produces a wide array of products whose distribution is described by the Anderson-Schulz-Flory distribution (ASF). The ASF model for product distribution is given by the following equation

$$W_n = n(1-\alpha)^2 \alpha^{n-1}$$

An important parameter in this expression is **α**, the chain growth probability. A higher alpha value results in higher selectivity towards longer and heavier hydrocarbon chains, while a smaller alpha value promotes a higher selectivity for lighter hydrocarbons. For this particular type of reactor, an alpha value of 0.90 is utilized. This produces a product distribution similar to the one shown by the graph below.

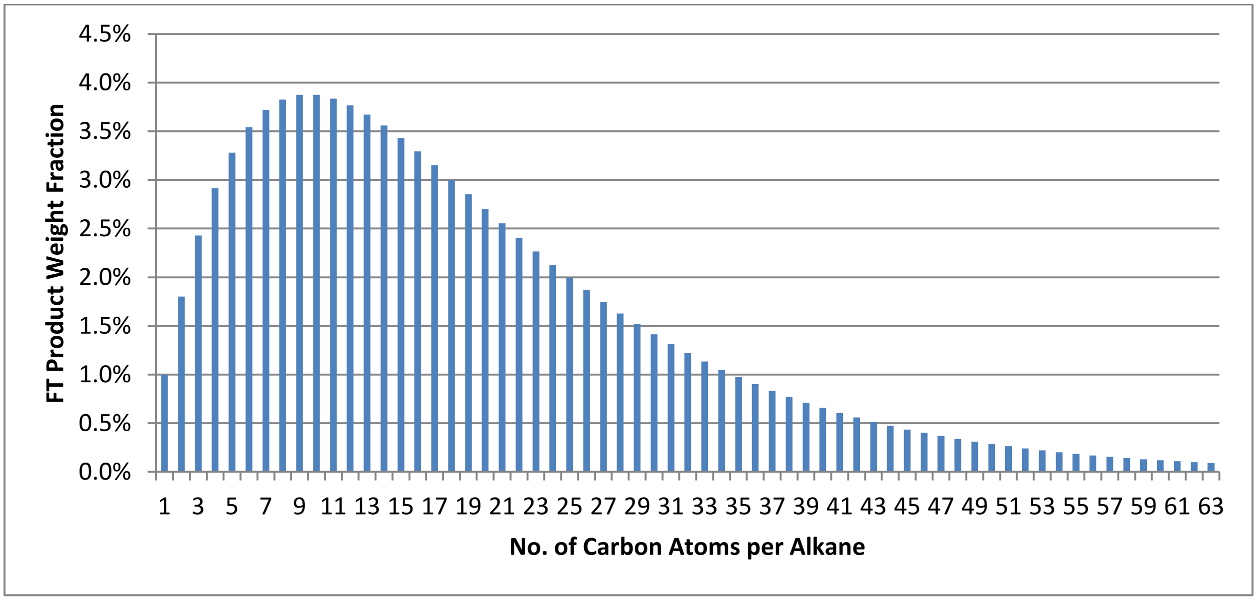


Figure 5 - Theoretical FT product distribution with an alpha value of 0.90. This graph was generated using the ASF model given above.

Section 8 - Energy Balances and Utility Requirements

This process has energy requirements that are satisfied by both energy conservation and utilities. The objective of this process is to transform gaseous and solid fuels to liquid fuel. The hearts of this transformation, the endothermic steam methane reforming and coal gasification reactions, are driven by burning a portion of that fuel. Coal gasification is operated autothermally by burning some of the coal in the gasifier to sustain the reaction. The reformer furnace (833 MMBtu/hr heat duty) similarly uses methane as fuel, but not directly from the natural gas feed to the process. Instead, it burns methane, ethane, propane, and carbon monoxide that are recycled byproducts of liquid fuel production. They are unwanted products and unreacted components leaving the FT reactor. These energy sources are not counted as utilities because they are either feedstocks or derived from feedstocks, but their use does demand some utility input (for example, electricity is used to power the air separation unit that delivers oxygen to the gasifier). Given the high temperatures and pressures of steam reforming and coal gasification, two water cooling cycles are present that use steam turbines to recover as much energy as possible in the form of electricity. Furthermore, there is more than enough methane and other light hydrocarbon byproducts exiting the FT reactor than is necessary to fuel the reformer. About 65% of these light gases are used to provide this fuel. The remainder is excess, but it cannot be efficiently recycled or sold because it contains overwhelming amounts of carbon dioxide, carbon monoxide, and hydrogen that are difficult and costly to separate. Instead, a gas turbine is used to burn this excess fuel and expand the resulting flue gas, producing additional electricity. The two steam turbines and the gas turbine actually produce more electricity than the process consumes. The extra electrical power is sold and supplied to the power grid.

Where possible, the process accomplishes stream heating and cooling by matching cold and hot streams in heat exchangers, but some stream and reactor cooling is still necessary via utilities. Process equipment such as pumps and compressors also has utility requirements. The following sections list each type of utility, how much is used at 100% of production capacity, and where it is used. Tables 1 and 2 summarize the cooling utilities, and Table 3 summarizes the electricity consumption and generation.

Table 1

Cooling Utilities by Unit					
Unit	Utility	Demand (MMBtu/hr)	Rate of Use (lb/hr)	Cost Rate ($/hr)	Yearly Cost ($/yr)
HX-4	Refrigeration	43	-	307	2,283,369
HX-5	Cooling water	666	22,273,445	202	1,503,336
HX-6	Chilled water	586	19,541,426	2,473	18,399,124
HX-8	Cooling water	416	14,208,364	129	958,987

Cooling Water

The two cooling cycles are Rankine cycles that convert heat to work. Each cycle has a condenser that condenses the steam outlet from the turbine to liquid using cooling water. The condenser in the FT cooling cycle, HX-5, uses 22 MMlb/hr of cooling water to satisfy the heat duty of 666 MMBtu/hr. The flue gas cooling cycle condenser, HX-8, uses 14 MMlb/hr of cooling water to satisfy the heat duty of 416 MMBtu/hr. At a cost of $\$9.07 \times 10^{-6}$/lb, the total cooling water use amounts to $331/hr ($2.5MM/yr).

Chilled Water

The products leaving the FT reactor are at 464°F and must be cooled to 81°F. Cooling water is not cold enough to reach this temperature, so chilled water at 40°F must be used instead. The cooling, accomplished in HX-6, has a heat duty of 586 MMBtu/hr and uses 20 MMlb/hr of chilled water. At a cost of $\$1.27 \times 10^{-6}$/lb, the total chilled water use amounts to $2,473/hr ($18.4MM/yr).

Refrigeration

The hot syngas from the coal gasifier must be cooled to 32°F in preparation for sulfur removal in the RECT-1. This low temperature necessitates refrigeration. R-134a (tetrafluoroethane) at -15°F is used in a closed cooling loop at a flow rate of 463,448 lb/hr to meet the cooling demand of 43 MMBtu/hr. At a cost of $6.70/GJ, the total refrigeration cost amounts to $307/hr ($2.3MM/yr).

Table 2

Cooling Utilities Summary			
Utility	**Rate of Use (lb/hr)**	**Factor**	**Yearly Cost ($/yr)**
Cooling water	36,481,809	$9.07E-6/lb	2,462,323
Chilled water	19,541,426	$1.27E-4/lb	18,399,124
Refrigeration	46 GJ/hr	$6.70/GJ	2,283,369

Electricity

There are several consumers and producers of electricity in this process. They are summarized in Table 3. The two compressors in Section G, CP-1 and CP-2, use 3977 kW and 1195 kW respectively. Compressor power requirements are generally higher, but the compression ratios for both compressors are relatively low, so the power requirements are correspondingly small. P-1 in Section C and the two cooling loop pumps, P-2 and P-3, have a very small total power consumption of 905 kW. The largest electricity consumer is the air separation unit for coal gasification, ASU-1. It uses 28.1 MW. All together, 34 MW of electricity are necessary to operate the plant. However, the three process turbines produce far more than enough electricity to power all of these units. ST-1, which drives an electrical generator by expanding hot, high-pressure steam produced by the exothermic FT reaction, contributes 34 MW. ST-2 generates a comparable amount, 32 MW, using the steam made by the hot process flue gases. Finally, the gas turbine, GT-1, generates 36 MW from the burning and expansion of the excess fuel. Together, the three turbines produce 101 MW, which is approximately three times more power than necessary. Subtracting the energy that is consumed by process equipment, there is a net electricity generation of 67 MW. This electricity will be sold to the main power grid in the plant area at a price of $0.08/kWh for a net profit of $40MM/yr. It is enough electricity to power approximately 50,000 homes.

Table 3

Electricity Consumed			
Unit	**Rate of Consumption (kW)**	**Cost Rate ($/hr)**	**Yearly Cost ($/yr)**
CP-1	3977	318	2,367,077
CP-2	1195	96	711,556
P-1	177	14	105,146
P-2	342	27	203,370
P-3	387	31	230,261
ASU-1	28100	2,248	16,725,120
Electricity Produced			
Unit	**Rate of Production (kW)**	**Credit Rate ($/hr)**	**Yearly Credit ($/yr)**
ST-1	33728	2,698	20,075,076
ST-2	31399	2,512	18,688,804
GT-1	35872	2,870	21,350,880
Totals			
Produced (MW)	-101	Cost Factor	$0.08/kWh
Consumed (MW)	34	Net Profit	$39,772,229/yr
Net (MW)	-67		

Section 9 - Equipment Descriptions

Every major piece of equipment in the process is described in detail in this section. Each unit's purpose, inlet and outlet streams, operating conditions, and physical details are included. Furthermore, equipment and catalyst costs are listed at the end of each unit description. These costs were estimated in several ways. For standard process units such as heat exchangers and pumps, costs were estimated using data and correlations from *Seider et al*. For non-standard equipment such as reactors and separation systems, costs were generally estimated from literature sources that detail similar industrial equipment. In some cases, size scaling factors were used to correct literature cost estimates. Specific cost sources for every unit in this section are included at the end of the corresponding unit specification sheet in Section 10.

Furthermore, overall heat transfer coefficients for heat exchangers were taken from *Seider et al.* or source 23.

SMR-1 • Steam Methane Reformer

This unit is a reactor which converts methane and steam to hydrogen and carbon monoxide (syngas). A side reaction, the water-gas shift reaction, occurs as well, producing additional hydrogen and unwanted carbon dioxide from carbon monoxide and steam. The unit consists of a tall rectangular furnace which provides direct radiant heat to sustain the endothermic reforming reaction. The reactions occur inside many long, narrow tubes packed with catalyst. Each tube is 24 ft long, has a 3 in diameter, and has a wall thickness of 0.5 in. There are 1,511 tubes in the reformer. The tubes are constructed from centrifugally cast 25% Cr - 20% Ni - 0.4% carbon alloy steel. These tubes are vertically aligned in rows and fixed in place inside the furnace using a steel structure. The reactants flow from top to bottom, entering in a feedstock header and then splitting evenly into the 1,511 tubes. An outlet header gathers the products and unconverted reactants. A pigtail connects each tube to the inlet and outlet headers. It functions to absorb the vertical expansion of the tubes and the horizontal expansion of the headers due to temperature fluctuations. The furnace burners are vertically fired. They reside at the top of the reformer between the rows of tubes. Gaseous fuel (mostly methane and carbon monoxide) is burned in air. The hot products of combustion pass co-currently down the outside of tubes, providing the heat for reforming. This flue gas is collected in coffins constructed from firebrick that lie along the bottom of the furnace. The coffins empty into a collecting duct which transfers the flue gas downstream.

The reformer operates at 1800°F and 25 bar (358 psi). A pressure drop of 2 psi occurs through the reformer tubes. The catalyst used is ReforMax 330 LDP by Sud-Chemie, a nickel catalyst on a calcium aluminate support (57-87 wt% aluminum oxide, 10-25 wt% nickel oxide, 3-18 wt% calcium oxide). The catalyst achieves 95 mol% conversion of methane. 88,906 lb of catalyst are used in the tubes. The feed steam to methane molar ratio is 3:1, and the product syngas hydrogen to carbon monoxide ratio is 4.45:1. The purchase cost for the entire unit, including the furnace box and tubes, but excluding catalyst, was estimated to be $139,900,000. The catalyst cost was found to be $1,334,000. Detailed sizing and design calculations for this unit are presented in the Appendix on page 98. The unit specification sheet can be found on page 50.

GAS-1 • Coal Gasifier

The coal gasifier (GAS-1) used in this process in a GE entrained flow, slurry fed gasifier. It operates at 2400°F and 815 psi. It process 2593 tons per day of coal. This coal is received as part of a coal-water slurry in stream C-203. 5,847 lbmol/hr of oxygen is supplied to the unit in stream C-205. The composition of the syngas produced in stream C-206 is modeled is Aspen based on a paper by Wen and Chaung. A summary of the model used is included in the Appendix on page 101.

In actuality, the GE gasifier includes not only the gasifier itself (GAS-1), but also the radiant cooler (RC-1), which is housed within the same vessel. RC-1 takes the syngas from a temperature of 2400°F in stream C-206 down to 1250°F in stream C-207. In the process, it boils the preheated feed water of stream BW-703, and sends it to the reformer section of the process in stream BW-704. The cost of the gasifier was estimated by scaling it with reference to a GE gasifier described in the NETL “Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity” report. In that study, a 2500 ton per day gasifier had a bare module cost of $142.4 million. Using a scaling factor of 0.6, this 2592 ton per day reactor is estimated to cost $145.6 million. The unit specification sheet can be found on page 51.

FT-1 • Fischer-Tropsch Reactor

The Microchannel Fischer-Tropsch reactor is responsible for handling and producing 15,500 bbl/day of syncrude, a mixture of varying in chain-length liquefied hydrocarbons that can be processed at another site for diesel, gasoline and other hydrocarbon-based products. The microchannel reactor is made up of many parallel catalyst-packed reaction and cooling water channels, flowing counter currently in relation to each other to maximize heat transfer. Divided into manageable modules that are typically the size of a 1 cubic meter box, scaling up is as easy as stacking or adding more modules in series. The reactor feed stream P-301 contains the syngas produced from the coal gasifier and the methane reforming unit. The feed stream hydrogen to carbon monoxide molar ratio is 2:1, and the alpha value governing the product syncrude hydrocarbon distribution is 0.9. The reactor operates at 464°F and 25 bar (358 psi). A total pressure drop of 90 psi occurs across the reactor. The catalyst used is designed by the *Oxford Catalyst Group*, an aluminum oxide based catalyst containing 30 wt% Cobalt and 4.5 wt% Rhenium. The catalyst achieves a conservative 80 mol% conversion of carbon monoxide. The catalyst exists as a spherical pellet with a 45 mm diameter, and is IP protected. Properties such as bulk density were suggested by the *Oxford Catalyst Group* to be estimated from a more common Nickel-based catalyst that was costed using Sigma-Aldrich. 9260 kg of catalyst are required to convert the CO present in the feed stream, and at $53.60/kg, the total cost of the catalyst is $496,500. Given the incoming syngas feed, calculations showed that 24 individual reactor modules are necessary. This amounts to a total vessel volume (including channels and casing) of 1900 cuft. The purchase cost and size for all 24 modules was estimated by taking dimensions from a microchannel Fischer-Tropsch reactor currently in use in Gussing, Austria that was developed and put into use by *Velocys*. Sizing information was also based on the information in U.S. Patent 7,084,180. The dimensions were used to estimate the amount of stainless steel required to build all of the reactor modules. The total bare module cost was found to be $23,725,000. Detailed sizing and design calculations for this unit are presented in the Appendix on page 103. The unit specification sheet can be found on page 52.

CP-1 • Centrifugal Compressor

CP-1 is a single-stage compressor which raises the pressure of the desulfurized natural gas feed to the required pressure for steam reforming. The feed to CP-1, G-103, enters at 213 psi (15 bar) and leaves in stream G-104 at 368 psi (25 bar). This compression results in a temperature increase from 700°F to 834°F. The compressor is constructed from carbon steel and is driven by an electric motor that consumes 3978 kW. The bare module cost for this compressor, including the motor, is estimated to be $3,504,500. The unit specification sheet can be found on page 53.

CP-2 • Centrifugal Compressor

CP-2 is a single-stage compressor which raises the pressure of the syngas produced from steam methane reforming to the pressure required for the FT reactions. The syngas has been partially cooled in HX-3 prior to entering CP-2. Only a small degree of compression is required because the SMR and FT reactor operate at the same pressure, so only the small pressure drops across preceding equipment must be accounted for. The feed to CP-2, G-108, enters at 351 psi (24.2 bar) and leaves in stream G-104 at 363 psi (25 bar). This compression results in a temperature increase from 594°F to 607°F. The compressor is constructed from carbon steel and is driven by an electric motor that consumes 1195 kW. The bare module cost for this compressor, including the motor, is estimated to be $2,945,500. The unit specification sheet can be found on page 54.

P-1 • Centrifugal Pump

P-1 is a centrifugal pump that raises the pressure of the liquid process water feed to the reformer to the desired operating pressure of the reformer. Stream BW-701 enters at 15 psi (1 bar) and 77°F and leaves at 363 psi (25 bar) as stream BW-702. This pressure increase corresponds to 946 ft of head. The volumetric flow rate of the water is 889 gal/min. P-1 is a horizontal split-case pump constructed from cast iron. It is driven by an electric motor with a shaft speed of 3600 RPM and with an open, drip-proof enclosure. The pump has an efficiency of 76% and the motor has an efficiency of 92%. Overall, P-1 consumes 258 HP (192 kW). The bare module cost for this pump and electric motor as well as a spare pump and motor is $732,000. The unit specification sheet can be found on page 55.

P-2 • Centrifugal Pump

P-2 is a centrifugal pump that raises the pressure of the condensed water in the FT cooling cycle prior to entering the FT reactor cooling channels, driving a Rankine cycle and producing usable electricity. Stream W-503 enters at 15 psi (1 bar) and 214°F and leaves at 368 psi (25 bar) as stream W-504. This pressure increase corresponds to 1018 ft of head. The volumetric flow rate of the water is 1803 gal/min. P-2 is a horizontal split-case pump constructed from cast iron. It is driven by an electric motor with a shaft speed of 3600 RPM and with an open, drip-proof enclosure. The pump has an efficiency of 81% and the motor has an efficiency of 93%. Overall, P-2 consumes 494 HP (369 kW). The bare module cost for this pump and electric motor as well as a spare pump and motor is $1,320,000. The unit specification sheet can be found on page 56.

P-3 • Centrifugal Pump

P-3 is a centrifugal pump that raises the pressure of the condensed water in the flue gas cooling cycle prior to entering the flue gas/cooling water heat exchanger (HX-7), driving a Rankine cycle and producing usable electricity. Stream W-511 enters at 15 psi (1 bar) and 214°F and leaves at 730 psi (50 bar) as stream W-512. This pressure increase corresponds to 2064 ft of head. The volumetric flow rate of the water is 974 gal/min. P-3 is a horizontal split-case pump constructed from cast iron. It is driven by an electric motor with a shaft speed of 3600 RPM and with an open, drip-proof enclosure. The pump has an efficiency of 77% and the motor has an efficiency of 93%. Overall, P-3 consumes 570 HP (425 kW). The bare module cost for this pump and electric motor as well as a spare pump and motor is $1,256,000. The unit specification sheet can be found on page 57.

ST-1 • Steam Turbine

ST-1 is a condensing steam turbine that recovers energy from the hot, high pressure steam produced in the FT cooling channels by expanding it, producing rotary motion that drives an electrical generator. Stream W-501 enters as superheated steam with a pressure of 363 psi (25 bar), a temperature of 446°F, and a volumetric flow rate of 97370 cuft/min. It expands across the turbine, leaving in stream W-502 at 20 psi (1.4 bar) and 229°F as partially condensed steam (91% vapor). The outlet pressure was set at 1.4 bar so that vacuum conditions (below atmospheric pressure) would not occur at any point in the cooling loop. The outlet temperature was thus set by this condition and was calculated using Aspen. 45200 HP (33.8 MW) of electrical power are produced in this process. ST-1 is constructed from carbon steel and has an efficiency of 72%. The bare module cost for this turbine is $13,490,000. The unit specification sheet can be found on page 58.

ST-2 • Steam Turbine

ST-2 is a condensing steam turbine that recovers energy from the hot, high pressure steam produced in the flue gas cooling cycle by expanding it, producing rotary motion that drives an electrical generator. Stream W-509 enters as superheated steam with a pressure of 725 psi (50 bar), a temperature of 1022°F, and a volumetric flow rate of 7630 cuft/min. It expands across the turbine, leaving in stream W-510 at 20 psi (1.4 bar) and 402°F. The outlet pressure was fixed as it was in ST-1. 43000 HP (32.1 MW) of electrical power are produced in this process. ST-2 is constructed from carbon steel and has an efficiency of 72%. The bare module cost for this turbine is $12,831,000. The unit specification sheet can be found on page 59.

GT-1 • Gas Turbine

Figure 6 - Siemens SGT-750 36 MW gas turbine (http://www.energy.siemens.com/hq/en/power-generation/gas-turbines/sgt-750.htm).

GT-1 is a gas turbine which is an all-in-one air compressor, fuel combustor, and turbine. It generates electricity from the excess light fuel gases by compressing air, combusting the fuel gases in that air, and expanding the hot pressurized flue gas to drive an electrical generator.

Stream F-408 enters carrying mostly carbon dioxide, carbon monoxide, hydrogen, and light alkanes at 81°F and 218 psi (15 bar). Stream F-409 contains air at 77°F and atmospheric pressure. The air is compressed in GT-1's compressor section to the pressure of the fuel stream. The two streams combine in the turbine's combustion chamber where the fuel is combusted at a firing temperature of 2350°F. From there the resulting flue gas is expanded across the turbine section of the unit to 29 psi (2 bar) and 1477°F. This expansion drives an electrical generator. The electricity production of GT-1, net of the compression power required, is 36 MW. It has an efficiency of 38.7% and is constructed in part from low alloy steel. The bare module cost for GT-1 is $57,600,000. The unit specification sheet can be found on page 60.

SR-1A & SR-1B • Desulfurization Vessel

SR-1 is two identical desulfurization vessels which removes sulfur compounds from the natural gas feed to the reformer. It reduces the concentration to a level that is below the SMR catalyst poisoning limit (< 0.5 ppm w/w sulfur) using a zinc oxide adsorbent. Stream G-102 enters SR-1 at 700°F and 213 psi with a sulfur concentration of 8.1 ppm w/w. The bulk of the sulfur in the feed is H_2S, and it reacts with the adsorbent according to the following: $H_2S + ZnO \rightarrow ZnS + H_2O$. The desulfurized natural gas feed leaves as stream G-103 at approximately the same temperature and pressure, but with a sulfur concentration of <0.1 ppm w/w, well below the poisoning limit. The adsorbent requires a 1500 hr^{-1} gas hourly space velocity, which corresponds to a residence time of 2.4 s. Because the adsorbent must be regenerated, two vessels are present in the process: SR-1A and SR-1B. Piping is installed that can direct the feed flow into either of these two vessels. While one vessel is operating, the other is down for adsorbent regeneration. The adsorbent has a maximum sulfur loading of 12.8 wt%. At the average sulfur level in the natural gas, this loading is reached in approximately 112 days. When this time has passed, the natural gas feed flow is switched to the inactive vessel. The exhausted adsorbent is then regenerated by flushing the vessel with a dilute oxygen stream (1-7 vol% O_2) at 700°F and 3-7 bar. This vessel rotation repeats every 112 days. SR-1A and SR-1B are constructed from carbon steel, have a 5 ft diameter, and are 15 ft tall, for a total volume of 290 cuft. Each vessel is filled with 19900 lb of dumped packed adsorbent. The bare module cost for both vertical pressure vessels, including platforms and ladders, is $408,000. The cost of the zinc oxide adsorbent for both vessels is approximately $174,000. The sizing calculations for these vessels can be found in the Appendix on page 106. The unit specification sheet can be found on page 61.

V-1 • Flash Vessel

V-1 is vapor-liquid-liquid equilibrium vertical flash vessel. It separates the FT products into the light hydrocarbon gas byproducts (P-306), the medium to long straight chain alkane product (P-304), and liquid waste water (P-305). The flash vessel operates at an equilibrium pressure of 218 psi (15 bar) and 81°F. Stream P-303, carrying the products from the FT reactor, enters at 357 psi (24.6 psi), 81°F, and a vapor fraction of 34%. An expansion valve reduces the pressure of the stream to 218 psi (15 bar) just before entering the vessel. After a residence time of 5 min, the outlet streams leave in equilibrium: P-306 from the top, P-304 from the side, and P-305 from the bottom. V-1 is constructed from carbon steel and is 6.5 ft in diameter and 19 ft tall, with a total volume of 630 cuft. The bare module cost for this vertical pressure vessel, including platforms and ladders is $316,000. The unit specification sheet can be found on page 62.

HX-1 • Heat Exchanger

HX-1 is a counter-current floating head shell and tube heat exchanger in Section G. It uses the partially cooled but still hot flue gas from the SMR furnace to preheat the natural gas feed prior to entering the desulfurization vessel. Steam G-101, which is the main natural gas feed, is heated from 70°F to 700°F on the shell side and leaves as stream G-102. On the tube side, stream F-406, which primarily contains carbon dioxide and air, is cooled from 1186°F to 1007°F and leaves as stream F-407. As a gas-gas heat exchanger, an overall heat transfer coefficient of 20 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 687°F and the heat duty is 51 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 3720 sqft. HX-1 is constructed from carbon steel using 20 ft long tubes. The bare module cost for this exchanger is estimated to be $171,000. Sizing and costing calculations for this heat exchanger can be found in the Appendix on page 107. Similar calculations apply to all other heat exchangers. The unit specification sheet can be found on page 63.

HX-2 • Heat Exchanger

HX-2 is a counter-current floating head shell and tube heat exchanger in Section G. It is an economizer which uses the hot flue gas from the SMR furnace to preheat the desulfurized natural gas feed and steam feed prior to entering the reformer. Steam G-105, which contains methane and steam, is heated from 403°F to 1200°F on the shell side and leaves as stream G-106. On the tube side, stream F-405, which primarily contains carbon dioxide and air, is cooled from 2000°F to 1186°F and leaves as stream F-406. As a gas-gas heat exchanger, an overall heat transfer coefficient of 20 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 792°F and the heat duty is 246 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 15500 sqft. Because of this large area, HX-2 is split into 2 identical heat exchangers operating in parallel, each with an area of 7750 sqft. HX-2 is constructed from carbon steel using 20 ft long tubes. The bare module cost for both identical exchangers is estimated to be $564,000. The unit specification sheet can be found on page 64.

HX-3 • Heat Exchanger

HX-3 is a counter-current floating head shell and tube heat exchanger in Section G. It uses the hot syngas from the SMR outlet to preheat the light fuel gases entering the reformer. Also, the syngas temperature reduction is desired because the FT reactor operates at a much lower temperature (464°F) than the SMR. Steam F-403, which contains mostly methane and carbon monoxide, is heated from 77°F to 1581°F on the shell side and leaves as stream F-404. On the tube side, stream G-107, which primarily contains carbon monoxide and hydrogen, is cooled from 1800°F to 594°F and leaves as stream G-108. As a gas-gas heat exchanger, an overall heat transfer coefficient of 20 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 348°F and the heat duty is 424 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of 60880 sqft. Because of this large area, HX-3 is split into 6 identical heat exchangers operating in parallel, each with an area of 10150 sqft. HX-3 is constructed from carbon steel using 20 ft long tubes. The bare module cost for all 6 identical exchangers is estimated to be $2,082,000. The unit specification sheet can be found on page 65.

HX-4 • Heat Exchanger

HX-4 is a counter-current floating head shell and tube heat exchanger in Section C. It uses a refrigerant, R-134a (tetrafluoroethane), to cool partially cooled but still hot syngas from the gasifier to the temperature necessary for sulfur removal in the Rectisol unit. Steam R-601, which contains liquid refrigerant, is vaporized on the shell side at -15°F and leaves as stream R-602. On the tube side, stream C-208, which primarily contains syngas, is cooled from 212°F to 32°F and leaves as stream C-209. As a boiling liquid-gas heat exchanger, an overall heat transfer coefficient of 30 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 114°F and the heat duty is 43 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 12700 sqft. HX-4 is constructed from carbon steel using 20 ft long tubes. The bare module cost for this exchanger is estimated to be $415,000. The unit specification sheet can be found on page 66.

HX-5 • Heat Exchanger

HX-5 is a counter-current floating head shell and tube heat exchanger in Section P. It is a condenser which uses cooling water to condense steam from steam turbine ST-1 in the Fischer-Tropsch cooling cycle. It is part of a Rankine cycle that produces usable electricity from the heat generated by the FT reaction. Steam W-505, which contains cooling water, is heated from 90°F to 120°F and leaves as stream W-506. On the tube side, stream W-502, which contains partially condensed steam (91% vapor), is completely condensed from 229°F to 214°F and leaves as stream W-503. As a liquid-condensing water heat exchanger, an overall heat transfer coefficient of 700 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 116°F and the heat duty is 666 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 8200 sqft. HX-5 is constructed from carbon steel using 20 ft long tubes. The bare module cost for this exchanger is estimated to be $295,000. The unit specification sheet can be found on page 67.

HX-6 • Heat Exchanger

HX-6 is a counter-current floating head shell and tube heat exchanger in Section P. It uses chilled water to cool the hot FT products to the optimal flash separation temperature prior to entering V-1. Steam W-507, which contains chilled water, is heated from 40°F to 70°F on the shell side and leaves as stream W-508. On the tube side, stream P-302, which contains the FT products (alkanes from C1 to C36+), carbon monoxide, carbon dioxide, and water, is cooled and partially condensed from 464°F to 81°F and leaves as stream P-303. Stream P-302 is almost all vapor but stream P-303 leaves as only 34% vapor. As a liquid-condensing vapor heat exchanger, an overall heat transfer coefficient of 150 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 156°F and the heat duty is 586 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 25050 sqft. Because of this large area, HX-6 is split into 3 identical heat exchangers operating in parallel, each with an area of 8350 sqft. HX-6 is constructed from carbon steel using 20 ft long tubes. The bare module cost for all 3 identical exchangers is estimated to be $894,000. The unit specification sheet can be found on page 68.

HX-7 • Heat Exchanger

HX-7 is a counter-current floating head shell and tube heat exchanger in Section P. It is a boiler which uses hot flue gas from the reformer furnace and the gas turbine outlet to generate steam from relatively cool high-pressure liquid water, driving a Rankine cycle and producing usable electricity. Steam W-512, which contains liquid water, is heated and vaporized from 216°F to 1022°F on the shell side and leaves as stream W-509. On the tube side, stream F-411, which primarily contains carbon dioxide and air, is cooled and from 1251°F to 320°F and is released to the atmosphere at stream F-412. As a boiling water-gas heat exchanger, an overall heat transfer coefficient of 35 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 162°F and the heat duty is 522 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 92040 sqft. Because of this large area, HX-7 is split into 8 identical heat exchangers operating in parallel, each with an area of 11500 sqft. HX-7 is constructed from carbon steel using 20 ft long tubes. The bare module cost for all 8 identical exchangers is estimated to be $3,072,000. The unit specification sheet can be found on page 69.

HX-8 • Heat Exchanger

HX-8 is a counter-current floating head shell and tube heat exchanger in Section P. It is a condenser which uses cooling water to condense steam from steam turbine ST-2 in the flue gas cooling cycle. It is part of a Rankine cycle that produces usable electricity from the high-temperature flue gas from the reformer furnace and the gas turbine. Steam W-513, which contains cooling water, is heated from 90°F to 120°F and leaves as stream W-514. On the tube side, stream W-510, which contains superheated steam, is completely condensed from 402°F to 214°F and leaves as stream W-511. As a liquid-condensing water heat exchanger, an overall heat transfer coefficient of 700 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 192°F and the heat duty is 416 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 3100 sqft. HX-8 is constructed from carbon steel using 20 ft long tubes. The bare module cost for this exchanger is estimated to be $155,000. The unit specification sheet can be found on page 70.

CC-1 • Heat Exchanger

CC-1 is a convective cooling counter-current floating head shell and tube heat exchanger in Block C. It uses the partially cooled but still hot syngas from the coal gasifier to produce partially vaporized water from process feedwater for steam methane reforming in SMR-1. Steam BW-702, which contains pressurized liquid water, is heated from 78°F to 434°F on the shell side and leaves partially vaporized as stream BW-703. On the tube side, stream C-207, which primarily contains syngas and water vapor from the gasifier, is cooled from 1250°F to 212°F and leaves as stream C-208. Some of the water vapor condenses on the tube side. As a boiling water-condensing steam heat exchanger, an overall heat transfer coefficient of 300 Btu/(hr-sqft-°R) was used. The log-mean temperature difference across this heat exchanger is 175°F and the heat duty is 212 MMBtu/hr. Using 2 tube passes and 1 shell pass, this corresponds to a heat transfer area of approximately 4040 sqft. CC-1 is constructed from carbon steel using 20 ft long tubes. The bare module cost for this exchanger is estimated to be $181,000. The unit specification sheet can be found on page 71.

ASU-1 • Air Separation Unit

This unit separates air into oxygen for the coal gasifier. The air is compressed to 353 psi and separated in a cryogenic distillation column. The utility costs for the compressor of the ASU are significant, requiring 28 MW. 187,000 lb/hr of oxygen are produced in stream C-205 from 803,000 lb/hr of air in stream C-204. The cost of the air separation unit was estimated by scaling it with reference to a unit from a similar process described in the NETL "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity" report. In that study, a unit that produced 1839 tons per day of oxygen had a bare module cost of $51,800,000. Using a scaling factor of 0.5, our 2245 ton per day unit is estimated to cost $57,200,000. The unit specification sheet can be found on page 72.

SP-1 • Coal Receiving and Handling

Unit SP-1 represents all of the equipment necessary to receive the coal and prepare them to be fed to the gasifier. This includes all the storage equipment, crushers, conveyors, hoppers, and slurry pumps and agitators. 2593 tons per day of coal are processed from stream C-201. This coal is prepared into a slurry with 52,069 lb/hr of water from stream C-202. This slurry, stream C-203, is then fed to the gasifier, GAS-1. The cost of the coal receiving and handling unit was estimated by scaling it with reference to a unit from a similar process described in the NETL "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity" report. In that study, a unit that handled 2500 tons per day of coal had a bare module cost of $45.8 million. Using a scaling factor of 0.6, our 2593 ton per day unit is estimated to cost $46.8 million. The unit specification sheet can be found on page 73.

RECT-1 • Rectisol

The Rectisol unit removes the H_2S from the syngas stream from the gasifier. The sulfur tolerance of the Fischer-Tropsch catalyst is less than 1 ppm. Rectisol operates by stripping the acid gases from the syngas using a cold methanol solvent (0 to -40°F), which is regenerated and recycled. Syngas enters as stream C-209 and is sent to the Fischer-Tropsch section of the process as stream C-210. The waste stream, C-212 contains essentially all of the H_2S, and 972 lbmol/hr of CO_2. The cost of the Rectisol unit was estimated by scaling it with reference to a unit from a similar process described in the NETL “Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity” report. In that study, a unit that purified 512,000 lb/hr of syngas had a bare module cost of $105 million. Using a scaling factor of 0.6, our 317,000 lb/hr unit is estimated to cost $78.8 million. The unit specification sheet can be found on page 74.

Section 10 - Equipment Specification Sheets

SMR-1

Item	Steam methane reformer
No. Required	1
Function:	Converts methane and steam to syngas (hydrogen and carbon monoxide) over nickel catalyst
Operation:	Continuous

Stream Data

	Reforming Tubes		Furnace	
	Inlet	Outlet	Inlet	Outlet
Stream No.	G-106	G-107	F-404	F-405
Flow Rate (lb/hr)	501951	501951	955161	955161
Flow Rate (lbmol/hr)	28358	41630	35856	33445
Mole Fractions				
CO_2	0.0%	4.3%	3.5%	12.6%
CO	0.0%	11.7%	5.0%	0.0%
N_2	0.8%	0.5%	63.1%	67.7%
H_2O	73.9%	30.1%	0.0%	16.1%
H_2	0.0%	52.1%	10.0%	0.0%
O_2	0.0%	0.0%	16.6%	3.6%
alkanes	24.6%	0.8%	1.7%	0.0%
Vapor Fraction	1	1	1	1
Temperature (F)	1200	1800	1579	2000
Pressure (psi)	358	356	39	39

Design Data:	Type	Vertically down-fired furnace with supported catalyst-packed tubes	Catalyst	ReforMax 330 LDP by Sud-Chemie (nickel catalyst on a calcium aluminate support)
	Conversion	95 mol% of methane	Mass of Catalyst per Tube	58.8 lb (26.7 kg)
	Operating Temperature	1800 F	Total Mass of Catalyst	88906 lb
	Operating Pressure	25 bar	Catalyst Density	50 lb/ft^3 (800 kg/m^3)
	Tube Length	24 ft	Heat Duty	833 MMBtu/hr (244 MW)
	Tube Diameter	3 in	Steam/Methane Feed Ratio	3
	Tube Thickness	0.5 in	Syngas Hydrogen/CO Ratio	4.45
	Ind. Tube Volume	1.18 ft^2	Tube Material	Centrifugally cast 25% Cr - 20% Ni - 0.4% Carbon alloy steel
	No. of Tubes	1511		

F.O.B. Purchase Cost	$ -	
Bare Module Cost	$ 139,900,000	
Catalyst Cost	$ 1,334,000	@ $750/cuft

Cost Source: "HTGR Integrated Hydrogen Production via Steam Methane Reforming Economic Analysis"; Idaho National Laboratory; 2010

GAS-1

Item	Entrained flow coal gasifier		
No. Required	1		
Function:	Produces syngas from coal, water, and oxygen via a steam reforming reaction		
Operation:	Continuous		
Stream Data			
	Inlet		Outlet
Stream No.	C-203	C-205	C-206
Total Flow Rate (lb/hr)	268122	187102	381133
Component Molar Flow Rates (lbmol/hr)			
CO_2	0	0	1144
CO	0	0	8947
N_2	0	0	55
H_2O	2890	0	3552
H_2	0	0	5942
O_2	0	5847	0
H_2S	0	0	71
CH_4	0	0	17
Coal Mass Flow (lb/hr)	216053	0	0
Temperature (F)	77	77	2400
Pressure (psi)	353	353	377
Design Data:	Gasifier Type	GE Entrained Flow, Slurry Fed Gasifier	
	Operation Mode	Radiant Syngas Cooling	
	Operating Temp. (F)	2400	
	Operating Pressure (psia)	815	
	Coal Fed (Tons per Day)	2600	
F.O.B. Purchase Cost	-		
Bare Module Cost	$ 138,600,000		

Cost Source: "Cost and Performance Baseline for Fossil Energy Plants," NETL 2010

FT-1	
Item	Microchannel Fischer-Tropsch Reactor
No. Required	1
Function:	Converts syngas (hydrogen and carbon monoxide) to a specified distribution of gaseous, liquid and solid hydrocarbons over aluminum oxide catalyst
Operation:	Continuous

Stream Data

	Inlet	Outlet
Stream No.	P-301	P-302
Flow Rate (lb/hr)	773677	773677
Flow Rate (lbmol/hr)	25749434	16213737
Mole Fractions		
CO_2	3.43%	5.45%
CO	24.33%	7.73%
N_2	0.49%	0.78%
H_2O	22.11%	66.02%
H_2	48.66%	15.47%
CH_4	0.65%	1.30%
C_2H_6-C_5H_{12}	0.33%	1.44%
C_6H_{14}-$C_{11}H_{24}$	0.00%	0.84%
$C_{12}H_{26}$-$C_{20}H_{42}$	0.00%	0.59%
$C_{21}H_{44}$+	0.00%	0.39%
Vapor Fraction	1	0.994
Temperature (F)	464	464
Pressure (bar)	25	25

Design Data:	Type	Microchannel	Catalyst	30 wt%Co/ 4.5 wt% Re/ Al_2O_3
	Conversion	80 mol% of CO	Mass of Catalyst per Channel	0.02856 lb (0.01295 kg)
	Alpha (Product Distribution)	0.9	No. of Channels	350729766
	Operating Temperature	464 F	Total Mass of Catalyst	20421 lb
	Operating Pressure	25 bar	Catalyst Bulk Density	54.6 lb/cuft (875 kg/m^3)
	Channel Height	0.0374 in (0.95 mm)	WHSV	4.9126 g CO/g cat hr
	Channel Length	4.593 ft (1400 mm)	Heat Duty	-2150 MMBtu/hr
	Channel Width (Rxn|Cool)	0.669 in | 0.118 in	H_2/CO Ratio	2
	Ind. Module Volume	79.45 ft^2	Syngas Hydrogen/CO Ratio	4.45
	No. of Modules	24	Plate/Channel Material	Galvanized Carbon Steel

F.O.B. Purchase Cost	$ -	
Bare Module Cost	$ 23,725,000	
Catalyst Cost	$ 496,500	@ $53.60/kg

Cost Source: http://www.meps.co.uk/World%20Carbon%20Price.htm

Catalyst Cost Source: Sigma-Aldrich

CP-1		
Item	Centrifugal compressor	
No. Required	1	
Function:	Increases the pressure of the natural gas feed into the SMR after desulfurization	
Operation:	Continuous	
Stream Data		
	Entry	Exit
Stream No.	G-103	G-104
Flow Rate (lb/hr)	124450	124450
Vapor Fraction	1	1
Temperature (F)	700	834
Pressure (psi)	213	368
Design Data:	Pressure Ratio	1.73
	Efficiency	72%
	Drive	Electric Motor
	Power Consumption (kW)	3,978
F.O.B. Purchase Cost	$ 1,630,000	
Bare Module Cost	$ 3,504,500	

Cost Source: Aspen Process Economic Analyzer V7.3.1

CP-2		
Item	Centrifugal compressor	
No. Required	1	
Function:	Increases the pressure of the syngas from the SMR to that required for the Fischer-Tropsch reactor prior to mixing with the coal syngas and entering the FT reactor	
Operation:	Continuous	
Stream Data		
	Entry	Exit
Stream No.	G-108	G-109
Flow Rate (lb/hr)	502030	502030
Vapor Fraction	1	1
Temperature (F)	594	607
Pressure (psi)	351	363
Design Data:	Pressure Ratio	1.02
	Efficiency	72%
	Drive	Electric Motor
	Power Consumption (kW)	1,195
F.O.B. Purchase Cost	$ 1,370,000	
Bare Module Cost	$ 2,945,500	

Cost Source: Aspen Process Economic Analyzer V7.3.1

P-1

Item	Centrigual pump + Electric motor	
No. Required	2	(1 main + 1 spare)
Function:	Raises the pressure of the process water feed to the reformer to the desired operating pressure of the reformer	
Operation:	Continuous	

Stream Data

	Entry	Exit
Stream No.	BW-701	BW-702
Flow Rate (lb/hr)	377569	377569
Vapor Fraction	0	0
Temperature (F)	77	78
Pressure (psi)	15	363

Design Data:	Volumetric Flow Rate	889 gal/min	Power Source	Electric motor
	Head	946 ft	Efficiency	76.0%
	Case-Split	Horizontal split-case	Shaft Speed	3600 RPM
	Fluid Power	180 HP (135 kW)	Motor Enclosure	Open, drip-proof
	Brake Power	237 HP (177 kW)	Motor Efficiency	92.0%
	Material	Cast iron	Power Consumption	258 HP (192 kW)

	Each			Total
	Pump	Motor	Pump and Motor	
F.O.B. Purchase Cost	$ 94,000	$ 17,000	$ 111,000	$ 222,000
Bare Module Cost	$ 310,000	$ 56,000	$ 366,000	$ 732,000

Pump Cost Source: Aspen Process Economic Analyzer V7.3.1

Motor Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

P-2

Item	Centrigual pump + Electric motor
No. Required	2 (1 main + 1 spare)
Function:	Increases the pressure of the condensed water in the FT cooling cycle prior to entering the FT reactor cooling channels, driving a Rankine cycle and producing usable electricity
Operation:	Continuous

Stream Data

	Entry	Exit
Stream No.	W-503	W-504
Flow Rate (lb/hr)	721911	721911
Vapor Fraction	0	0
Temperature (F)	214	215
Pressure (psi)	15	368

Design Data:	Volumetric Flow Rate	1803 gal/min	Power Source	Electric motor
	Head	1018 ft	Efficiency	81.0%
	Case-Split	Horizontal split-case	Shaft Speed	3600 RPM
	Fluid Power	371 HP (277 kW)	Motor Enclosure	Open, drip-proof
	Brake Power	458 HP (342 kW)	Motor Efficiency	92.7%
	Material	Cast iron	Power Consumption	494 HP (369 kW)

	Each			Total
	Pump	Motor	Pump and Motor	
F.O.B. Purchase Cost	$ 171,000	$ 29,000	$ 200,000	$ 400,000
Bare Module Cost	$ 564,000	$ 96,000	$ 660,000	$ 1,320,000

Pump Cost Source: Aspen Process Economic Analyzer V7.3.1

Motor Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

P-3

Item	Centrigual pump + Electric motor
No. Required	2 (1 main + 1 spare)
Function:	Increases the pressure of the condensed water in the flue gas cooling cycle prior to entering the flue gas/cooling water heat exchanger, driving a Rankine cycle and producing usable electricity
Operation:	Continuous

Stream Data

	Entry	Exit
Stream No.	W-511	W-512
Flow Rate (lb/hr)	389928	389928
Vapor Fraction	0	0
Temperature (F)	214	215
Pressure (psi)	15	730

Design Data:	Volumetric Flow Rate	974 gal/min	Power Source	Electric motor
	Head	2064 ft	Efficiency	76.9%
	Case-Split	Horizontal split-case	Shaft Speed	3600 RPM
	Fluid Power	406 HP (303 kW)	Motor Enclosure	Open, drip-proof
	Brake Power	529 HP (394 kW)	Motor Efficiency	92.8%
	Material	Cast iron	Power Consumption	570 HP (425 kW)

	Each			Total
	Pump	Motor	Pump and Motor	
F.O.B. Purchase Cost	$ 159,000	$ 31,400	$ 190,400	$ 380,800
Bare Module Cost	$ 525,000	$ 104,000	$ 628,000	$ 1,256,000

Pump Cost Source: Aspen Process Economic Analyzer V7.3.1

Motor Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

ST-1		
Item	Condensing expansion steam turbine	
No. Required	1	
Function:	Expands hot, high pressure steam from FT cooling channels to low pressure steam, driving a Rankine cycle and producing usable electricity	
Operation:	Continuous	
Stream Data		
	Entry	Exit
Stream No.	W-501	W-502
Flow Rate (lb/hr)	721911	721911
Vapor Fraction	1	0.912
Temperature (F)	446	229
Pressure (psi)	363	20
Design Data:	Utility Produced	Electricity
	Power Produced	45228 HP (33.8 MW)
	Inlet Volumetric Flow Rate	97372 cuft/min
	Material	Carbon steel
	Efficiency	72.0%
F.O.B. Purchase Cost	$ 4,202,000	
Bare Module Cost	$ 13,490,000	

Cost Source: http://midwestcleanenergy.org/archive/pdfs/060216_industrial_steam.pdf

ST-2		
Item	Condensing expansion steam turbine	
No. Required	1	
Function:	Expands hot, high pressure steam in the flue gas cooling cycle to low pressure steam, driving a Rankine cycle and producing usable electricity	
Operation:	Continuous	
Stream Data		
	Entry	Exit
Stream No.	W-509	W-510
Flow Rate (lb/hr)	389928	389928
Vapor Fraction	1	1
Temperature (F)	1022	402
Pressure (psi)	725	20
Design Data:	Utility Produced	Electricity
	Power Produced	43015 HP (32.1 MW)
	Inlet Volumetric Flow Rate	7627 cuft/min
	Material	Carbon steel
	Efficiency	72.0%
F.O.B. Purchase Cost	$ 3,997,000	
Bare Module Cost	$ 12,831,000	

Cost Source: http://midwestcleanenergy.org/archive/pdfs/060216_industrial_steam.pdf

GT-1

Item	Gas turbine
No. Required	1
Function:	Generates electricity from excess light fuel gases by compressing air, combusting the fuel gases in that air, and expanding the hot pressurized flue gas to drive an electrical generator
Operation:	Continuous

Stream Data

	Entry		Exit
Stream No.	F-408	F-409	F-410
Flow Rate (lb/hr)	72356	984300	1056656
Mole Fractions			
CO_2	16.7%	0%	6.1%
CO	24.2%	0%	0%
N_2	2.4%	79.0%	75.5%
H_2O	0.2%	0%	7.8%
H_2	48.4%	0%	0%
O_2	0%	21.0%	10.6%
alkanes	8.1%	0%	0%
Vapor Fraction	1	1	1
Temperature (F)	81	77	1477
Pressure (psi)	218	15	29

Design Data:	Utility Produced	Electricity	Shaft Speed	6100 RPM
	Power Produced	48105 HP (35.9 MW)	Firing Temperature	2350 F
	Material	Low alloy steel	Efficiency	38.7%

F.O.B. Purchase Cost	$ 28,800,000
Bare Module Cost	$ 57,600,000

Cost Source: Gas Turbine World, 2012 GTW Handbook, Volume 29

SR-1				
Item	Vertical pressure vessel			
No. Required	2			
Function:	Removes sulfur compounds from the natural gas feed to the SMR to a level that prevents SMR catalyst poisoning (< 0.5 ppm w/w sulfur)			
Operation:	Continuous			
Stream Data				
	Entry		Exit	
Stream No.	G-102		G-103	
Flow Rate (lb/hr)	124451		124449	
Sulfur Concentration	8.1 ppm w/w		< 0.1 ppm w/w	
Temperature (F)	700		700	
Pressure (psi)	213		211	
Design Data:	Catalyst	Zinc Oxide Desulfurization Adsorbent by Northwest Research Institute of Chemical Industry	Diameter	5 ft
	Catalyst Bulk Density	69 lb/ft^3 (1100 kg/m^3)	Height	15 ft
	Total Mass of Catalyst	19908 lb	Volume	290 ft^3
	Gas Hourly Space Velocity	1500 hr^{-1}	Material	Carbon Steel
	Residence Time	2.4 s	Operating Pressure	15 bar
	Operating Temperature	700 F		
	Each			Total
	Vessel	Platforms and Ladders	Vessel + Platforms and Ladders	
F.O.B. Purchase Cost	$ 41,000	$ 8,000	$ 49,000	$ 98,000
Bare Module Cost	$ 171,000	$ 33,000	$ 204,000	$ 408,000
Catalyst Cost	$ 174,000	@ $300/cuft		

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

Catalyst Cost Source: "HTGR Integrated Hydrogen Production via Steam Methane Reforming Economic Analysis"; Idaho National Laboratory; 2010

V-1				
Item	Vertical pressure vessel			
No. Required	1			
Function:	Separates FT products into liquid waste water, heavier alkane product, and light hydrocarbon gas byproducts			
Operation:	Continuous			
Stream Data				
	Inlet	Outlets		
Stream No.	P-303	P-304	P-305	P-306
Flow Rate (lb/hr)	773678	141628	424686	207364
Flow Rate (lbmol/hr)	35745	770	23567	11408
Mass Fractions				
CO_2	11%	1%	0%	40%
CO	10%	0%	0%	37%
N_2	1%	0%	0%	4%
H_2O	55%	0%	100%	0%
H_2	1%	0%	0%	5%
CH_4	1%	0%	0%	4%
C_2H_6-C_5H_{12}	3%	3%	0%	8%
C_6H_{14}-$C_{11}H_{24}$	5%	23%	0%	1%
$C_{12}H_{26}$-$C_{20}H_{42}$	6%	32%	0%	0%
$C_{21}H_{44}$+	7%	40%	0%	0%
Vapor Fraction	0.34	0.00	0.00	1.00
Temperature (F)	80.6	80.6	80.6	80.6
Pressure (psi)	357	218	218	218
Design Data:	Flash Type	V-L-L Equilibrium	Diameter	6.5 ft
	Material	Carbon Steel	Height	19 ft
	Residence Time	5 min	Volume	630 ft^3
	Operating Pressure	15 bar	Operating Temperature	81 F
	Vessel	Platforms and Ladders	Total	
F.O.B. Purchase Cost	$ 64,000	$ 12,000	$ 76,000	
Bare Module Cost	$ 266,000	$ 50,000	$ 316,000	

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-1				
Item	Floating head shell-and-tube heat exchanger			
No. Required	1			
Function:	Use hot flue gas from SMR furnace to preheat natural gas feed into desulfulization bed			
Operation:	Continuous			
Stream Data				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	G-101	G-102	F-406	F-407
Flow Rate (lb/hr)	124451	124451	954665	954665
Vapor Fraction	1	1	1	1
Temperature (F)	70	700	1186	1007
Pressure (psi)	217.6	212.6	33.5	28.5
Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	20 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	687 F	Tube Length	20 ft
	Area	3722 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	51146390 Btu/hr
	Each	Total		
F.O.B. Purchase Cost	$ 54,000	$ 54,000		
Bare Module Cost	$ 171,000	$ 171,000		

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-2

Item	Floating head shell-and-tube heat exchanger
No. Required	2
Function:	SMR economizer that preheats natural gas and steam feed using hot flue gas from furnace
Operation:	Continuous

Stream Data

	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	G-105	G-106	F-405	F-406
Flow Rate (lb/hr)	502028	502028	954665	954665
Vapor Fraction	0.99	1	1	1
Temperature (F)	403	1200	2000	1186
Pressure (psi)	363	358	39	34

Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	20 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	792 F	Tube Length	20 ft
	Area (per exchanger)	7755 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	245669206 Btu/hr

	Each	Total
F.O.B. Purchase Cost	$ 89,000	$ 178,000
Bare Module Cost	$ 282,000	$ 564,000

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-3

Item	Floating head shell-and-tube heat exchanger
No. Required	6
Function:	Use hot syngas from SMR-1 to preheat air and light fuel gases entering the reforming furnace
Operation:	Continuous

Stream Data

	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	F-403	F-404	G-107	G-108
Flow Rate (lb/hr)	954665	954665	502028	502028
Vapor Fraction	1	1	1	1
Temperature (F)	77	1581	1800	594
Pressure (psi)	44	39	356	351

Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	20 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	348 F	Tube Length	20 ft
	Area (per exchanger)	10146 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	423694095 Btu/hr

	Each	Total
F.O.B. Purchase Cost	$ 109,500	$ 657,000
Bare Module Cost	$ 347,000	$ 2,082,000

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-4

Item	Floating head shell-and-tube heat exchanger
No. Required	1
Function:	Uses R-134a refrigerant to cool hot syngas from the coal gasifier prior to entering the Rectisol separation system
Operation:	Continuous

Stream Data

	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	R-601	R-602	C-208	C-209
Flow Rate (lb/hr)	463448	463448	381133	381133
Vapor Fraction	0	1	0.86	1
Temperature (F)	-15	-15	212	32
Pressure (psi)	14.7	14.7	367	362

Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	30 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	114 F	Tube Length	20 ft
	Area	12695 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	43416328 Btu/hr

	Each	Total
F.O.B. Purchase Cost	$ 131,000	$ 131,000
Bare Module Cost	$ 415,000	$ 415,000

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-5

Item	Floating head shell-and-tube heat exchanger			
No. Required	1			
Function:	Uses cooling water to condense steam from turbine outlet in the FT cooling cycle, driving a Rankine cycle and producing usable electricity			
Operation:	Continuous			

Stream Data

	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	W-505	W-506	W-502	W-503
Flow Rate (lb/hr)	22275719	22275719	721985	721985
Vapor Fraction	0	0	0.912	0
Temperature (F)	90	120	229	214
Pressure (psi)	20	15	20	15

Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	700 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	116 F	Tube Length	20 ft
	Area	8202 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	666017246 Btu/hr

	Each	Total
F.O.B. Purchase Cost	$ 93,000	$ 93,000
Bare Module Cost	$ 295,000	$ 295,000

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-6				
Item	Floating head shell-and-tube heat exchanger			
No. Required	3			
Function:	Use chilled water to cool the hot FT products to the optimal flash separation temp			
Operation:	Continuous			
Stream Data				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	W-507	W-508	P-302	P-303
Flow Rate (lb/hr)	19544248	19544248	773753	773753
Vapor Fraction	0	0	0.99	0.34
Temperature (F)	40	70	464	81
Pressure (psi)	19.7	14.7	362	357
Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	150 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	156 F	Tube Length	20 ft
	Area (per exchanger)	8349 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	586072685 Btu/hr
	Each	Total		
F.O.B. Purchase Cost	$ 94,000	$ 282,000		
Bare Module Cost	$ 298,000	$ 894,000		

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-7

Item	Floating head shell-and-tube heat exchanger			
No. Required	8			
Function:	Reduces temp. of hot flue gas from SMR furnace and gas turbine to a level acceptable for release into the environment by heating pressurized water to steam, driving a Rankine cycle and producing usable electricity			
Operation:	Continuous			
Stream Data				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	W-512	W-509	F-411	F-412
Flow Rate (lb/hr)	381846	381846	2011322	2011322
Vapor Fraction	0	1	1	1
Temperature (F)	216	1022	1251	320
Pressure (psi)	730	725	29	24
Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	35 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	162 F	Tube Length	20 ft
	Area (per exchanger)	11505 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	521867443 Btu/hr
	Each	Total		
F.O.B. Purchase Cost	$ 121,000	$ 968,000		
Bare Module Cost	$ 384,000	$ 3,072,000		

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

HX-8

Item	Floating head shell-and-tube heat exchanger
No. Required	1
Function:	Uses cooling water to condense steam from turbine outlet in the flue gas cooling cycle, driving a Rankine cycle and producing usable electricity
Operation:	Continuous

Stream Data

	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	W-513	W-514	W-510	W-511
Flow Rate (lb/hr)	13913866	13913866	381846	381846
Vapor Fraction	0	0	1	0
Temperature (F)	90	120	402	214
Pressure (psi)	20	15	20	15

Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	700 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	192 F	Tube Length	20 ft
	Area	3095 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	416007869 Btu/hr

	Each	Total
F.O.B. Purchase Cost	$ 49,000	$ 49,000
Bare Module Cost	$ 155,000	$ 155,000

Cost Source: Seider et al.; Product and Process Design Principles, 3rd Edition; 2009

CC-1

Item	Floating head shell-and-tube heat exchanger
No. Required	1
Function:	Uses hot syngas from the coal gasifier (GAS-1) to heat the cold process water feed to the reformer
Operation:	Continuous

Stream Data

	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	BW-702	BW-703	C-207	C-208
Flow Rate (lb/hr)	20958	20958	19728	19728
Vapor Fraction	0	0.19	1	0.86
Temperature (F)	78	434	1250	212
Pressure (psi)	363	358	372	367

Design Data:	Flow Type	Counter-current	No. of Tube Passes	2
	U	300 Btu/(hr-sqft-R)	No. of Shell Passes	1
	LMTD	175 F	Tube Length	20 ft
	Area (per exchanger)	4039 sqft	Tube Pitch	1.25 in (triangular)
	Material	Carbon Steel	Duty	212067398 Btu/hr

	Each	Total
F.O.B. Purchase Cost	$ 57,000	$ 57,000
Bare Module Cost	$ 181,000	$ 181,000

Cost Source: Aspen Process Economic Analyzer V7.3.1

ASU-1		
Item	Air separation unit	
No. Required	1	
Function:	Separates air to produce oxygen	
Operation:	Continuous	
Stream Data		
	Inlet	Outlet
Stream No.	C-204	C-205
Total Flow Rate (lb/hr)	803428	187102
Component Mole Flows (lbmol/hr)		
CO_2	0	0
CO	0	0
N_2	21996	0
H_2O	0	0
H_2	0	0
O_2	5847	5847
H_2S	0	0
CH_4	0	0
C_2H_6-C_5H_{12}	0	0
C_6H_{14}-$C_{11}H_{24}$	0	0
$C_{12}H_{26}$-$C_{20}H_{42}$	0	0
$C_{21}H_{44}$+	0	0
Temperature (F)	77	77
Pressure (psi)	15	353
Design Data:	Operating Pressure	73 psi
	Air Compressor Power	28 MW
F.O.B. Purchase Cost	-	
Bare Module Cost	$ 57,190,000	

Cost Source: "Cost and Performance Baseline for Fossil Energy Plants," NETL 2010

SP-1			
Item	Coal Receiving and Handling		
No. Required	1		
Function:	Receives coal, stores, crushes, prepares coal-water slurry		
Operation:	Continuous		
Stream Data			
	Inlet		Outlet
Stream No.	C-201	C-202	C-203
Total Flow Rate (lb/hr)	216053	52069	268122
Component Mole Flows (lbmol/hr)			
CO_2	0	0	0
CO	0	0	0
N_2	0	0	0
H_2O	0	2890	2890
H_2	0	0	0
O_2	0	0	0
H_2S	0	0	0
CH_4	0	0	0
C_2H_6-C_5H_{12}	0	0	0
C_6H_{14}-$C_{11}H_{24}$	0	0	0
$C_{12}H_{26}$-$C_{20}H_{42}$	0	0	0
$C_{21}H_{44}$+	0	0	0
Coal Mass Flow (lb/hr)	216053	0	216053
Temperature (F)	450	794	77
Pressure (psi)	353	353	353
Design Data:	Coal Handling Capacity	2593 tons per day	
	Components	Coal Storage	Conveyor
		Crusher	Mill
		Hopper	Slurry Vessel
		Slurry Agitator	Slurrry Pump
F.O.B. Purchase Cost	-		
Bare Module Cost	$ 46,830,000		

Cost Source: "Cost and Performance Baseline for Fossil Energy Plants," NETL 2010

RECT-1			
Item	Rectisol acid-gas removal		
No. Required	1		
Function:	Removes acid gas from coal syngas		
Operation:	Continuous		
Stream Data			
	Inlet	Outlet	
Stream No.	C-209	C-210	C-212
Total Flow Rate (lb/hr)	317235	272030	45205
Component Mole Flows (lbmol/hr)			
CO_2	1144	172	972
CO	8947	8947	0
N_2	55	55	0
H_2O	5	5	0
H_2	5942	5942	0
O_2	0	0	0
H_2S	71	0	71
CH_4	17	17	0
C_2H_6-C_5H_{12}	0	0	0
C_6H_{14}-$C_{11}H_{24}$	0	0	0
$C_{12}H_{26}$-$C_{20}H_{42}$	0	0	0
$C_{21}H_{44}$+	0	0	0
Temperature (F)	32	32	32
Pressure (psi)	362	362	362
Design Data:	Operating Temperature	0 F	
	Recycled Methanol Rate	3800 lbmol/hr	
F.O.B. Purchase Cost	-		
Bare Module Cost	$ 78,750,000		

Cost Source: "Cost and Performance Baseline for Fossil Energy Plants," NETL 2010

Section 11 - Economic Analysis

Capital Investment

Table 4

Equipment	**Bare Module Cost**
Coal Gasifier (GAS-1)	$145,600,000
Steam Methane Reformer (SMR-1)	$139,900,000
Rectisol (RECT-1)	$78,750,000
Gas Turbine System (GT-1)	$57,600,000
Air Separation Unit (ASU-1)	$57,190,000
Coal Receiving and Handling (SP-1)	$46,830,000
Fischer Tropsch Reactor (FT-1)	$17,800,000
Steam Turbine 1 (ST-1)	$13,490,000
Steam Turbine 2 (ST-2)	$12,830,000
Compressor 1 (CP-1)	$3,500,000
Heat Exchanger 7 (HX-7)	$3,070,000
Compressor 2 (CP-2)	$2,950,000
Heat Exchanger 3 (HX-3)	$2,080,000
SMR catalyst	$1,330,000
Heat Exchanger 6 (HX-6)	$890,000
Pump 2 (P-2)	$660,000
Pump 2 Spare (P-2)	$660,000
Pump 3 (P-3)	$630,000
Pump 3 Spare (P-3)	$630,000
Heat Exchanger 2 (HX-2)	$560,000
Fischer Tropsch Catalyst	$500,000
Heat Exchanger 4 (HX-4)	$420,000
Sulfur Removal Bed (SR-1)	$410,000
Pump 1 (P-1)	$370,000
Pump 1 Spare (P-1)	$370,000
Flash Separation Vessel (V-1)	$320,000
Heat Exchanger 5 (HX-5)	$290,000
Convective Cooler (CC-1)	$180,000
Heat Exchanger 1 (HX-1)	$170,000
Sulfur Removal Sorbent	$170,000
Heat Exchanger 8 (HX-8)	$160,000
Total Bare Module Cost	**$590,310,000**

The costs for all pumps, compressors, heat exchangers, and flash vessels were estimated using Aspen Economic Evaluator and the equations provided in *Seider et al*. The costs for the more sophisticated units were estimated by making appropriate scaling and inflation adjustment s to reference units that were found in the literature. This approach was used for the coal gasifier, steam methane reformer, Fischer-Tropsch reactor, solids handling, air separation unit, Rectisol plant, and the gas turbine. Details for the reference units and scaling calculations can be found in the appendix. The total bare module cost for all of the equipment was estimated to be $590 million.

The steam methane reformer and coal gasifier account for a large portion of the equipment costs, at a total of $286 million, or 48% of the total cost. Efforts to more accurately cost this project should therefore be focused on these more expensive units, because they have a huge effect of the potential profitability of the project.

The of site preparations and service facilities were assumed to be 5% of the total bare module costs, resulting in direct permanent investment of $650 million. Contingencies and contractor fees are estimated at 18% of direct permanent investment, so the total depreciable capital was calculated to be $767 million. Finally, land and plant startup were assumed to cost 2% and 18% percent of total depreciable capital, respectively. To account for the location of the plant in southwestern Pennsylvania, the total permanent investment was adjusted by a site factor of 1.10. The adjusted total permanent investment of this project is projected to be $945 million.

Table 5

Total Capital Cost Summary	(Millions)
Bare Module Costs	**$590.9**
Cost of Site Preparations	*$29.5*
Cost of Service Facilities	*$29.5*
Direct Permanent Investment	**$649.9**
Cost of Contingencies and Contractor Fees	*$117.0*
Total Depreciable Capital	**$766.9**
Cost of Land	*$15.3*
Cost of Plant Startup	*$76.7*
Total Permanent Investment (Unadjusted)	**$859.0**
Site Factor	*1.10*
Total Permanent Investment	**$944.9**

Fixed Costs

Every year that the plant is in operation there are operations costs, maintenance costs, operating overhead costs, and property taxes and insurance. These are all fixed costs that are incurred regardless of the level of syncrude production.

Table 6

Fixed Cost Summary		
Operations		
Direct Wages and Benefits	$	2,912,000
Direct Salaries and Benefits	$	437,000
Operating Supplies and Servic	$	175,000
Total Operations	**$**	**3,524,000**
Maintenance		
Wages and Benefits	$	37,799,000
Salaries and Benefits	$	9,450,000
Materials and Services	$	37,799,000
Maintenance Overhead	$	1,890,000
Total Maintenance	**$**	**86,937,000**
Operating Overhead		
General Plant Overhead:	$	3,592,000
Mechanical Department Servic	$	1,214,000
Employee Relations Departmen	$	2,985,000
Business Services:	$	3,744,000
Total Operating Overhead	**$**	**11,536,000**
Property Taxes and Insurance		
Property Taxes and Insurance:	$	16,799,000
Total Fixed Costs	**$**	**118,796,000**

Eight operators per shift were included in the direct wages and benefits estimation: 2 operators for each of Blocks G and P, and 4 operators for Block C. Each operator’s wage is estimated at the typical rate ($35/hr) for operators in the United States. Maintenance wages and benefits were escalated from the standard fluids-processing-only level of 3.5% of total depreciable capital to 4.5% for solids-fluids-processing.

The rest of the fixed costs are unchanged from the standard estimates described by *Seider et al*. The total annual fixed costs are $119MM. These costs are summarized in Table 6.

Variable Costs

Every year that the plant is producing product there are general expenses, raw material cost, and utility costs. These are variable costs that depend on the level of production or the quantity of sales in any given year. All syncrude produced is assumed to be sold, so no distinction is made between these two dependencies. Table 7 summarizes the variable costs, taking the syncrude production level into account, for the first four years of production. Production capacity levels off at 90% in 2016. Thus, the variable costs in 2016 and 2017 are representative of the majority of the operating years of the plant. The general expenses are based on the estimates of *Seider et al.* The selling / transfer expenses are set as 3% of sales, the administrative expense is set as 2% of sales, and the management incentive compensation is set as 1.25% of sales. No direct or allocated research is included because there is minimal quality control or additional research necessary. The natural gas and coal prices were projected using

Table 7

Variable Cost Summaries (millions of $)					
	Year	2014	2015	2016	2017
	Production Capacity	45%	68%	90%	90%
General Expenses					
Selling / Transfer		$ 6.9	$ 10.4	$ 13.8	$ 13.8
Administrative		$ 4.6	$ 6.9	$ 9.2	$ 9.2
Management Incentive Compensation		$ 2.9	$ 4.3	$ 5.8	$ 5.8
Total General Expenses		**$ 14.4**	**$ 21.6**	**$ 28.8**	**$ 28.8**
Raw Materials					
Natural Gas	(0.1672 short ton/barrel syncrude)	$ 45.6	$ 70.0	$ 93.7	$ 95.5
Coal	(4.341 thous. scf/barrel syncrude)	$ 24.9	$ 37.9	$ 50.3	$ 50.9
Total Raw Materials		**$ 70.4**	**$ 107.9**	**$ 144.0**	**$ 146.4**
Utilities					
Refrigeration	(0.0712 GJ/barrel syncrude)	$ 1.0	$ 1.5	$ 2.1	$ 2.1
Cooling Water	(56462 lb/barrel syncrude)	$ 1.1	$ 1.7	$ 2.2	$ 2.2
Chilled Water	(30244 lb/barrel syncrude)	$ 8.3	$ 12.4	$ 16.6	$ 16.6
Electricity (consumed)	(52.9 kWh/barrel syncrude)	$ 9.2	$ 13.7	$ 18.3	$ 18.3
Electricity (generated)	(156.3 kWh/barrel syncrude)	$(27.1)	$ (40.6)	$ (54.1)	$ (54.1)
Process Water	(332.5 lb/barrel syncrude)	$ 0.2	$ 0.2	$ 0.3	$ 0.3
Total Utilities		**$ (7.3)**	**$ (11.0)**	**$ (14.6)**	**$ (14.6)**
Total Variable Costs		**$ 77.5**	**$ 118.5**	**$ 158.2**	**$ 160.6**

the Energy Information Administration's (EIA) *2012 Annual Energy Outlook* report. This report supplies projections through 2035. The projection was extended to 2043 using the average annual growth rate for the last three years of the study. The price of natural gas fluctuates to a much greater degree than the price of coal over this period. Natural gas prices range from \$4.86/thous. scf to \$9.22/thous. scf, and coal prices range from \$68.74/short ton to \$81.71/short ton. Finally, the utilities costs are actually a credit because of the high electricity production of the plant. This helps decrease the overall variable costs. The utilities are detailed further in the Section 8 - Energy Balance and Utility Requirements. The prices for all utilities except for electricity are taken from the estimates of *Seider et al*, and the price of electricity is estimated in the EIA's 2012 report.

Sales

The process has been designed to produce 15,500 barrels per day of liquid products. For the purposes of economic analysis, it is assumed that 90% of that capacity is actually produced, beginning in the second year of production. It has been assumed that the product will be sold as crude to a refinery for further separating and upgrading to various petroleum products. Therefore the product price used is the price of low sulfur crude oil.

Because the price of oil is expected to vary over the course of the study, future projections for the price of oil were obtained from the Energy Information Administration's *2012 Annual Energy Outlook*. This report projects the price of oil to increase from \$110 per barrel in 2014 to \$145 per barrel in 2035, the last year of the EIA study. To extend the projection out to 2043, the average growth rate from the last three years was used.

The profitability of this venture is highly dependent on the price of oil, so high and low oil price scenarios were also evaluated and are discussed in the sensitivity analysis section of this report.

Profitability

To evaluate the profitability of this process, a cash flow analysis was done using the information described in the preceding sections. It was assumed that there would be one year each for design and construction, and 30 years of production. Pennsylvania has a flat 9.99%

corporate tax rate, which combined with a 35% federal corporate tax rate, results in an effective tax rate of 41.5%. The plant is assumed to operate 310 days per year at 90% of the designed capacity.

The net present value of the project was evaluated under several scenarios at discount rates of 10%, 15%, and 20%. Internal rates of return were also calculated. The cash flow for the baseline EIA oil price and regular assumptions at a discount rate of 15% is shown on the following page. For this baseline scenario, the project has a net present value of $94 million and an IRR of 16.7%.

In addition to the baseline EIA oil price scenario, the profitability was evaluated at high and low oil price scenarios, at 10% above or below the EIA baseline. The results are shown in Table 8. As shown in the table, changes in the price of oil can have a large effect on the on profitability of the project. Holding other costs constant, the price of oil can drop as far as 6% below the EIA projections and the project will still be profitable at a 15% discount rate.

Table 8

Oil Price Sensitivity	**Net Present Value ($MM)**			**IRR**
	10%	*15%*	*20%*	
High Oil Prices (+10%)	777	233	(44)	19.0%
Baseline Oil Prices	546	94	(136)	16.7%
Low Oil Prices (-10%)	316	(45)	(228)	14.1%

Because there is a low level of certainty in the capital costs at this point in the analysis of this project, profitability was also evaluated at increased and decreased total permanent investment, ranging for 20% below to 20% above the baseline case. The results shown in Table 9 demonstrate that the capital costs have a significant effect on the overall profitability of the project.

Table 9

Total Permanent Investment ($MM)		**Net Present Value ($MM)**			**IRR**
		10%	*15%*	*20%*	
+20%	1,134	375	(70)	(293)	13.9%
+10%	1,039	461	12	(215)	15.2%
Baseline	945	546	94	(136)	16.7%
-10%	850	632	176	(57)	18.5%
-20%	756	718	259	22	20.6%

Cash Flow for EIA Baseline Projections

Year	Oil Price	Sales	Capital Costs	Working Capital	Total Costs	Depreciation	Taxable Income	Taxes	Net Earnings	Cash Flow	Cumulative NPV, 15%
2012		-	-	-	-	-	-	-	-	-	-
2013		-	(944.9)	(26.2)	-	-	-	-	-	(971.0)	(844.4)
2014	$110.43	238.8	-	(13.1)	(186.4)	(153.4)	(101.0)	41.9	(59.1)	81.2	(783.0)
2015	$116.55	378.0	-	(13.1)	(227.4)	(245.4)	(94.8)	39.3	(55.5)	176.9	(666.7)
2016	$119.58	517.1	-	-	(267.1)	(147.3)	102.7	(42.6)	60.1	207.4	(548.1)
2017	$122.78	530.9	-	-	(269.5)	(88.4)	173.1	(71.8)	101.3	189.6	(453.9)
2018	$124.03	536.4	-	-	(272.2)	(88.4)	175.9	(73.0)	102.9	191.2	(371.2)
2019	$125.30	541.9	-	-	(274.6)	(44.2)	223.1	(92.6)	130.5	174.7	(305.5)
2020	$126.58	547.4	-	-	(276.4)	-	271.0	(112.5)	158.6	158.6	(253.7)
2021	$127.74	552.4	-	-	(280.3)	-	272.1	(112.9)	159.2	159.2	(208.4)
2022	$128.97	557.7	-	-	(285.6)	-	272.1	(112.9)	159.2	159.2	(169.1)
2023	$130.15	562.8	-	-	(289.0)	-	273.8	(113.6)	160.2	160.2	(134.7)
2024	$131.33	567.9	-	-	(291.6)	-	276.3	(114.7)	161.6	161.6	(104.4)
2025	$132.50	573.0	-	-	(293.5)	-	279.5	(116.0)	163.5	163.5	(77.9)
2026	$133.67	578.1	-	-	(297.7)	-	280.4	(116.4)	164.0	164.0	(54.7)
2027	$134.85	583.2	-	-	(300.8)	-	282.4	(117.2)	165.2	165.2	(34.4)
2028	$135.97	588.0	-	-	(301.4)	-	286.6	(119.0)	167.7	167.7	(16.5)
2029	$137.18	593.2	-	-	(300.6)	-	292.6	(121.4)	171.2	171.2	(.6)
2030	$138.51	599.0	-	-	(302.1)	-	296.9	(123.2)	173.7	173.7	13.5
2031	$139.79	604.5	-	-	(306.0)	-	298.5	(123.9)	174.6	174.6	25.7
2032	$141.02	609.8	-	-	(310.8)	-	299.0	(124.1)	174.9	174.9	36.4
2033	$142.13	614.6	-	-	(314.0)	-	300.6	(124.8)	175.9	175.9	45.8
2034	$143.41	620.2	-	-	(317.4)	-	302.8	(125.7)	177.2	177.2	54.0
2035	$144.56	625.1	-	-	(321.9)	-	303.3	(125.9)	177.4	177.4	61.1
2036	$145.76	630.3	-	-	(325.7)	-	304.6	(126.4)	178.2	178.2	67.3
2037	$146.97	635.6	-	-	(329.7)	-	305.9	(127.0)	179.0	179.0	72.8
2038	$148.19	640.8	-	-	(333.7)	-	307.2	(127.5)	179.7	179.7	77.5
2039	$149.42	646.1	-	-	(337.8)	-	308.3	(128.0)	180.4	180.4	81.6
2040	$150.65	651.5	-	-	(342.0)	-	309.5	(128.4)	181.1	181.1	85.3
2041	$151.90	656.9	-	-	(346.3)	-	310.6	(128.9)	181.7	181.7	88.4
2042	$153.16	662.4	-	-	(350.7)	-	311.6	(129.3)	182.3	182.3	91.2
2043	$154.43	667.9	-	52.4	(355.3)	-	312.6	(129.7)	182.9	235.2	94.3

Conclusion

Under the baseline cost and price scenario at a discount rate of 15%, the project appears to be profitable, with a net present value of $94 million. However, changes in the overall cost of the project or the price of oil, among other factors, could have a large impact on that profitability. The price of oil is subject to factors that are very difficult to predict with good accuracy. On the other hand, the capital costs of the project can be better estimated as the project progresses and more engineering and design work is completed. Because the main reactors are such a large part of the total cost, it is recommended that efforts to refine cost estimates are focused on these units.

The cost of capital is also an important consideration in the profitability of this project. While this project has been evaluated at discount rates of 10%, 15%, and 20%, the capital situation for any particular firm considering the project should be taken into account. Given that the IRR of the project in the baseline scenario is 16.7%, a company with a hurdle rate below the IRR may view this as an attractive project. The capital position of interested firms is therefore also an important factor to determine whether this is a worthwhile undertaking.

Section 12 - Other Considerations

Plant Safety

Three main types of safety risks exist throughout this process. A safety threat can be can be categorized as either: high temperature and pressure, flammability, or chemical exposure. The most obvious safety hazard is the presence of highly combustible fluids throughout the process. Although the feed and product streams do not contain oxygen, any leak could lead to a runaway fire. The risk of leaks is compounded by the fact that most of the process operates around 300 psi. Proper maintenance and replacement of worn parts is essential to mitigate this threat.

The next potential source of accidents is related to the high operating temperature and pressure. Most fluids throughout the process are at over 300°F and about 20 bar. As result, third degree burns are a persistent danger. It is important to design and construct all vessels to meet and exceed the desired operating conditions. Additionally, personnel should avoid direct contact with high temperature streams.

Although dangerous chemicals are not directly added to this process, dangerous products are produced throughout the process as both desired and undesired products. Carbon monoxide is generated in both the coal gasifier and the steam methane reformer. This compound is a necessary feed for the FT reactor, but it is also toxic to people. Carbon monoxide leaks are especially more dangerous because the gas is colorless and odorless. In order to mitigate any risk it is recommended that operators wear gas meters that can detect CO in the atmosphere. Proper ventilation of the facility also contributes to reducing the risk of carbon monoxide poisoning.

Environmental

The FT reactor produces a waste water stream that is separated from the final product stream near the end of the process. This waste water stream contains trace amounts of hydrocarbons, and to avoid polluting nearby water bodies, it was determined that the water could be sold to nearby gas drilling facilities. The water would be used for hydraulic fracturing. Hot exhaust gases from the combustion of light hydrocarbons are treated in order to remove all sulfur content and cooled before releasing it into the atmosphere.

Plant Startup

In order to minimize utility costs, light hydrocarbon gases recovered from the FT process are combusted in the steam reformer to heat the endothermic reaction within the packed tubes. During plant startup, this stream is not available. During the initial operation of the plant, the SMR reactor is not active, only the coal gasification section provides the FT reactor with syngas. As this gas is processed and converted to hydrocarbons, light hydrocarbons will become available to the SMR reactor for combustion. As this happens the SMR reactor will begin to process natural gas and provide an increasing stream of syngas until it reaches a steady state flow rate. Along with not having light hydrocarbons as a fuel source, the inlet SMR feed requires a supply of steam, which originates from the coal gasification section. This means that the steam reforming section can only operate once the coal gasification unit is online.

Section 13 - Alternative Process Options

Several alternate pathways could have been taken to produce syngas with a H_2/CO molar ratio of 2 using natural gas and coal. One potential approach is to use a shell-and-tube type piece of equipment in which steam methane reforming takes place in the tubes and coal gasification takes place in the larger surrounding shell. The two reactions are physically separate but this method offers the advantage of direct heat transfer from the exothermic partial oxidation coal gasification reaction to the endothermic methane reforming reaction. This would reduce or eliminate fuel requirements to sustain the SMR. The two outlet syngas streams would then be mixed for further processing. Another potential is to perform SMR inside the coal gasifier by injecting natural gas at some position. The SMR reaction would likely benefit from the catalytic effects of coal char and ash that are produced from gasification as well as the heat generated. However, this approach would cause the coal and natural gas to be mixed before removing sulfur and other impurities from the coal, making the impurities in the outlet syngas more dilute and difficult to separate.

The approach taken in this project uses the main idea from these alternatives but without the novel equipment. Heat generated from the exothermic coal gasification is transferred to the endothermic reforming reaction. The process water feed to the reformer is used as the vehicle for this heat transfer. Multiple heat exchangers transfer heat from the gasifier and the outlet coal syngas to boil feedwater to generate steam. This approach was chosen because the resulting process would have a greater basis in existing technologies and thus be more meaningful. Separate steam methane reformers and coal gasifiers are proven technologies, but a single unit that combines both is an untested possibility. A process design using such a unit would not be as substantial or feasible.

There were several different types of Fischer-Tropsch reactors available for the liquefied hydrocarbon product. The Fischer-Tropsch reactor configurations most commonly used in industry today are the slurry and fixed bed configurations. Both configurations have significantly lower conversion rates of carbon monoxide, typically 60% conversion per pass compared to the microchannel configuration with 85%+ conversion per pass. Higher conversions are attainable with the slurry and fixed bed reactor by adding a recycle; however, while this is common practice in industry, microchannel reactors can have significant advantages. The microchannel configuration is a recently developed technology within the past 6 years and currently has only one “proof of concept” industrial plant in service. With its significantly larger percent conversion of carbon monoxide per pass, simplified scalability, easier maintenance, unrivaled heat-transfer capabilities and secondary function as a steam supply for turbine power generation, the choice was made to implement the microchannel configuration.

Section 14 - Conclusions and Recommendations

A hybrid coal and natural gas to liquids process is technically and thermodynamically feasible, with both CTL and GTL processes having been successfully implemented elsewhere separately. The combined process designed here achieves the desired hydrogen to carbon dioxide ratio without the need for water-gas shift reactors, and heat from the coal gasifier is recovered as steam for the steam methane reformer. Additionally, this process is able to generate electricity from the gaseous output of the Fischer-Tropsch reactor.

The project is estimated to have a total capital cost of $945 million. Based on that estimate and EIA projections for the price of oil, coal, and natural gas, at a 15% discount rate this process will have a NPV of $94 million with an IRR of 16.7%. A company with a cost of capital less than the IRR may find this to be an attractive project to pursue further.

The profitability of the venture is especially dependent on the total capital investment and the price of the product. Future effort should be focused on more accurate costing of the main equipment, especially the gasifier, reformer, and Fischer-Tropsch reactor, which make up the majority of the capital cost. Additionally, because the liquid product does not have the same composition of crude, the product price may be over or under valued. For example, the product contains almost no sulfur, but also had a different distribution than regular crude.

The microchannel FT reactor design possesses favorable features that deserve future investigation and design improvements. The reactor setup has very favorable reaction kinetics, excellent heat transport (good temperature control) and high single pass conversion. However, this technology has not been applied on a commercial scale. Further research is required to determine if the promise shown on the bench scale can be translated to a larger project. There is also a large amount of uncertainty in the cost for this unit.

Section 15 - Acknowledgements

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Appendix

SMR-1 • Steam Methane Reformer Calculations

Kinetic Model

The SMR reactor design is based on currently available and utilized process units. Aspen IPE did not offer sufficient detail in order to produce an accurate cost estimation for the entire SMR reactor. This fact is especially true for components such as coffins and pigtails. The inlet pigtails are connected to the feedstock header. The header is responsible for bringing in the Natural gas feedstock, which is already combined with high-pressure steam. The inlet pigtails are each linked to an individual tube within the reactor, providing each packed reactor with a uniform flow of feed. At the bottom of the SMR reactor the coffin is responsible for even distribution of hot flue gases within the furnace box. The coffins, made of firebrick, have ports that transfer the flue gases to the convective section of the SMR. The product syngas exits the bottom of the packed tube reactors, through outlet pigtails and to a main outlet pipe. It was necessary to research scholarly articles in order to properly factor in the cost of some of the above-mentioned components in the reactor.

The number of packed tube reactors was estimated using reaction kinetics. The packed bed reactor tubes were assumed to be 24 feet, 3 inches long with an internal diameter of 3 inches and a wall thickness of 0.5 in. John Wismer provided these typical reactor dimensions. The number of reforming tubes was calculated using the kinetic model for the SMR reaction determined by Froment, Part II. For this calculation it was assumed that the reforming reaction was carried out under isothermal conditions. Initially a mass of catalyst (used as a reference value) is calculated by multiplying the bulk density of the catalyst and the volume of a reforming tube. An Excel spreadsheet was used in order to solve the production rate expression, below, for a chemical reaction through a packed bed under isothermal conditions.

$$\frac{dN_A}{dV} = -(1-\varepsilon)\eta(r_1 - r_2) \qquad (1)$$

In equation 1, *r* represents the reaction rate for the steam reforming reaction. The reaction rates are shown below. The constants used are shown in Table 10. They were given as a function of temperature and calculated at the operating temperature of the reformer.

$$r_1 = \frac{k_1}{p_{H_2}^{2.5}}\left(p_{CH_4}p_{H_2O} - \frac{p_{H_2}^3 p_{CO}}{K_1}\right)\Big/(DEN)^2 \qquad (2)$$

$$r_2 = \frac{k_2}{p_{H_2}}\left(p_{CO}p_{H_2O} - \frac{p_{H_2}p_{CO_2}}{K_2}\right)\Big/(DEN)^2 \qquad (3)$$

$$DEN = 1 + K_{CO}p_{CO} + K_{H_2}p_{H_2} + K_{CH_4}p_{CH_4} + K_{H_2O}p_{H_2O}/p_{H_2} \qquad (4)$$

Table 10

k_1	$4.32 \bullet 10^5$
k_2	$3.15 \bullet 10^3$
k_3	$7.24 \bullet 10^4$
K_1	6509.8
K_2	.6324
K_3	80012.7
$1-\varepsilon$	.31
η	.02
T (K)	1255

The Excel spreadsheet was set up such that it performed an Euler approximation in order to solve the differential equation based on a volume step. A 95% conversion was specified for the process. The number of steps/intervals used to calculate the volume of each volume step. The mass of catalyst required is determined by summing the amount of catalyst required for each volume step. In this way it is possible to calculate the mass of catalyst used to accomplish a specified overall conversion.

Adjusting the number of tubes in SMR-1 affects the inlet flow of the components through each tube. This in turn affects the mass of catalyst required to achieve the specified convergence. In order to determine the correct number of tubes, it is necessary to vary the number of tubes until the reference catalyst mass calculation matches the catalyst mass value obtained from the reaction kinetics.

Pressure Drop Through Tubes

Steam Methane Reformer Pressure Drop Calculation

$$\mu = 0.030\ \text{cP} \times 0.001\ \frac{\text{kg}}{\text{m}\cdot\text{s}} = 3.0\times10^{-5}\ \frac{\text{kg}}{\text{m}\cdot\text{s}}$$

$$\rho = 4.25\times10^{-3}\ \frac{\text{g}}{\text{cm}^3} \times \frac{1\ \text{kg}}{1000\ \text{g}} \times \frac{100^3\ \text{cm}^3}{1\ \text{m}^3} = 4.25\ \frac{\text{kg}}{\text{m}^3}$$

$$Q = 1.03\times10^{6}\ \frac{\text{L}}{\text{min}} \times \frac{1\ \text{m}^3}{1000\ \text{L}} \times \frac{1\ \text{min}}{60\ \text{s}} / 1511\ \text{tubes} = 1.14\times10^{-2}\ \text{m}^3/\text{s}$$

$$A = 4.56048\times10^{-3}\ \text{m}^2$$

$$u_0 = Q/A = 1.14\times10^{-2}\ \frac{\text{m}^3}{\text{s}} / 4.56048\times10^{-3}\ \text{m}^2 = 2.49\ \text{m/s}$$

$$D_p = 21.8\ \text{mm} = 0.0218\ \text{m} \qquad L = 7.315\ \text{m}$$

$$1-\varepsilon = \frac{\rho_b}{\rho_p} = \frac{1041.2\ \text{kg/m}^3}{3317.5\ \text{kg/m}^3} = .31 \Rightarrow \varepsilon = .686$$

$$Re = \frac{\rho u_0 D_p}{(1-\varepsilon)\mu} = \frac{(4.25)(2.17)(0.0175)}{(.31)(3.0\times10^{-5})} = 17354 \Rightarrow \text{Turbulent flow}$$

$$-\frac{\Delta P}{\rho u_0^2}\frac{D_p}{L}\frac{\varepsilon^3}{1-\varepsilon} = 1.75 \Longleftarrow \text{Ergun eqn}$$

$$\frac{\Delta P}{(4.25\ \text{kg/m}^3)(2.49\ \text{m/s})^2} \cdot \frac{0.0218\ \text{m}}{7.315\ \text{m}} \cdot \frac{(.686)^3}{.31} = 1.75$$

$$\Delta P = 15050\ \text{Pa} = 0.15\ \text{bar} = 2.18\ \text{psi}$$

GAS-1 • Coal Gasifier Model Summary

The Aspen model used for the gasifier section of this process is based on the paper “Entrainment Coal Gasification Modeling,” by Wen and Chaung. The key points of the model they developed are summarized here.

This model divides the reactor into three reaction zones: pyrolysis and devolatization zone, combustion and gasification zone, and the gasification zone. In each zone, a different combination of reactions is assumed to occur. The various reactions are in Tables 11-13 on this and the following page. In the first zone, the coal is decomposed into char and volatile components. Combustion reactions which occur in the first two zones provide heat for the reactor. In the second zone, the char reacts with steam, oxygen, and carbon dioxide, and the product gases are combusted. In the final zone, the char also reacts with hydrogen, and in the gaseous phase methane reforming and water-gas shift reactions occur. The gas-solid reactions are assumed to be surface reactions, which are described by an unreacted shrinking core model, which takes into account the reaction kinetics as well as diffusion through the gas and ash layers.

Table 11

Zone	Solid Phase Reactions	Gas Phase Reactions
Pyrolysis and Devolatization	1	1, 2, 3, 4
Gasification and Combustion	2, 3, 4	1, 2, 3
Gasification	3, 4, 5	5, 6

Table 12

Gas Phase Gasifier Reactions

1 $H_2 + {}^1/_2O_2 \rightarrow H_2O$

2 $CO + {}^1/_2O_2 \rightarrow CO_2$

3 $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

4 $C_6H_6 + {}^{15}/_2O_2 \rightarrow 6CO_2 + 3H_2O$ (assuming that tar is C_6H_6)

5 $CO + H_2O \rightleftarrows CO_2 + H_2$ **(water-gas shift reaction)**

6 $CH_4 + H_2O \rightleftarrows CO + 3H_2$ **(methane reforming reaction)**

Table 13

	Solid Phase Gasifier Reactions	
1	$C_{\alpha_i}H_{\beta_i}O_{\gamma_i}N_{\delta_i}S_{\epsilon_i}A$ (raw fuel) $\xrightarrow{\Delta}$ $C_\alpha H_\beta O_\gamma N_\delta S_\epsilon A$ (char) + volatiles ($CO + H_2 + CO_2 + CH_4 + H_2S + N_2$ + tar)	**(pyrolysis)**
2	$C_\alpha H_\beta O_\gamma N_\delta S_\epsilon A + \left(\frac{\alpha}{\phi} - \frac{\gamma}{2} + \frac{\beta}{2} - \epsilon\right)O_2 \rightarrow$ $2\left(1 - \frac{1}{\phi}\right)\alpha CO + \left(\frac{2}{\phi} - 1\right)\alpha CO_2 + \left(\frac{\beta}{2} - \epsilon\right)H_2O + \epsilon H_2S + \frac{\delta}{2}N_2 + \text{ash}$	**(char-oxygen reaction)**
3	$C_\alpha H_\beta O_\gamma N_\delta S_\epsilon A + (\alpha - \gamma)H_2O \rightarrow$ $\alpha CO + \left(\alpha - \gamma + \frac{\beta}{2} - \epsilon\right)H_2 + \epsilon H_2S + \frac{\delta}{2}N_2 + \text{ash}$	**(char- steam reaction)**
4	$C_\alpha H_\beta O_\gamma N_\delta S_\epsilon A + \alpha CO_2 \rightarrow$ $2\alpha CO + \frac{\gamma}{2}H_2O + \left(\frac{\beta}{2} - \epsilon - \gamma\right)H_2 + \epsilon H_2S + \frac{\delta}{2}N_2 + \text{ash}$	**(char-carbon dioxide reaction)**
5	$C_\alpha H_\beta O_\gamma N_\delta S_\epsilon A + \left(2\alpha + \gamma + \epsilon - \frac{\beta}{2}\right)H_2 \rightarrow$ $\alpha CH_4 + \gamma H_2O + \epsilon H_2S + \frac{\delta}{2}N_2 + \text{ash}$	**(char-hydrogen reaction)**

FT-1 • Fischer-Tropsch Reactor Calculations

Microchannel Fischer-Tropsch Reactor Sizing

Totals		**Notes/Calculations**	
CO Feed To FT [kg/hr] (1)	175000	--------->	**48.61 [kg/sec]**
Total Flow To FT [L/min] (2)	732000	--------->	**12,200 [L/sec]**
Vol. Capacity Given CT [L] (3)	3172	(2)*(8)	vol. allowed by catalyst void fraction
Void Fraction (Catalyst) (4)	40%		
Total Vol. Required (Cat+void) [L] (5)	7930	(3)/(4) -------->	7.93 [m^3]
Catalyst			
		Note: IP protected from Oxford Catalyst, Bulk Density	
Composition	30 wt % Co	estimated using Ni based Al2O3 catalyst	
	4.5 wt % Re		
	Al_2O_3		
Description	Spherical Pellet		
Conversion (6)	80%		
Alpha (7)	0.9		
Recommended Contact time (s) (8)	0.26	(Oxford Catalyst)	
Bulk Density [kg/m^3] (9)	875		
Diameter [µm] (10)	45		
WHSV [g CO/g cat s] (11)	0.001364		
Required Catalyst Amt [kg] (12)	9263	(1)/(11)*(8)	
Volume of Pure Catalyst [m^3] (13)	10.59	(12)/(9)	
Volume of Void Space [m^3] (13a)	4.23	(13)*(4) --> This is greater than the minimum volume required (3). Use (13) instead of (5)	
Pricing[$/kg] (14)	$ 53.60		(Sigma-Aldrich)
Catalyst Total Cost ($) (15)	$ 496,498	(21)*(14)	
Plate Geometry			
Width [mm] (16)	1000		
Length [mm] (17)	1500		
Height [mm] (18)	1500		
Margins [mm] (19)	50		
Active Channel Length [mm] (20)	1400	(17)-2*(19)	
Total Volume/Module [m^3] (21)	2.25	(16)*(17)*(18)*$1x10^{-9}$	
Reaction Channels			
Height [mm] (22)	0.95		
Width [mm] (23)	17		
Length [mm] (24)	1400		
Plate Thickness [mm] (25)	1.0		
Vol/rxn channel [m^3] (26)	0.0000226	(22)*(23)*(24)*$1x10^{-9}$	
Packed Catalyst/rxn channel [kg] (27)	0.0197838	(26)*(9)	
# of Reaction Channels Needed (28)	468214	(13)/(26)	
Cooling Channels			
Height [mm] (29)	0.95		
Width [mm] (30)	3		
Length [mm] (31)	1400		
Plate Thickness [mm] (32)	1.0		
Vol H2O/channel [m^3] (33)	0.00000399	(29)*(30)*(31)	
Reaction/Cooling Channel Pairs			
Total Width [mm] (34)	22		
Active Plate Width [mm] (35)	900	(16)-2*(19)	
Total Pairs/plate (width wise) (36)	41	(35)/(34)	Also # of rxn Channels
Total # RXN Channels/Module			
Height/channel "unit"[mm] (37)	2.95	--->	includes plate thickness
Active Height Available (38)	1400	(18)-2*(19)	
Total Channels (height wise) (39)	475	(38)/(37)	
Total RXN Channels/Module (40)	*19414*	(39)*(36)	
Total # Modules Required (41)	24	(28)/(40)	
Total Volume of Modules [m^3] (42)	54	(21)*(41)	

----> Assumed that modules are stacked on top of each other and in parallel to form a box

The table above outlines the procedure for estimating the size of the microchannel Fischer-Tropsch reactor. As a reference for reading the table, each element is assigned a number in parentheses, and if a element is derived from a calculation involving multiple elements, the method of calculation and the number corresponding to the element(s) are indicated in the far right-hand column.

The first three parameters considered when sizing the microchannel reactor was the total volumetric flow feed rate into the reactor, the total mass flow rate of carbon monoxide into the reactor, the weight –hourly-space-velocity (WHSV) and the recommended catalyst contact time as suggested per the manufacturer of the catalyst. A quick overview of the calculations illustrated in the table starts with calculating the required amount of catalyst using the mass carbon monoxide feed to the reactor and the catalyst's given WHSV. Using the bulk density of the catalyst and an assumed void fraction of 0.4 for spherical pellets (accounting for non-ideal packing conditions), the **total** volume required within the *entire* microchannel Fischer-Tropsch reactor to handle. An important parameter considered for reactor sizing was the recommended catalyst contact time with the carbon monoxide given from the catalyst manufacturer (*Oxford Catalyst Group*). This value of 0.26 seconds was crudely assumed to represent the residence time of any single carbon monoxide molecule within the reactor. The contact time was multiplied by the total inlet volumetric flow rate to get the volume taken up by the syngas within the reactor during the elapsed residence time. After further exploration, it is found that the void space provided by the amount of catalyst on its own is more than enough to accommodate the amount of syngas moving through the reactor, and the bulk volume of catalyst was used as the basis of the microchannel sizing. From here, the dimensions of the each individual reaction or cooling channel were used to calculate the volume of one module, and then scaled up to meet the process's production needs.

Microchannel Fischer-Tropsch Reactor Costing

Outer Plates	Material	QTY	Vol. Material [m3]	$/kg	Density [kg/m3]	Cost
1500x1000x50	304 Stainless Steel	4	0.15	$ 3.413	8010	$ 16,402.88
1500x1500x50	304 Stainless Steel	2	0.225	$ 3.413	8010	$ 12,302.16
					Total Cost:	**$ 28,705.04**

"Level Plates"	Material	QTY	Vol. Material [m3]	$/kg	Density [kg/m3]	Cost
1400x1000x2	304 Stainless Steel	473	0.0028	$ 3.413	8010	$ 36,174.18
					Total Cost:	**$ 36,174.18**

"Spacers"	Material	QTY	Vol. Material [m3]	$/kg	Density [kg/m3]	Cost
1x0.95x1400	304 Stainless Steel	19414	0.00000133	$ 3.413	8010	$ 705.91
					Total Cost:	**$ 705.91**

Total Cost/Module	**$**	**65,585**
Total Material Cost:	**$**	**1,581,699**
Manufacturing Factor (x15):	**$**	**23,725,490**

SR-1 • Natural Gas Desulfurization Vessel Sizing Calculations

Desulfurization Vessel Size

- Catalyst: Zinc Oxide Desulfurization Adsorbent

$SV = 1500\ hr^{-1}$ $\quad H/D = 3$

$SV = \frac{\dot{V}_{in}}{V_R}$ $\quad \dot{V}_{in} = 205221\ L/min \times \frac{60\ min}{hr} = 12313260\ L/hr$

$$V_R = \dot{V}_{in}/SV = \frac{12313260\ L/hr}{1500\ hr^{-1}} = 8209\ L = 8.2\ m^3 = 290\ ft^3$$

$$V = \pi(D/2)^2 H = \frac{\pi}{4} D^2 (3D) \Rightarrow D = 4.97\ ft \approx 5\ ft$$

$$H = 14.91\ ft \approx 15\ ft$$

$\rho_{catalyst,\ bulk} = 1.1\ \frac{kg}{L}$

$m_{catalyst} = 1.1\ kg/L \times 8209\ L = 9030\ kg = 19908\ lb$

9030 kg catalyst × (.128) = 1159.8 kg sulfur loading

catalyst sulfur loading (wt %) 12.8

H_2S flow rate = .458 kg/hr

$$.458\ \frac{kg}{hr}\ H_2S \left(\frac{1\ kmol}{34.08\ kg}\right)\left(\frac{1\ kmol\ S}{1\ kmol\ H_2S}\right)\left(\frac{32.065\ kg}{1\ kmol\ S}\right) = .4309\ \frac{kg}{hr}\ \text{sulfur.}$$

$$\text{Breakthrough time} = \frac{9030\ kg}{.4309\ \frac{kg}{hr}} = 2691.5\ \text{hrs.} = 112.1\ \text{days.}$$

Heat Exchanger Sample Calculation

HX-1

$T_{c,in} = 70^\circ F$ $T_{h,in} = 1186^\circ F$ $C_{p,c} = 0.6523\ BTU/lb\text{-}^\circ F$

$T_{c,out} = 700^\circ F$ $T_{h,out} = ?$ $C_{p,h} = 0.2993\ BTU/lb\text{-}^\circ F$

$\dot{m}_c = 124451\ lb/hr$ $\dot{m}_h = 954665\ lb/hr$

$Q = \dot{m}_c C_{p,c}(T_{c,out} - T_{c,in})$

$Q = (124451\ lb/hr)(0.652\ BTU/lb\text{-}^\circ F)(700^\circ F - 70^\circ F)$

$Q = 5.11 \times 10^7\ BTU/hr$

$Q = \dot{m}_h C_{p,h}(T_{h,in} - T_{h,out})$

$5.11 \times 10^7\ BTU/hr = (954665\ lb/hr)(0.299\ BTU/lb\text{-}^\circ F)(1186^\circ F - T_{h,out})$

$T_{h,out} = 1007^\circ F$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$$

For a countercurrent HTX,

$\Delta T_1 = T_{h,in} - T_{c,out}$

$\Delta T_2 = T_{h,out} - T_{c,in}$

$$\Delta T_{lm} = \frac{(1186-700) - (1007-70)}{\ln((1186-700)/(1007-70))} = 687^\circ F$$

$Q = UA\Delta T_{lm}$ Assume $U = 20\ \frac{BTU}{hr \cdot ft^2 \cdot {}^\circ F}$ for gas-gas HTX

$5.11 \times 10^7\ BTU/hr = \left(20\ \frac{BTU}{hr \cdot ft^2 \cdot {}^\circ F}\right) A (687^\circ F)$

$A = 3722\ ft^2$

Cost Correlation from Seider et al.

$C_B = \exp[11.667 - 0.8709 \ln A + 0.09005(\ln A)^2]$

$C_B = \$54,259$

$C_P = F_P F_M F_L C_B$ $F_P \simeq 1,\ F_M = F_L = 1$

$C_P \approx C_B = \$54,259$

$C_{BM} = F_{BM} C_P = (3.17)(54,259)$

$C_{BM} = \$171,000$

Floating head, shell & tube

$150 < A < 12,000\ ft^2$

Carbon steel

20 ft tubes

3/4 or 1 in. O.D. tubes

Problem Statement

Alkanes from Pennsylvania Coal and Marcellus Natural Gas by Hybrid Processing (recommended by John A. Wismer, Arkema)

The conversion of natural gas to liquid fuels (GTL) has long been an area of industrial research. Historically, it has focused on converting remote “stranded natural gas” to easily transportable liquids. In fact, a previous design group used a variant of this technology to convert Alaskan natural gas to hydrocarbon liquids[7]. The coal industry has also pursued technologies that convert coal to liquids (CTL)[6,8]. As a feedstock for liquid fuels, both coal and natural gas are cheaper than crude oil. In the case of natural gas, the cost advantage has increased in recent years. Since 2006, the price of “wellhead” natural gas has dropped from about $8/MM Btu to <$4/MMBtu while crude oil has increased from $60/bbl to >$80/bbl. At this price, a substantial portion of the “delivered” natural gas price is comprised of transportation and distribution costs. Note that the wellhead price is usually about $0.25/MMBtu less than the widely quoted NYMEX Henry Hub price. The drop in wellhead price is in large part due to the development of new drilling techniques that have made formerly inaccessible deposits economically attractive to produce. Many of these deposits come from the Marcellus shale – a formation that includes portions of Pennsylvania and West Virginia that also have substantial coal deposits.

Your client is a natural gas producer and a coal mining company that has several leases in Pennsylvania and West Virginia. Most of Pennsylvania’s Marcellus gas comes from either the southwestern or northeastern parts of the state. In the southwestern corner, Greene County has several large coal mines and gas wells in the same vicinity. Your client wants to know whether a hybrid process to convert both coal and gas to hydrocarbon liquids could be economically viable. Hybrid processing offers an elegant solution to one of the drawbacks of the separate conversion technologies: coal as a feedstock for liquid alkanes is too hydrogen-lean and methane is too hydrogen-rich. By hybridizing the processes, it becomes possible to optimize the carbon to hydrogen ratio to produce liquid alkanes at maximum carbon efficiency. By locating the plant near gas wells and coal mines, feedstock transportation costs would be minimized and product would be shipped to nearby U.S. refineries.

The base technology combines steam reforming with Fischer-Tropsch synthesis. The reforming step produces a combination of CO and H2, known as synthesis gas, in a highly endothermic reaction:

$$(1)\quad CH_4 + H_2O \rightarrow 3H_2 + CO \quad \text{(natural gas)}$$

$$(2)\quad CH_x + H_2O \rightarrow (1+0.5x)H_2 + CO \quad \text{(coal)} \qquad 0.35 < x < 0.85$$

The values of x in Eq. (2) are is on the low side for anthracite and on the high side for bituminous coals. For coal, the water-gas shift reaction is used to enrich the gas in H_2 relative to

CO:

(3) $H_2O + CO \leftrightarrow H_2 + CO_2$

The optimum H_2/CO ratio for Fischer-Tropsch (FT) synthesis is about 2:1. Of course, the shift reaction unfortunately degrades some carbon to carbon dioxide. The use of natural gas as a co-feed limits the shift-reaction carbon loss to that which naturally occurs in the reformer.

Hybrid processing has been an area of academic research for some time, but there is no agreed-upon best way to introduce the natural gas into the coal-based process. In one approach, carbon dioxide from the coal gasification reacts with the natural gas.[1] In another, the gas is added to post-treat the liquid effluent of the coal-based FT reactor.[3] Another concept combines the coal gasification with natural-gas reforming in a single shell- and-tube unit wherein the heat required for gas reforming is supplied by the hot gases from coal gasification.[2] Also, the coal and gas can be mixed at the reformer inlet with the reforming reactions at the same conditions.[4] A variant of this approach is to introduce oxygen into the reformer.[5] The latter approach, sometimes called autothermal reforming, uses partial oxidation to supply much of the heat required for the reforming reaction. Furthermore, the coal char can have a catalytic effect that precludes the need for a precious-metal reforming catalyst. You are not expected to carry out a detailed analysis of every option. However, you should understand them sufficiently well to make and defend a rational decision on the choice of technology.

The Fischer Tropsch chemistry is as follows:

(4) $nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$

Also, the evaluation should use the best available technology in its FT processing scheme. For example, the 2009 design group used micro-channel reactors for its FT reactor. This concept might also be applicable to the FT section of the hybrid processing scheme.

The Southwestern PA gas wells are in close proximity to productive bituminous coal mines – and less than 300 miles from the Ohio refineries. The railroad infrastructure of the mine can be used for shipping finished product.

Two simplifying assumptions regarding this process have been specified by your client. Whereas much academic research includes biomass as a potential feedstock in hybrid processing schemes, your client is only interested in coal and natural gas. Furthermore, much of the academic research includes carbon dioxide recycle and/or sequestration as a part of the process simulations. Hybrid processing already offers better carbon efficiency and decreased CO_2 emissions compared with conventional coal-to-liquids processing.

Your client is not interested in processes that involve CO_2 sequestration or non-economical CO_2 recycles.

Your plant should be sized for at least 15,000 bbl/day of hydrocarbon liquids that will be available as a feedstock to the Ohio refineries.

Material Safety Data Sheet (MSDS) Reports

Sprague
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MATERIAL SAFETY DATA SHEET
BITUMINOUS COAL

Content Last Revised 1/94; 10/12/00; 07/26/02; 06/05
4 pages.

SECTION 1 - MATERIAL IDENTIFICATION

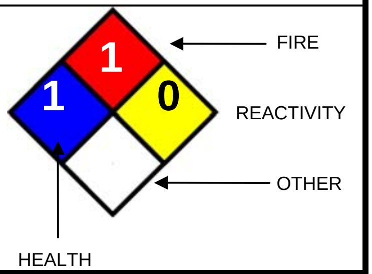
PRODUCT / CHEMICAL NAME:	BITUMINOUS COAL
PRODUCT / CHEMICAL SYNONYMS:	WASHED COAL, CLEAN COAL, SOFT COAL
CHEMICAL FAMILY / FORMULA:	ALIPHATIC AND AROMATIC HYDROCARBONS / VARIABLE
MATERIAL USE OR OCCURRENCE:	-

24 HOUR EMERGENCY INFORMATION

Sprague:	603-431-1000
Chemtrec:	800-424-9300

HMIS / NFPA HAZARD RATING

4=EXTREME
3=SERIOUS
2=MODERATE
1=SLIGHT
0=MINIMAL



SECTION 2 – INGREDIENTS & RECOMMENDED OCCUPATIONAL EXPOSURE LIMITS

COMPOSITION	% WEIGHT AS RECEIVED	OSHA PEL	ACGIH TLV
MOISTURE	(Typical) 1.0 – 10.0	None established.	None established.
ASH	4.0-20.0	15 mg/M^3 as nuisance dust less than 1% quartz	10 mg/M^3 as nuisance dust less than 1% quartz
TOTAL SULFUR	0.5-2.2	5.0 ppm as SO_2	2.00 ppm as SO_2
FIXED CARBON	50.0-72.0	None established	None established
VOLATILE MATTER* INCLUDING ELEMENTAL AND COMPOUNDS OF:	17.0-37.0		
HYDROGEN	4.8-5.3	None established	None established
NITROGEN	1.2-1.6	None established	None established
CHLORINE	.08-.19	1.0 ppm	1.0 ppm
COAL DUST		2.4 mg/ M^3 respirable fraction, < 5% SiO_2 $\frac{10\ mg/\ M^3}{\%\ SiO_{2+2}}$ > 5% SiO_2	2 mg/M^3 respirable fraction, < 5% SiO_2 $\frac{10\ mg/\ M^3}{\%\ SiO_{2+2}}$ > 5% SiO_2

SECTION 3 - PHYSICAL DATA

IGNITION TEMPERATURE:	260°-365°F	**% VOLATILITY BY VOLUME:**	Negligible
MELTING POINT:	750° F	**VAPOR DENSITY (AIR = 1):**	N/A
AVERAGE SPECIFIC GRAVITY (H2O = 1):	1.43	**SOLUBILITY IN WATER:**	Non-soluble

HETEROGENOUS - CARBONACEOUS

APPEARANCE & ODOR: Irregular, rectangular-shaped chunks or particles, dense, grayish-black to black color with slight, minimal dank odor.

SECTION 4 - FIRE AND EXPLOSION HAZARD DATA

FLASH POINT: When exposed to flame of temperatures in excess of 260º F.

EXTINGUISHING MEDIUM: Foam, carbon dioxide, dry chemical, halon, and water fog.

SPECIAL FIRE FIGHTING PROCEDURES: Use washdown and spread out method.

UNUSUAL FIRE AND EXPLOSION HAZARDS: Susceptible to spontaneous combustion. Highly combustible and/or explosive when in dust or powder form.

SECTION 5 - HEALTH DATA

TOXICOLOGICAL TEST DATA: Coal may liberate various polycyclic aromatic hydrocarbons (PAH's) upon thermal decomposition. There is no clear evidence that coal is carcinogenic to man or experimental animals because of their polycyclic aromatic hydrocarbon content. However, there is evidence that these PAH's may play an active role in the generation of lung cancer seen in cigarette smokers or tar-roofing workers.

Coal may release small quantities of methane gas over a period of time. Progression of tuberculosis is greatly increased in pneumoconiosis but susceptibility is apparently not increased.

	ACUTE HEALTH EFFECTS	CHRONIC HEALTH EFFECTS
INHALATION	The principal health hazard associated with coal occurs during its mining and transport. Coal workers' pneumoconiosis (CWP) can occur in miners after as little as 15 years of excessive inhalation of respirable coalmine dust. Respirable quartz particles and free silica may be co-implicated. Coal dust is deposited in the lungs where its site of action is the lung parenchyma, lymph nodes and hila. The severity of the disease is directly related to the amount of coal dust in the lungs. In the simple stages, the disease is detectable by x-ray as round, irregular "macules"of 1-5 mm. This stage typically does not change lung function or shorten life.	The chronic stage of CWP, however, involves massive pulmonary fibrosis that does impair pulmonary function and shorten life. Chronic Bronchitis (lung inflammation, coughing attacks, difficult breathing, etc.) and emphysema can result from excessive coal dust inhalation. Rheumatoid arthritis can be exacerbated by pneumonias leading to rapidly developing lung damage (Caplan's Syndrome).
INGESTION	May cause irritation.	No data available
SKIN CONTACT	May cause irritation.	No data available.
EYE CONTACT	Irritation of the eye.	No data available

FIRST AID PROCEDURES

First aid procedures generally don't apply to this product. Maintain exposure to coal dust according to applicable regulatory standards.

SECTION 6 - REACTIVITY DATA

STABILITY:	Stable if properly stored to inhibit oxidation.
HAZARDOUS POLYMERIZATION:	Hazardous polymerization has not been known to occur under normal temperatures and pressures. However, coal dust may react slowly with oxygen at room temperature. Heat accelerates the process, which could lead to spontaneous ignition in piles of coal dust.
CONDITIONS TO AVOID:	1. Allowing coal to stand in water. 2. Storing coal on loose or porous ground. 3. Piling coal around upright steel or wooden posts, crane supports, underground drains, steam or hot water lines or areas where there is refuse such as wood, straw, growing vegetation or other organic material. 4. Storage in closed hampers, bins, receptacles, etc. without positive ventilation.
INCOMPATIBLES:	
TYPICAL DECOMPOSITION PRODUCTS:	May liberate hydrogen, methane, carbon monoxide, oxides of sulfur and hydrogen, coal tar pitch volatiles upon thermal decomposition.

SECTION 7 - SPECIAL PROTECTION

RESPIRATORY PROTECTION:		Use with adequate ventilation.
VENTILATION	**LOCAL EXHAUST:**	MSHA/NIOSH approved dust respirator. Appropriate respirator depends upon type and magnitude of exposure.
	MECHANICAL (General):	Recommended for use in enclosed or semi-enclosed work areas.
EYE PROTECTION:		Splash goggles or shields with safety glasses
PROTECTIVE GLOVES:		Neoprene, PVC
OTHER PROTECTIVE CLOTHING OR EQUIPMENT:		Employee must wear appropriate impervious clothing and equipment to prevent repeated or prolonged skin contact with this substance.

SECTION 8 - SPECIAL PRECAUTIONS

PRECAUTIONS FOR SAFE HANDLING & STORAGE:	Do not permit accumulation of dust or spillage. See also conditions to avoid, above.
SPILL AND LEAK PROCEDURES:	Cleanup by excavation, vacuum collection or washdown.
WASTE DISPOSAL METHOD:	1. Incinerate in combustion device or system. 2. Dispose in approved, regulated landfill.

SECTION 9 - DOT HAZARDOUS MATERIAL INFORMATION

PROPER SHIPPING NAME: BITUMINOUS COAL		**REQUIRED PLACARDING:** NONE
HAZARD CLASS: Non-Hazardous	**PACKING GROUP (P.G.):** III	**N.A/U.N. NUMBER:** NONE

SECTION 10 - EPA SARA TITLE III INFORMATION

SECTION 311/312 **HAZARD CLASSIFICATION: Non-Hazardous**	**ACUTE:** N/A		**CHRONIC:** N/A
	FIRE: N/A	**PRESSURE:** N/A	**REACTIVE:** N/A

SECTION 11 – REMARKS

This material contains fused polycyclic hydrocarbons. The OSHA interpretation of coal tar pitch volatiles (Section 1910, 1002) is as follows: “Coal tar pitch volatiles include the fused polycyclic hydrocarbons which volatize from the distillation residues of coal, petroleum, wood, and other organic matter.” The OSHA PEL and ACGIH TLV for coal tar pitch volatiles is 0.2 mg/M^3 (basis one soluble fraction).

SECTION 12 - ADDITIONAL REGULATORY DATA

REPORTABLE COMPONENTS: FEDERAL EPA	**%**	**SARA RQ**	**CERCLA RQ**	**RCRA NO.**
BITUMINOUS COAL	100	-----	-----	-----

NOTE: OSHA Regulations 29 CFR 1910.1200 (Hazard Communication) do not consider coal as a “hazardous material” and a Material Safety Data Sheet (MSDS) is not required. The information contained herein is based on data available at this time and is believed to be accurate. However, no warranty is expressed or implied regarding the accuracy of these data or the results to be obtained from the use thereof. Since information contained herein may be applied under conditions beyond our control and with which we may be unfamiliar, no responsibility is assumed for the results of its use. The person receiving this information shall make his own determination of the suitability of the material for his particular purpose.

Praxair Material Safety Data Sheet

1. Chemical Product and Company Identification

Product Name: Carbon monoxide, compressed (MSDS No. P-4576-J)	**Trade Names:** Carbon Monoxide
Chemical Name: Carbon monoxide	**Synonyms:** Carbonic oxide, carbon oxide
Chemical Family: Permanent gas	**Product Grades:** 1.85, 2.5, Ultra High Purity – 3.0, Research - 4.0

Telephone: **Emergencies:** 1-800-645-4633*
CHEMTREC: 1-800-424-9300*
Routine: 1-800-PRAXAIR

Company Name: Praxair, Inc.
39 Old Ridgebury Road
Danbury, CT 06810-5113

**Call emergency numbers 24 hours a day only for spills, leaks, fire, exposure, or accidents involving this product. For routine information, contact your supplier, Praxair sales representative, or call 1-800-PRAXAIR (1-800-772-9247).*

2. Hazards Identification

EMERGENCY OVERVIEW

☠ **DANGER! Poisonous, flammable, odorless high-pressure gas.** ☠

Acts on blood, causing damage to central nervous system (CNS).
Can be fatal even with adequate oxygen.
Can form explosive mixtures with air.
Harmful if inhaled.
Self-contained breathing apparatus must be worn by rescue workers.
Under ambient conditions, this product is a colorless, odorless gas.

OSHA REGULATORY STATUS: This material is considered hazardous by the OSHA Hazard Communications Standard (29 CFR 1910.1200).

POTENTIAL HEALTH EFFECTS:

Effects of a Single (Acute) Overexposure

Inhalation. Depending on the concentration and duration of exposure, may cause headache, drowsiness, dizziness, excitation, rapid breathing, pallor, cyanosis, excess salivation, nausea, vomiting, hallucinations, confusion, angina, convulsions, and unconsciousness. With well-established poisoning, the mucosal surface will be bright red (cherry red). Lack of oxygen can kill.

Skin Contact. No harm expected.

Swallowing. An unlikely route of exposure. This product is a gas at normal temperature and pressure.

Eye Contact. No harm expected.

Effects of Repeated (Chronic) Overexposure. Repeated hypoxia from carbon monoxide exposure will cause gradually increasing CNS damage, with loss of sensation in the fingers, poor memory, and mental deterioration. Chronic exposure may facilitate development of atherosclerosis.

Other Effects of Overexposure. Other effects include embryotoxicity, impaired cardiovascular function, pulmonary edema, pneumonia, gross neuropsychiatric damage, memory impairment, permanent CNS damage, and cerebral edema with irreversible brain damage. Late, fatal demyelinization is a rare, but possible, complication.

Medical Conditions Aggravated by Overexposure. Hypoxia from carboxyhemoglobin formation may aggravate established coronary and cerebral circulatory insufficiency.

CARCINOGENICITY: Carbon monoxide is not listed by NTP, OSHA, and IARC.

POTENTIAL ENVIRONMENTAL EFFECTS: No known effects. For further information, see section 12, Ecological Information.

3. Composition/Information on Ingredients

See section 16 for important information about mixtures.

COMPONENT	CAS NUMBER	CONCENTRATION
Carbon Monoxide	630-08-0	>99%*

**The symbol > means "greater than."*

4. First Aid Measures

INHALATION: Immediately remove to fresh air. If not breathing, give artificial respiration with supplemental oxygen given by qualified personnel. If breathing, qualified personnel should give oxygen. Call a physician.

SKIN CONTACT: Wash skin with soap and water. If irritation persists or contact has been prolonged, call a physician.

SWALLOWING: An unlikely route of exposure. This product is a gas at normal temperature and pressure.

EYE CONTACT: An unlikely route of exposure. Flush with water. Hold the eyelids open and away from the eyeballs to ensure that all surfaces are thoroughly flushed. Get medical attention if discomfort persists.

NOTES TO PHYSICIAN: *There is no specific antidote. Treatment of overexposure should be directed at the control of symptoms and the clinical condition of the patient. Angina and depression of the ST segment of the electrocardiogram indicate myocardial hypoxia. Exposure to high concentrations can result in cerebral edema. With severe doses, the use of hyperbaric oxygen may be beneficial. Individuals repeatedly overexposed may present positive Romberg's sign.*

Contact the Poison Control Center in your area for additional information on patient management and follow-up.

5. Fire Fighting Measures

FLAMMABLE PROPERTIES: Cannot be detected by odor. Forms explosive mixtures with air and oxidizing agents.

SUITABLE EXTINGUISHING MEDIA: CO_2, dry chemical, water spray, or fog.

PRODUCTS OF COMBUSTION: Carbon dioxide

PROTECTION OF FIREFIGHTERS: DANGER! Poisonous, flammable, odorless high-pressure gas. Evacuate all personnel from danger area. Do not approach area without self-contained breathing apparatus. Immediately cool cylinders with water spray from maximum distance, taking care not to extinguish flames. Remove ignition sources if without risk. If flames are accidentally extinguished, explosive reignition may occur. Stop flow of gas if without risk, while continuing cooling water spray. Remove all cylinders from area of fire if without risk. Allow fire to burn out. On-site fire brigades must comply with OSHA 29 CFR 1910.156.

Specific Physical and Chemical Hazards. Heat of fire can build pressure in cylinder and cause it to rupture. No part of cylinder should be subjected to a temperature higher than 125°F (52°C). Carbon monoxide cylinders are equipped with a pressure relief device. (Exceptions may exist where authorized by DOT.) If leaking carbon monoxide catches fire, do not extinguish flames. Flammable and toxic vapors may spread from leak and could explode if reignited by sparks or flames. Explosive atmospheres may linger. Before entering area, especially confined areas, check with an appropriate device.

Protective Equipment and Precautions for Firefighters. Firefighters should wear self-contained breathing apparatus and full fire-fighting turnout gear.

6. Accidental Release Measures

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED:

DANGER! Poisonous, flammable, odorless high-pressure gas.

Personal Precautions. Cannot be detected by odor. Immediately evacuate all personnel from danger area. Do not approach area without self-contained breathing apparatus. May form explosive mixtures with air. Toxic, flammable gas may spread. Before entering area, especially a confined area, check atmosphere with an appropriate device. Remove all sources of ignition if without risk. Reduce gas with fog or fine water spray. Shut off flow if without risk. Ventilate area or move cylinder to well-ventilated area.

Environmental Precautions. Prevent waste from contaminating the surrounding environment. Keep personnel away. Discard any product, residue, disposable container, or liner in an environmentally acceptable manner, in full compliance with federal, state, and local regulations. If necessary, call your local supplier for assistance.

7. Handling and Storage

PRECAUTIONS TO BE TAKEN IN HANDLING: May form explosive mixtures with air. Protect cylinders from damage. Use a suitable hand truck to move cylinders; do not drag, roll, slide, or drop. Keep away from heat, sparks, and open flame. Use only spark-proof tools and explosion-proof equipment. Never attempt to lift a cylinder by its cap; the cap is intended solely to protect the valve. Never insert an object (e.g., wrench, screwdriver, pry bar) into cap openings; doing so may damage the valve and cause a leak. Use an adjustable strap wrench to remove over-tight or rusted caps. Open valve slowly. If valve is hard to open, discontinue use and contact your supplier. Close valve after each use; keep closed even when empty. For other precautions in using carbon monoxide, see section 16.

PRECAUTIONS TO BE TAKEN IN STORAGE: Store and use with adequate ventilation. Protect cylinders from direct sunlight. Separate carbon monoxide cylinders from oxygen and other oxidizers by at least 20 ft (6.1 m), or use a barricade of noncombustible material. This barricade should be at least 5 ft (1.53 m) high and have a fire resistance rating of at least ½ hr. Firmly secure cylinders upright to keep them from falling or being knocked over. Screw valve protection cap firmly in place by hand. Store only where temperature will not exceed 125°F (52°C). Store full and empty cylinders separately. Use a first-in, first-out inventory system to prevent storing full cylinders for long periods. Post "No Smoking or Open Flames" signs in storage and use areas. There must be no sources of ignition. All electrical equipment in storage areas must be explosion-proof. Storage areas must meet national electric codes for Class 1 hazardous areas.

RECOMMENDED PUBLICATIONS: For further information on storage, handling, and use of this product, see Praxair publications P-14-153, *Guidelines for Handling Gas Cylinders and Containers,* and P-15-437, *Safe Handling of Carbon Monoxide*. Obtain from your local supplier.

8. Exposure Controls/Personal Protection

COMPONENT	OSHA PEL	ACGIH TLV-TWA (2009)
Carbon Monoxide	50 ppm	25 ppm

TLV-TWAs should be used as a guide in the control of health hazards and not as fine lines between safe and dangerous concentrations.

IDLH = 1200 ppm

ENGINEERING CONTROLS:

Local Exhaust. Use an explosion-proof local exhaust system with sufficient air flow to keep the carbon monoxide concentration below the applicable exposure limits in the worker's breathing zone.

Mechanical (General). Not recommended as a primary ventilation system to control worker's exposure.

Special. None

Other. None

PERSONAL PROTECTIVE EQUIPMENT:

Skin Protection. Wear work gloves when handling cylinders.

Eye/Face Protection. Wear safety glasses when handling cylinders. Select per OSHA 29 CFR 1910.133.

Respiratory Protection. A respiratory protection program that meet OSHA 29 CFR 1910.134, ANSI Z88.2, or MSHA 30 CFR 72.710 (where applicable) requirements must be followed whenever workplace conditions warrant respirator use. Use an air-supplied or air-purifying cartridge if the action level is exceeded. Ensure the respirator has the appropriate protection factor for the exposure level. If cartridge type respirators are used, the cartridge must be appropriate for the chemical exposure (e.g., an organic vapor cartridge). For emergencies or instances with unknown exposure levels, use a self-contained breathing apparatus.

9. Physical and Chemical Properties

APPEARANCE:	Colorless gas
ODOR:	Odorless
ODOR THRESHOLD:	Not applicable.
PHYSICAL STATE:	Gas at normal temperature and pressure
pH:	Not applicable.
MELTING POINT at 1 atm**:**	-337°F (-205.0°C)
BOILING POINT at 1 atm**:**	-312.61°F (-191.45°C)
FLASH POINT (test method)**:**	Flammable gas, not applicable.
EVAPORATION RATE (Butyl Acetate = 1)**:**	Not applicable.
FLAMMABILITY:	Flammable
FLAMMABLE LIMITS IN AIR, % by volume**:**	**LOWER:** 12.5% **UPPER:** 74%
VAPOR PRESSURE:	Not applicable.
VAPOR DENSITY at 68°F (20°C) and 1 atm**:**	0.0725lb/ft^3 (1.161kg/m^3)
SPECIFIC GRAVITY (H_2O = 1)**:**	Not applicable.
SPECIFIC GRAVITY (Air = 1) at 70°F (21.1°C) and 1 atm**:**	0.9676
SOLUBILITY IN WATER, vol/vol at 32°F (0°C) and 1 atm**:**	0.035
PARTITION COEFFICIENT: n-octanol/water:	Not available.
AUTOIGNITION TEMPERATURE:	1128°F (608.9°C)
DECOMPOSITION TEMPERATURE:	752°F (400°C)
PERCENT VOLATILES BY VOLUME:	100
MOLECULAR WEIGHT:	28.01
MOLECULAR FORMULA:	CO

10. Stability and Reactivity

CHEMICAL STABILITY: ☐ Unstable ☒ Stable

CONDITIONS TO AVOID: Temperatures above 752°F (400°C)

INCOMPATIBLE MATERIALS: Oxidizing agents, oxygen, flammables, metal oxides, halogenated fluorides, metals in the presence of moisture and/or sulfur compounds

HAZARDOUS DECOMPOSITION PRODUCTS: Carbon monoxide will decompose above 752°F (400°C) to form carbon dioxide and carbon.

POSSIBILITY OF HAZARDOUS REACTIONS: ☒ May Occur ☐ Will Not Occur

Forms explosive mixtures with air and oxidizing agents.

11. Toxicological Information

ACUTE DOSE EFFECTS: LC_{50} = 3760 ppm, 1 hr rat.

STUDY RESULTS: Carbon monoxide produces embryofetal toxicity in laboratory animals but only at doses that cause maternal toxicity. There is no information available on possible effects in humans.

12. Ecological Information

ECOTOXICITY: No information available on ecological effects.

OTHER ADVERSE EFFECTS: Carbon monoxide does not contain any Class I or Class II ozone-depleting chemicals.

13. Disposal Considerations

WASTE DISPOSAL METHOD: Do not attempt to dispose of residual or unused quantities. Return cylinder to supplier.

14. Transport Information

DOT/IMO SHIPPING NAME: Carbon monoxide, compressed

HAZARD CLASS: 2.3	**PACKING GROUP/Zone:** NA/D	**IDENTIFICATION NUMBER:** UN1016	**PRODUCT RQ:** None

SHIPPING LABEL(s): POISON GAS, FLAMMABLE GAS*

PLACARD (when required): POISON GAS, FLAMMABLE GAS*

**The words in the POISON GAS diamond are INHALATION HAZARD.*

SPECIAL SHIPPING INFORMATION: Cylinders should be transported in a secure position, in a well-ventilated vehicle. Cylinders transported in an enclosed, non-ventilated compartment of a vehicle can present serious safety hazards.

Additional Marking Requirement: INHALATION HAZARD

Shipment of compressed gas cylinders that have been filled without the owner’s consent is a violation of federal law [49 CFR 173.301(b)].

MARINE POLLUTANTS: Carbon monoxide is not listed as a marine pollutant by DOT.

15. Regulatory Information

The following selected regulatory requirements may apply to this product. Not all such requirements are identified. Users of this product are solely responsible for compliance with all applicable federal, state, and local regulations.

U.S. FEDERAL REGULATIONS:

EPA (ENVIRONMENTAL PROTECTION AGENCY)

CERCLA: COMPREHENSIVE ENVIRONMENTAL RESPONSE, COMPENSATION, AND LIABILITY ACT OF 1980 (40 CFR Parts 117 and 302):

Reportable Quantity (RQ): None

SARA: SUPERFUND AMENDMENT AND REAUTHORIZATION ACT:

SECTIONS 302/304: Require emergency planning based on Threshold Planning Quantity (TPQ) and release reporting based on Reportable Quantities (RQ) of Extremely Hazardous Substances (EHS) (40 CFR Part 355):

TPQ: None
EHS RQ (40 CFR 355): None

SECTIONS 311/312: Require submission of MSDSs and reporting of chemical inventories with identification of EPA hazard categories. The hazard categories for this product are as follows:

IMMEDIATE: Yes	**PRESSURE:** Yes
DELAYED: Yes	**REACTIVITY:** No
	FIRE: Yes

SECTION 313: Requires submission of annual reports of release of toxic chemicals that appear in 40 CFR Part 372.

Carbon monoxide is not subject to reporting under Section 313.

40 CFR 68: RISK MANAGEMENT PROGRAM FOR CHEMICAL ACCIDENTAL RELEASE PREVENTION: Requires development and implementation of risk management programs at facilities that manufacture, use, store, or otherwise handle regulated substances in quantities that exceed specified thresholds.

Carbon monoxide is not listed as a regulated substance.

TSCA: TOXIC SUBSTANCES CONTROL ACT: Carbon monoxide is listed on the TSCA inventory.

OSHA: OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION:

29 CFR 1910.119: PROCESS SAFETY MANAGEMENT OF HIGHLY HAZARDOUS CHEMICALS: Requires facilities to develop a process safety management program based on Threshold Quantities (TQ) of highly hazardous chemicals.

Carbon monoxide is not listed in Appendix A as a highly hazardous chemical. However, any process that involves a flammable gas on site in one location in quantities of 10,000 lb (4536 kg) or greater is covered under this regulation unless the gas is used as a fuel.

STATE REGULATIONS:

CALIFORNIA: Carbon monoxide is listed by California under the SAFE DRINKING WATER AND TOXIC ENFORCEMENT ACT OF 1986 (Proposition 65).

WARNING: Carbon monoxide is a chemical known to the State of California to cause birth defects or other reproductive harm. *(California Health and Safety Code §25249.5 et seq.)*

PENNSYLVANIA: Carbon monoxide is subject to the PENNSYLVANIA WORKER AND COMMUNITY RIGHT-TO-KNOW ACT (35 P.S. Sections 7301-7320).

16. Other Information

Be sure to read and understand all labels and instructions supplied with all containers of this product.

OTHER HAZARDOUS CONDITIONS OF HANDLING, STORAGE, AND USE: ***Poisonous, flammable, odorless high-pressure gas.*** Cannot be detected by odor. Use piping and equipment adequately designed to withstand pressures to be encountered. Use only in a closed system. Use a backflow prevention device in any piping. Ground all equipment. Electrical equipment must be non-sparking or explosion-proof. Never work on a pressurized system. If a leak occurs, close the cylinder valve, blow down the system by venting vapor to a safe place in an environmentally safe manner in compliance with all federal, state, and local laws; then repair the leak. Follow safe practices when returning cylinder to supplier. Be sure valve is closed; then install valve outlet cap or plug, leak-tight. Never place a compressed gas cylinder where it may become part of an electrical circuit.

NOTE: *Prior to using any plastics, confirm their compatibility with carbon monoxide. Avoid using pure nickel. Corrosion of pure nickel in carbon monoxide atmospheres exceeds 50 mil/yr (1.27 mm/yr) at room temperatures.*

Mixtures. When you mix two or more gases or liquefied gases, you can create additional, unexpected hazards. Obtain and evaluate the safety information for each component before you produce the mixture. Consult an industrial hygienist or other trained person when you evaluate the end product. Remember, gases and liquids have properties that can cause serious injury or death.

HAZARD RATING SYSTEMS:

NFPA RATINGS:		**HMIS RATINGS:**	
HEALTH	= 3	HEALTH	= 1
FLAMMABILITY	= 4	FLAMMABILITY	= 4
INSTABILITY	= 0	PHYSICAL HAZARD	= 3
SPECIAL	= None		

**An asterisk used in conjunction with HMIS health hazard ratings designates a carcinogenic or reproductive hazard.*

STANDARD VALVE CONNECTIONS FOR U.S. AND CANADA:

THREADED:	CGA-350 connection is standard
PIN-INDEXED YOKE:	NA
ULTRA-HIGH-INTEGRITY CONNECTION:	CGA-724 *NOTE: Do not use a nickel gasket*

Use the proper CGA connections. **DO NOT USE ADAPTERS.** Additional limited-standard connections may apply. See CGA pamphlet V-1 listed below.

Ask your supplier about free Praxair safety literature as referred to in this MSDS and on the label for this product. Further information can be found in the following pamphlets published by the Compressed Gas Association, Inc. (CGA), 4221 Walney Road, 5th Floor, Chantilly, VA 20151-2923, Telephone (703) 788-2700, http://www.cganet.com/Publication.asp.

AV-1	*Safe Handling and Storage of Compressed Gases*
P-1	*Safe Handling of Compressed Gases in Containers*
V-1	*Compressed Gas Cylinder Valve Inlet and Outlet Connections*
—	*Handbook of Compressed Gases, Fourth Edition*

Praxair asks users of this product to study this MSDS and become aware of product hazards and safety information. To promote safe use of this product, a user should (1) notify employees, agents, and contractors of the information in this MSDS and of any other known product hazards and safety information, (2) furnish this information to each purchaser of the product, and (3) ask each purchaser to notify its employees and customers of the product hazards and safety information.

The opinions expressed herein are those of qualified experts within Praxair, Inc. We believe that the information contained herein is current as of the date of this Material Safety Data Sheet. Since the use of this information and the conditions of use of the product are not within the control of Praxair, Inc., it is the user's obligation to determine the conditions of safe use of the product.

Praxair MSDSs are furnished on sale or delivery by Praxair or the independent distributors and suppliers who package and sell our products. To obtain current MSDSs for these products, contact your Praxair sales representative or local distributor or supplier, or download from www.praxair.com. If you have questions regarding Praxair MSDSs, would like the form number and date of the latest MSDS, or would like the names of the Praxair suppliers in your area, phone or write the Praxair Call Center (**Phone:** 1-800-PRAXAIR; **Address:** Praxair Call Center, Praxair, Inc., PO Box 44, Tonawanda, NY 14151-0044).

Praxair, Inc.
39 Old Ridgebury Road
Danbury, CT 06810-5113

PS0198

Dan Helfrich
502-634-7200

SÜD-CHEMIE
Creating Performance Technology

Date-Issued: 12/01/2004
MSDS Ref. No: 0032
Date-Revised: 01/23/2006
Revision No: 1

MATERIAL SAFETY DATA SHEET

ReforMax 330 LDP

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1. PRODUCT AND COMPANY IDENTIFICATION

PRODUCT NAME: ReforMax 330 LDP

GENERAL USE: Catalyst

Manufacturer/Supplier

[illegible]d-Chemie Inc.
P.O. Box 32370
Louisville, KY 40232
Customer Service: 001(502) 634-7200

24 HR. EMERGENCY TELEPHONE NUMBERS

CHEMTREC :	(800) 424 - 9300
Outside the U.S. Call Collect :	001 (703) 527-3887

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2. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW

PHYSICAL APPEARANCE: Gray powder, extrusions, pellets, cylinders, wheels, rings, tablets, or spheres.

IMMEDIATE CONCERNS: Irritating to eyes, respiratory system and skin. May cause allergic reaction. Cancer hazard. Prolonged or repeated overexposure causes lung damage.

POTENTIAL HEALTH EFFECTS

EYES: Irritating and may injure eye tissue if not removed promptly.

SKIN: Irritating to skin. May cause sensitization by skin contact.

INGESTION: Substance may be harmful if swallowed. May cause allergic reaction, nausea, vomiting and/or diarrhea.

INHALATION: Harmful if inhaled. Prolonged or repeated overexposure may cause lung damage. May cause allergic respiratory reaction. Cancer hazard.

SIGNS AND SYMPTOMS OF OVEREXPOSURE

EYES: Burning, abrasion, damage to cornea (necrosis).

SKIN: Dermatitis, skin sensitization, chronic itching.

INGESTION: Burning, irritation, upset stomach, intestinal distress.

INHALATION: Coughing, wheezing, shortness of breath.

CARCINOGENICITY: Cancer Hazard. Contains nickel or nickel compounds which can cause cancer.

MEDICAL CONDITIONS AGGRAVATED: Breathing problems, skin problems.

ROUTES OF ENTRY: Inhalation, ingestion, eyes, skin.

TARGET ORGAN STATEMENT: Lungs, nasal cavity, larynx, kidneys, skin.

SENSITIZATION: Contains nickel or nickel compounds which may cause sensitization by inhalation or skin contact.

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3. COMPOSITION / INFORMATION ON INGREDIENTS

Chemical Name	Wt.%	CAS#
Aluminum oxide	57 - 87	1344-28-1
Nickel oxide	10 - 25	1313-99-1
Calcium oxide	3 - 18	1305-78-8

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4. FIRST AID MEASURES

EYES: Immediately flush with gently flowing, lukewarm water for at least 30 minutes while holding eyelids open. Obtain medical attention.

SKIN: Brush dry material from skin. Immediately flush with large quantites of lukewarm water for at least 30 minutes while removing contaminated clothing. Get medical attention if irritation or other symptoms develop.

INGESTION: If victim is conscious give 2-6 ounces of water. Do not induce vomiting. Get immediate medical attention.

INHALATION: Remove to fresh air. Seek medical attention if cough or other symptoms develop or persist.

NOTES TO PHYSICIAN: Skin sensitization may lead to chronic eczema "nickel itch". Lung damage is cumulative and may include cancer of lung, nasal cavity and larynx. May cause pulmonary eosinophilia (Loeffler's Syndrome).

5. FIRE FIGHTING MEASURES

GENERAL HAZARD: Material is not flammable. Material may generate heat upon contact with water. If water is used to fight fire use sufficient quantity to dissipate heat.

EXTINGUISHING MEDIA: Use extinguishing agent applicable to surrounding fire.

FIRE FIGHTING PROCEDURES: As in any fire, wear self-contained breathing apparatus operated in pressure-demand mode, (MSHA/NIOSH approved or equivalent) and full protective gear.

6. ACCIDENTAL RELEASE MEASURES

SMALL SPILL: With shovel or scoop, place material into clean, dry container; move containers from spill area. Minimize airborne particulates. Protect against inhalation of dusts. Wear gloves and long sleeves. Avoid contact with skin. Use eye protection.

LARGE SPILL: Use same methods described for small spills.

7. HANDLING AND STORAGE

GENERAL PROCEDURES: Avoid contact with skin and eyes. Do not breathe (dust, vapor, mist, gas). Minimize dust generation and accumulation.

STORAGE: Keep container tightly closed and dry.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

EXPOSURE GUIDELINES:

OSHA HAZARDOUS COMPONENTS (29 CFR 1910.1200)

		EXPOSURE LIMITS			
		OSHA PEL		ACGIH TLV	
		ppm	Mg/m^3	ppm	Mg/m^3
Aluminum oxide	TWA	[1]	15		10
Nickel oxide	TWA		1.0	[2]	0.2
Calcium oxide	TWA		5		2

OSHA TABLE COMMENTS:

1. 5 mg/m3 respirable
2. Inhalable.

ENGINEERING CONTROLS: If user operations generate dust, fume or mist, use ventilation to keep exposure to airborne contaminants below the exposure limit.

PERSONAL PROTECTIVE EQUIPMENT

EYES AND FACE: Wear safety glasses with side shields or goggles.

SKIN: Wear protective clothing, including long sleeves and gloves, to prevent skin contact. Thoroughly wash clothing before reuse.

RESPIRATORY: Wear NIOSH approved filtering face piece rated 100 or equivalent in the absence of proper environmental control. Type of respirator depends on level of exposure.

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9. PHYSICAL AND CHEMICAL PROPERTIES

PHYSICAL STATE: Solid

ODOR: None

COLOR: Gray

PERCENT VOLATILE: None

VAPOR PRESSURE: Not Applicable

VAPOR DENSITY: Not applicable.

MELTING POINT: Not Determined

SOLUBILITY IN WATER: Insoluble

DENSITY: 60-70 lb/cu. ft.

MOLECULAR FORMULA: Al_2O_3+CaO+NiO

---

10. STABILITY AND REACTIVITY

STABLE: YES

HAZARDOUS POLYMERIZATION: NO

INCOMPATIBLE MATERIALS: Keep away from water. A rise in temperature may result from contact with water.

---

11. TOXICOLOGICAL INFORMATION

SENSITIZATION: Hypersensitivity to nickel is common and can cause allergic contact dermatitis, pulmonary asthma, conjuctivitis, and inflammatory reactions. (Lewis, R.J. Sax's Dangerous Properties of Industrial Materials. New York, NY: Van Nostrand Reinhold)

CARCINOGENICITY:

IARC: Group 1: Nickel and nickel compounds are carcinogenic to humans.

NTP: The National Toxicology Program's Eleventh Report on Carcinogens lists nickel compounds as "Known Human Carcinogens."

OSHA: Not listed.

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12. ECOLOGICAL INFORMATION

ENVIRONMENTAL DATA: May be harmful to aquatic life in very low concentrations. May be dangerous if allowed to directly enter water intakes. Notify local health and wildlife officials as required by local and state regulations. Notify operators of nearby water intakes.

ECOTOXICOLOGICAL INFORMATION: LC100 (Fish) = 5-50 ug/L (24-96 hr) (Nickel)

LC50 (Fish larvae, young fish) = 0.1-5 ug/L (Nickel)

Nickel and its compounds can have high acute and chronic toxicity to aquatic life. Nickel toxicity to aquatic organisms is determined by water hardness - the softer the water, the higher the toxicity. (Australian Government Department of the Environment and Heritage: *National Pollutant Inventory Substance Profile,* *Nickel and Its Compounds.* Oct-2003)

CHEMICAL FATE INFORMATION: Nickel does not appear to collect in fish, plants or animals used for food. (Australian Government Department of the Environment and Heritage, *National Polluant Inventory Substance Profile, Nickel and Its Compounds.* Oct-2003)

13. DISPOSAL CONSIDERATIONS

DISPOSAL METHOD: This product, if discarded as sold, is not a Federal RCRA hazardous waste. Processing, use or contamination of this product may change the waste management options. State and local disposal regulations may differ from federal disposal regulations. Catalyst products often offer postive recycle value. Contact SCI Safety, Health and Environment (502-634-7492) for more information regarding recycle options.

14. TRANSPORT INFORMATION

DOT (DEPARTMENT OF TRANSPORTATION)

PROPER SHIPPING NAME: Not regulated

15. REGULATORY INFORMATION

UNITED STATES

SARA TITLE III (SUPERFUND AMENDMENTS AND REAUTHORIZATION ACT)

311/312 HAZARD CATEGORIES:

FIRE: NO **PRESSURE GENERATING:** NO **REACTIVITY:** YES **ACUTE:** YES **CHRONIC:** YES

313 REPORTABLE INGREDIENTS: Nickel and nickel compounds

CERCLA (COMPREHENSIVE RESPONSE, COMPENSATION, AND LIABILITY ACT)

CERCLA REGULATORY: Contains ingredient(s) listed under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), 40 CFR 302.

CERCLA RQ: Nickel and Nickel compounds are considered to be CERCLA hazardous materials and subject to CERCLA/Superfund liability. However, there is no specific CERCLA reportable quantity for generic nickel compounds.

TSCA (TOXIC SUBSTANCE CONTROL ACT)

TSCA STATUS: All components are listed on the TSCA Inventory or are excluded or exempt.

RCRA STATUS: This product, if discarded as sold, is not a Federal RCRA hazardous waste. Processing, use or contamination of this product may change the waste management options. State and local disposal regulations may differ from federal disposal regulations.

CLEAN AIR ACT

APPENDIX A: HAZARDOUS AIR POLLUTANTS (AIR TOXICS): Contains component(s) contained on the original list of hazardous air pollutants.

CANADA

WHMIS HAZARD SYMBOL AND CLASSIFICATION

D2A/D2B

WHMIS Toxic

WHMIS (WORKPLACE HAZARDOUS MATERIALS INFORMATION SYSTEM): This MSDS has been prepared according to the hazard criteria of the Controlled Products Regulations (CPR) and the MSDS contains all of the information required by the CPR.

CANADA INGREDIENT DISCLOSURE LIST: Contains component(s) listed on the Canadian Hazardous Products Act Ingredient Disclosure List.

CANADIAN ENVIRONMENTAL PROTECTION ACT: All ingredients are listed on the Canadian Domestic Substances List inventory.

STATE REGULATIONS California

CALIFORNIA PROPOSITION 65: WARNING: Contains chemical(s) known by the State of California to cause cancer.

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16. OTHER INFORMATION

APPROVED BY: Prepared and approved by SHE Dept. Sud-Chemie Inc.

INFORMATION CONTACT: 502-634-7492

REVISION SUMMARY

Date-Issued: 12/01/2004

Revision #: 1 This MSDS replaces the December 01, 2004 MSDS. Any changes in information are as follows: In Section 1 Product Code In Section 2 Sensitization Signs & Symptoms - Eyes Carcinogenicity In Section 4 Firstaid - Eyes Firstaid - Skin Notes to Physician In Section 5 Explosion Hazards In Section 7 Storage In Section 9 (Group Field) for Vapor Pressure (Group Field) for Vapor Pressure Density (Group Field) for Percent Volatile In Section 11 Eye Effects Sensitization In Section 12 Ecotoxicological Information Chemical Fate Information In Section 13 Disposal

MANUFACTURER DISCLAIMER: The information presented herein is believed to be accurate but is not warranted. Recipients are advised to confirm in advance that the information is current, applicable and suitable to their circumstances.

Catalyst Specification Sheet

SÜD-CHEMIE
Creating Performance Technology

Steam Reforming Catalyst ReforMax 330 LDP (G-90LDP)

General Description	Nickel catalyst on a calcium aluminate support	Designed for fired reformer (primary reformer) and oxygen blown secondary reformer (ATR)

Chemical Composition **1000 ℃ Calcined Basis**		**Specifications**	**Test Method**
Nickel*	%	11.0 ± 1.5	Q_SH1190
Calcium Aluminate Support		Balance	

Physical Properties		**Specifications**	**Test Method**
Form/Shape		**19 x 16 mm Tablets**	
Average Crush Strength*	N	700 ± 100	Q_SH1373
Shipping Density*	g/l	800 ± 100	Q_SH0489

Shipping Information

Standard packaging is 200 liter metal drums.

Contact your Süd-Chemie representative for your special requirements

Material Classification

R49 - May cause cancer by inhalation. R43 - May cause sensitization by skin contact. R53 - May cause long-term adverse effects in the aquatic environment.

For further details refer to our Material Safety Data Sheet.

** Properties measured by Quality Control**

153245004

Effective: 06/15/2005 Replaces: 06/15/2005 Print Date: 01/27/2006

Material Safety Data Sheet

1. Product and company identification

Product name	Mississippi Canyon 252 Weathered Crude Oil (Louisiana Light Sweet Crude) The primary exposure hazard of weathered crude is by physical contact with the skin.
MSDS #	0000003277
Code	0000003277
Product use	Oil spill recovery / cleanup.
Synonyms	Crude Oil, Louisiana Sweet Crude Oil
Supplier	BP America Production Company 501 WestLake Park Boulevard Houston TX 77079
EMERGENCY HEALTH INFORMATION:	1 (800) 447-8735 Outside the US: +1 703-527-3887 (CHEMTREC)
EMERGENCY SPILL INFORMATION:	1 (800) 424-9300 CHEMTREC (USA)
OTHER PRODUCT INFORMATION	1 (866) 4 BP - MSDS (866-427-6737 Toll Free - North America) email: bpcares@bp.com

2. Hazards identification

Physical state	Viscous liquid./Semi-solid
Color	Various Colors Brown. to Black. and Reddish brown Orange.
Emergency overview	WARNING ! CAUSES EYE AND SKIN IRRITATION. Prolonged or repeated contact can defat the skin and lead to irritation and/or dermatitis. May be combustible at high temperature. Keep away from heat, sparks and flame. Avoid contact with eyes, skin and clothing. Use adequate ventilation. Do not ingest. If ingested, do not induce vomiting. Wash thoroughly after handling.
Routes of entry	Skin contact. Eye contact. Inhalation. Ingestion.
Potential health effects	
Eyes	Causes eye irritation.
Skin	Causes skin irritation. Prolonged or repeated contact can defat the skin and lead to irritation and/or dermatitis. See toxicological information (section 11).
Inhalation	Potential for toxic vapor exposures is very low: with the loss of the highly volatile components, weathered oil does not present an inhalation hazard.
Ingestion	Causes gastrointestinal irritation and diarrhea.

See toxicological information (section 11)

3. Composition/information on ingredients

Low molecular weight, highly volatile components are not present.
Hydrogen sulfide and sulfur dioxide have not been detected in air sampled above sources of this weathered oil.
A complex mixture of hydrocarbons consisting predominantly of paraffins, cyclic paraffins, and aromatic hydrocarbons having carbon numbers of C10 or greater.

Ingredient name	CAS #	%
Crude oil	8002-05-9	98 - 100
Contains: Naphthalene	91-20-3	< 1 ppm

4. First aid measures

Eye contact	In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Get medical attention.
Skin contact	Immediately wash exposed skin with soap and water. Remove contaminated clothing and shoes. Wash clothing before reuse. Clean shoes thoroughly before reuse.
Inhalation	If inhaled, remove to fresh air. Get medical attention if symptoms occur.
Ingestion	Aspiration hazard if swallowed. Can enter lungs and cause damage. Do not induce vomiting. Never give anything by mouth to an unconscious person. Get medical attention.

5. Fire-fighting measures

Flammability of the product	May be combustible at high temperature.
Flash point	Closed cup: >93°C (>199.4°F) ESTIMATED.
Fire/explosion hazards	May be combustible at high temperature.
Unusual fire/explosion hazards	None identified.
Extinguishing media	
Suitable	Use dry chemical, CO_2, water spray (fog) or foam.
Not suitable	Do not use water jet.
Fire-fighting procedures	Promptly isolate the scene by removing all persons from the vicinity of the incident if there is a fire. No action shall be taken involving any personal risk or without suitable training. Move containers from fire area if this can be done without risk. Use water spray to keep fire-exposed containers cool.
Hazardous combustion products	Combustion products may include the following: carbon oxides (CO, CO_2) (carbon monoxide, carbon dioxide) sulfur oxides (SO_2, SO_3 etc.) nitrogen oxides (NO, NO_2 etc.)
Protective clothing (fire)	Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

6. Accidental release measures

Environmental precautions	Avoid material runoff and contact with soil, waterways, drains and sewers. Contact Gulf of Mexico Response: Environmental hotline and to report oiled shoreline: +1 866.448.5816
Personal protection in case of a large spill	Safety glasses with side shields or chemical goggles. Tyvek protective suit. Rubber boots. Gloves. (Nitrile. or Polyethylene) Suggested protective clothing might not be adequate. Consult a specialist before handling this product.

Methods for cleaning up

Large spill	Contact Gulf of Mexico Response: Environmental hotline and to report oiled shoreline: +1 866.448.5816
Small spill	Contact Gulf of Mexico Response: Environmental hotline and to report oiled shoreline: +1 866.448.5816

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7. Handling and storage

Handling Put on appropriate personal protective equipment (see section 8). Workers should wash hands and face before eating, drinking and smoking. Avoid contact with eyes, skin and clothing. Do not ingest. Use with adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Store and use away from heat, sparks, open flame or any other ignition source.

Storage Store in accordance with local regulations. Store in a segregated and approved area. Store away from direct sunlight in a dry, cool and well-ventilated area, away from incompatible materials (see section 10). Eliminate all ignition sources. Separate from oxidizing materials. Keep container tightly closed and sealed until ready for use. Containers that have been opened must be carefully resealed and kept upright to prevent leakage. Do not store in unlabeled containers. Use appropriate containment to avoid environmental contamination.

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8. Exposure controls/personal protection

Occupational exposure limits

Ingredient name	**Occupational exposure limits**
Weathered Crude Oil	None established.

Other Applicable Exposure limit values:

Mineral oil	**ACGIH TLV (United States).** TWA: 5 mg/m³ 8 hour(s). Issued/Revised: 2/2010 Form: Mineral oil, mist **NIOSH REL (United States).** STEL: 10 mg/m³ 15 minute(s). Form: Oil mist, mineral TWA: 5 mg/m³ 10 hour(s). Form: Oil mist, mineral **OSHA PEL (United States).** TWA: 5 mg/m³ 8 hour(s). Form: Oil mist, mineral

While specific OELs for certain components may be shown in this section, other components may be present in any mist, vapor or dust produced. Therefore, the specific OELs may not be applicable to the product as a whole and are provided for guidance only.

Some states may enforce more stringent exposure limits.

Control Measures Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits. The engineering controls also need to keep gas, vapor or dust concentrations below any lower explosive limits.

Hygiene measures Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing.

Personal protection

Eyes	Avoid contact with eyes. Safety glasses with side shields or chemical goggles.
Skin and body	Avoid contact with skin and clothing. Wear Tyvek protective suit.
Respiratory	Use adequate ventilation. If ventilation is inadequate, use a NIOSH certified P95 particulate respirator.
Hands	Wear protective gloves. (Nitrile. or Polyethylene)
	Consult your supervisor or Standard Operating Procedure (S.O.P) for special handling instructions.

9. Physical and chemical properties

Physical state	Viscous liquid./Semi-solid
Color	Various Colors Brown. to Black. and Reddish brown Orange.
Odor	Petroleum Hydrocarbon [Slight]
Flash point	Closed cup: >93°C (>199.4°F) ESTIMATED.
Specific gravity	<1 [Water = 1]
Solubility	insoluble in water.

10. Stability and reactivity

Stability and reactivity	The product is stable.
Possibility of hazardous reactions	Under normal conditions of storage and use, hazardous reactions will not occur.
Conditions to avoid	Avoid all possible sources of ignition (spark or flame). Avoid excessive heat.
Incompatibility with various substances	Reactive or incompatible with the following materials: oxidizing materials.
Hazardous decomposition products	carbon oxides (CO, CO_2) (carbon monoxide, carbon dioxide) sulfur oxides (SO_2, SO_3 etc.) nitrogen oxides (NO, NO_2 etc.)
Hazardous polymerization	Under normal conditions of storage and use, hazardous polymerization will not occur.

11. Toxicological information

Classification

Product/ingredient name	**IARC**	**NTP**	**OSHA**
Crude oil	3	-	-

IARC :
3 - Not classifiable as a human carcinogen.

Other information

Crude oil is a naturally occurring complex mixture of hydrocarbons whose exact composition and physical properties can vary widely depending upon its source. Weathered crude oil is different from complete crude oil due to the loss of low molecular weight, highly volatile components.

Specific toxicity tests have not been conducted on this material. Our hazard evaluation is based on information from similar materials, the ingredients, technical literature, and/or professional experience.

Exposure to sunlight may increase the degree of skin irritation.
Crude oil administered orally or dermally to pregnant rats during gestation produced increased numbers of resorptions and decreases in fetal weight at maternally toxic doses. Repeated exposures to some crude oils in rats have produced effects on the blood, liver and thymus.

From skin-painting studies in laboratory animals, it has been concluded that most, if not all, petroleum crudes, regardless of source, possess carcinogenic activity to some degree. This means that workers who practice poor personal hygiene and who are repeatedly exposed by direct skin contact to crude oil over many years may potentially be at risk of developing skin cancer. However, intermittent or occasional skin contact with petroleum crude oils is not expected to have serious health effects as long as good personal hygiene measures such as those outlined in this material safety data sheet are followed. Crude oil has not been identified as a carcinogen by NTP, IARC or OSHA.

Potential chronic health effects

Carcinogenicity	No known significant effects or critical hazards.

Medical conditions aggravated by over-exposure	Individuals with preexisting disease of the skin may be at increased risk from exposure to this chemical.

12. Ecological information

Ecotoxicity

No testing has been performed by the manufacturer.

13. Disposal considerations

Waste information	The generation of waste should be avoided or minimized wherever possible. Empty containers or liners may retain some product residues. This material and its container must be disposed of in a safe way. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Avoid material runoff and contact with soil, waterways, drains and sewers.

NOTE: The generator of waste has the responsibility for proper waste identification (based on characteristic(s) or listing), transportation and disposal

14. Transport information

International transport regulations

Regulatory information	UN number	Proper shipping name	Class	Packing group	Additional information
DOT Classification	----	Proper classification to be determined at the time of shipment	-----	-	-
TDG Classification	----	Proper classification to be determined at the time of shipment	-----	-	-
IMDG Classification	----	Proper classification to be determined at the time of shipment	-----	-	-
IATA/ICAO Classification	----	Proper classification to be determined at the time of shipment	-----	-	-

15. Regulatory information

U.S. Federal Regulations

United States inventory (TSCA 8b)	All components are listed or exempted.

TSCA 12(b) one-time export: Naphthalene

SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: No products were found.
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: Mississippi Canyon 252 Weathered Crude Oil (Louisiana Light Sweet Crude): Immediate (acute) health hazard, Delayed (chronic) health hazard

SARA 313

Form R - Reporting requirements	This product does not contain any hazardous ingredients at or above regulated thresholds.
Supplier notification	This product does not contain any hazardous ingredients at or above regulated thresholds.
CERCLA Sections 102a/103 Hazardous Substances (40 CFR Part 302.4):	CERCLA: Hazardous substances.: Naphthalene: 100 lbs. (45.4 kg);

State regulations

Massachusetts Substances	The following components are listed: Petroleum Crude Oil
New Jersey Hazardous Substances	The following components are listed: Petroleum distillates, Petroleum Crude Oil
Pennsylvania RTK Hazardous Substances	The following components are listed: PETROLEUM
California Prop. 65	**WARNING:** This product contains a chemical known to the State of California to cause cancer. Naphthalene

Inventories

Canada inventory	All components are listed or exempted.
Europe inventory	All components are listed or exempted.
Australia inventory (AICS)	All components are listed or exempted.
China inventory (IECSC)	All components are listed or exempted.
Japan inventory (ENCS)	Not determined.
Korea inventory (KECI)	All components are listed or exempted.
Philippines inventory (PICCS)	All components are listed or exempted.

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16. Other information

Label requirements

WARNING !

CAUSES EYE AND SKIN IRRITATION.

HMIS® Rating :

Health	*	2
Flammability		2
Physical Hazard		0
Personal protection		X

National Fire Protection Association (U.S.A.)

History

Date of issue	06/28/2010.
Date of previous issue	05/28/2010.
Prepared by	Product Stewardship

Notice to reader

All reasonably practicable steps have been taken to ensure this data sheet and the health, safety and environmental information contained in it is accurate as of the date specified below. No warranty or representation, express or implied is made as to the accuracy or completeness of the data and information in this data sheet.

The data and advice given apply when the product is sold for the stated application or applications. Additionally this data and advice apply to weathered crude oil that is recovered from the environment for potential reuse or recycling. You should not use the product other than for these stated application or applications without seeking advice from us.

It is the user's obligation to evaluate and use this material safely and to comply with all applicable laws and regulations. The BP Group shall not be responsible for any damage or injury resulting from use, other than the stated product use of the material, from *any failure to adhere to recommendations, or from any hazards inherent in the nature of the material. Purchasers of the product for supply to a third party for use at work, have a duty to take all necessary steps to ensure that any person handling or using the product is provided with the information in this sheet. Employers have a duty to tell employees and others who may be affected of any hazards described in this sheet and of any precautions that should be taken.*

MATERIAL SAFETY DATA SHEET

Date Printed: 04/03/2012
Date Updated: 09/03/2009
Version 1.1

Section 1 - Product and Company Information

Product Name	THALESNANO MICROCATCART CATALYST CARTRIDGE SYSTEM, 30MM X 4MM L X DIAM., NI/SIO2-AL2O3
Product Number	THS04143
Brand	ALDRICH
Company	Sigma-Aldrich
Address	3050 Spruce Street SAINT LOUIS MO 63103 US
Technical Phone:	800-325-5832
Fax:	800-325-5052
Emergency Phone:	314-776-6555

Section 2 - Composition/Information on Ingredient

Substance Name	CAS #	SARA 313
THALESNANO CATCART CATALYST CARTRIDGE SYSTEM, NI/SIO2-AL2O3	None	Yes

Ingredient Name	CAS #	Percent	SARA 313
ALUMINA	1344-28-1	>= 19.5 <= 23.3	Yes
NICKEL, POWDER	7440-02-0	>= 63 <= 69	Yes
SILICON DIOXIDE	60676-86-0	>= 11.5 <= 13.7	No

Section 3 - Hazards Identification

EMERGENCY OVERVIEW

Flammable (USA) Highly Flammable (EU). Harmful.
Flammable. Limited evidence of a carcinogenic effect. May cause sensitization by skin contact.
Possible Carcinogen (US). Target organ(s): Lungs. Nose. Bones.
Calif. Prop. 65 carcinogen.

HMIS RATING
- HEALTH: 3*
- FLAMMABILITY: 2
- REACTIVITY: 1

NFPA RATING
- HEALTH: 3
- FLAMMABILITY: 2
- REACTIVITY: 1

*additional chronic hazards present.

For additional information on toxicity, please refer to Section 11.

Section 4 - First Aid Measures

ORAL EXPOSURE

If swallowed, wash out mouth with water provided person is conscious. Call a physician.

INHALATION EXPOSURE

If inhaled, remove to fresh air. If breathing becomes difficult, call a physician.

DERMAL EXPOSURE

In case of skin contact, flush with copious amounts of water for at least 15 minutes. Remove contaminated clothing and shoes. Call a physician.

EYE EXPOSURE

In case of contact with eyes, flush with copious amounts of water for at least 15 minutes. Assure adequate flushing by separating the eyelids with fingers. Call a physician.

Section 5 - Fire Fighting Measures

FLASH POINT

N/A

AUTOIGNITION TEMP

N/A

FLAMMABILITY

N/A

EXTINGUISHING MEDIA

Suitable: Water spray. Carbon dioxide, dry chemical powder, or appropriate foam.

FIREFIGHTING

Protective Equipment: Wear self-contained breathing apparatus and protective clothing to prevent contact with skin and eyes.
Specific Hazard(s): Emits toxic fumes under fire conditions.

Section 6 - Accidental Release Measures

PROCEDURE(S) OF PERSONAL PRECAUTION(S)

Wear respirator, chemical safety goggles, rubber boots, and heavy rubber gloves.

METHODS FOR CLEANING UP

Sweep up, place in a bag and hold for waste disposal. Avoid raising dust. Ventilate area and wash spill site after material pickup is complete.

Section 7 - Handling and Storage

HANDLING

User Exposure: Avoid breathing dust. Avoid contact with eyes, skin, and clothing. Avoid prolonged or repeated exposure.

STORAGE

Suitable: Keep tightly closed.

Section 8 - Exposure Controls / PPE

ENGINEERING CONTROLS

Mechanical exhaust required.

PERSONAL PROTECTIVE EQUIPMENT

Respiratory: Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU). Where risk assessment shows air-purifying respirators are appropriate use a dust mask type N95 (US) or type P1 (EN 143) respirator.

Other: Wear appropriate government approved respirator, chemical-resistant gloves, safety goggles, other protective clothing.

GENERAL HYGIENE MEASURES

Wash thoroughly after handling. Wash contaminated clothing before reuse.

Section 9 - Physical/Chemical Properties

Appearance	Physical State: Solid	
Property	**Value**	**At Temperature or Pressure**
pH	N/A	
BP/BP Range	N/A	
MP/MP Range	N/A	
Freezing Point	N/A	
Vapor Pressure	N/A	
Vapor Density	N/A	
Saturated Vapor Conc.	N/A	
Bulk Density	N/A	
Odor Threshold	N/A	
Volatile%	N/A	
VOC Content	N/A	
Water Content	N/A	
Solvent Content	N/A	
Evaporation Rate	N/A	
Viscosity	N/A	
Surface Tension	N/A	
Partition Coefficient	N/A	
Decomposition Temp.	N/A	
Flash Point	N/A	
Explosion Limits	N/A	
Flammability	N/A	
Autoignition Temp	N/A	
Refractive Index	N/A	
Optical Rotation	N/A	
Miscellaneous Data	N/A	
Solubility	N/A	

N/A = not available

Section 10 - Stability and Reactivity

STABILITY

Stable: Stable.

Materials to Avoid: Oxidizing agents.

HAZARDOUS DECOMPOSITION PRODUCTS

Hazardous Decomposition Products: Nature of decomposition products not known.

HAZARDOUS POLYMERIZATION

Hazardous Polymerization: Will not occur

Section 11 - Toxicological Information

ROUTE OF EXPOSURE
Skin Contact: May cause skin irritation.
Skin Absorption: May be harmful if absorbed through the skin.
Eye Contact: May cause eye irritation.
Inhalation: May be harmful if inhaled. Material may be irritating to mucous membranes and upper respiratory tract.
Ingestion: May be harmful if swallowed.

SENSITIZATION
Respiratory: May cause allergic respiratory reaction.
Skin: May cause allergic skin reaction.

TARGET ORGAN(S) OR SYSTEM(S)
Lungs. Nose. Bones.

SIGNS AND SYMPTOMS OF EXPOSURE
To the best of our knowledge, the chemical, physical, and toxicological properties have not been thoroughly investigated.

Section 12 - Ecological Information

No data available.

Section 13 - Disposal Considerations

APPROPRIATE METHOD OF DISPOSAL OF SUBSTANCE OR PREPARATION
Contact a licensed professional waste disposal service to dispose of this material. Dissolve or mix the material with a combustible solvent and burn in a chemical incinerator equipped with an afterburner and scrubber. Observe all federal, state, and local environmental regulations.

Section 14 - Transport Information

DOT
Proper Shipping Name: Metal powders, flammable, n.o.s.
UN#: 3089
Class: 4.1
Packing Group: Packing Group II
Hazard Label: Flammable solid
PIH: Not PIH

IATA
Proper Shipping Name: Metal powder, flammable, n.o.s.
IATA UN Number: 3089
Hazard Class: 4.1
Packing Group: II

Section 15 - Regulatory Information

EU ADDITIONAL CLASSIFICATION
Symbol of Danger: F-Xn
Indication of Danger: Highly Flammable. Harmful.
R: 10-40-43
Risk Statements: Flammable. Limited evidence of a carcinogenic effect. May cause sensitization by skin contact.
S: 16-36/37
Safety Statements: Keep away from sources of ignition - no

smoking. Wear suitable protective clothing and gloves.

US CLASSIFICATION AND LABEL TEXT

Indication of Danger: Flammable (USA) Highly Flammable (EU). Harmful.

Risk Statements: Flammable. Limited evidence of a carcinogenic effect. May cause sensitization by skin contact.

Safety Statements: Keep away from sources of ignition - no smoking. In case of contact with eyes, rinse immediately with plenty of water and seek medical advice. Take precautionary measures against static discharges. Wear suitable protective clothing and gloves.

US Statements: Possible Carcinogen (US). Target organ(s): Lungs. Nose. Bones. Calif. Prop. 65 carcinogen.

UNITED STATES REGULATORY INFORMATION

SARA LISTED: Yes

NOTES: This product is or contains a component that is subject to SARA313 reporting requirements.

CANADA REGULATORY INFORMATION

WHMIS Classification: This product has been classified in accordance with the hazard criteria of the CPR, and the MSDS contains all the information required by the CPR.

DSL: Yes

NDSL: No

Section 16 - Other Information

DISCLAIMER

For R&D use only. Not for drug, household or other uses.

WARRANTY

The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of the product. Sigma-Aldrich Inc., shall not be held liable for any damage resulting from handling or from contact with the above product. See reverse side of invoice or packing slip for additional terms and conditions of sale.

Praxair Material Safety Data Sheet

1. Chemical Product and Company Identification

Product Name: Hydrogen, refrigerated liquid (MSDS No. P-4603-G)	**Trade Names:** Liquid Hydrogen
Chemical Name: Hydrogen	**Synonyms:** Hydrogen (cryogenic liquid)
Chemical Family: Cryogenic liquid	**Product Grades:** None assigned.

Telephone:	**Emergencies:**	1-800-645-4633*	**Company Name:**	Praxair, Inc.
	CHEMTREC:	1-800-424-9300*		39 Old Ridgebury Road
	Routine:	1-800-PRAXAIR		Danbury, CT 06810-5113

**Call emergency numbers 24 hours a day only for spills, leaks, fire, exposure, or accidents involving this product. For routine information, contact your supplier, Praxair sales representative, or call 1-800-PRAXAIR (1-800-772-9247).*

2. Hazards Identification

EMERGENCY OVERVIEW

DANGER! Extremely cold, flammable liquid and gas under pressure.
Can form explosive mixtures with air.
Can cause severe frostbite.
Burns with invisible flame.
Liquid or cold gas can freeze air in vent lines.
May cause dizziness and drowsiness.
Self-contained breathing apparatus and protective clothing may be required by rescue workers.
Under ambient conditions, this is a colorless, odorless, cryogenic liquid.

OSHA REGULATORY STATUS: This material is considered hazardous by the OSHA Hazard Communications Standard (29 CFR 1910.1200).

POTENTIAL HEALTH EFFECTS:

Effects of a Single (Acute) Overexposure

Inhalation. Asphyxiant. Effects are due to lack of oxygen. Moderate concentrations may cause headache, drowsiness, dizziness, excitation, excess salivation, vomiting, and unconsciousness. Lack of oxygen can kill.

Skin Contact. No harm expected from vapor. Cold gas or liquid may cause severe frostbite.

Swallowing. An unlikely route of exposure, but severe frostbite of the lips and mouth may result from contact with the liquid.

Eye Contact. No harm expected from vapor. Cold gas or liquid may cause severe frostbite.

Effects of Repeated (Chronic) Overexposure. No harm expected.

A vertical line in the left margin indicates revised or new material.

Other Effects of Overexposure. Hydrogen is an asphyxiant. Lack of oxygen can kill.

Medical Conditions Aggravated by Overexposure. The toxicology and the physical and chemical properties of hydrogen suggest that overexposure is unlikely to aggravate existing medical conditions.

CARCINOGENICITY: This product is not listed by NTP, OSHA, or IARC.

POTENTIAL ENVIRONMENTAL EFFECTS: None known. For further information, see section 12, Ecological Information.

3. Composition/Information on Ingredients

See section 16 for important information about mixtures.

COMPONENT	CAS NUMBER	CONCENTRATION
Hydrogen	1333-74-0	>99%*

**The symbol > means "greater than."*

4. First Aid Measures

INHALATION: Remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, qualified personnel may give oxygen. Call a physician.

SKIN CONTACT: For exposure to cold gas, liquid, or solid, immediately warm frostbite area with warm water not to exceed 105°F (41°C). In case of massive exposure, remove contaminated clothing while showering with warm water. Call a physician.

SWALLOWING: An unlikely route of exposure. This product is a gas at normal temperature and pressure.

EYE CONTACT: For exposure to cold gas, liquid, or solid, immediately flush eyes thoroughly with warm water for at least 15 minutes. Hold the eyelids open and away from the eyeballs to ensure that all surfaces are flushed thoroughly. See a physician, preferably an ophthalmologist, immediately.

NOTES TO PHYSICIAN: *There is no specific antidote. Treatment of overexposure should be directed at the control of symptoms and the clinical condition of the patient.*

5. Fire Fighting Measures

FLAMMABLE PROPERTIES: Highly flammable, extremely cold cryogenic liquid and gas. Flame is nearly invisible. Escaping gas may ignite spontaneously. Hydrogen has a low ignition energy. Fireball forms if gas cloud ignites immediately after release. Forms explosive mixtures with air and oxidizing agents.

SUITABLE EXTINGUISHING MEDIA: CO_2, dry chemical, water spray, or fog

PRODUCTS OF COMBUSTION: Water (H_2O)

PROTECTION OF FIREFIGHTERS: DANGER! Extremely cold, flammable liquid and gas under pressure. Evacuate all personnel from danger area. Immediately spray containers with water from maximum distance until cool, taking care not to direct spray onto vents on top of container. Do not discharge sprays into liquid hydrogen. Liquid hydrogen will freeze water rapidly. Shut off flow of gas if without risk, while continuing cooling water spray. Remove ignition sources if without risk. If flames are accidentally extinguished, explosive re-ignition may occur. All personnel including, fire and rescue workers, should leave the area immediately. Re-approach with extreme caution. When containers have cooled, move them away from fire area if without risk. Self-contained breathing apparatus and protective clothing may be required by rescue workers. On-site fire brigades must comply with OSHA 29 CFR 1910.156.

Specific Physical and Chemical Hazards. Liquid causes severe frostbite, a freezing injury resembling a burn. Liquid will solidify air, concentrating oxygen and creating a potential explosion hazard. Heat of fire can build pressure in container and cause it to rupture. Liquid hydrogen containers are equipped with pressure relief devices. No part of a container should be subjected to a temperature higher than 125°F (52°C). If venting or leaking hydrogen catches fire, do not extinguish flames. Flammable gas may spread from leak, creating an explosive re-ignition hazard. Vapors can be ignited by pilot lights, other flames, smoking, sparks, heaters, electrical equipment, static discharge, or other ignition sources at locations distant from product handling point. Explosive atmospheres may linger. Before entering area, especially confined areas, check atmosphere with approved explosion meter.

Protective Equipment and Precautions for Firefighters. Firefighters should wear self-contained breathing apparatus and full fire-fighting turnout gear.

6. Accidental Release Measures

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED:

DANGER! Extremely cold, flammable liquid and gas under pressure.

Personal Precautions. Forms explosive mixtures with air. (See section 5.) Immediately evacuate all personnel from danger area. Liquid hydrogen will condense moisture in the atmosphere, producing a vapor cloud. The zone of flammability may extend beyond this cloud, so personnel should be evacuated well beyond any visible moisture. Avoid contact with cold liquid, vapor, or frosty condensation. Liquid hydrogen can freeze air, oxygen, and other gases. Contact with liquid or solid gases can cause severe frostbite, a burn-like injury. (See section 2.) Flammable gas may spread from leak. Approach suspected leak area with caution. Before entering area, especially confined areas, check atmosphere with an appropriate device. Self-contained breathing apparatus and protective clothing may be required by rescue workers. Remove all sources of ignition if without risk. Reduce gas with fog or fine water spray. Shut off flow if without risk. Ventilate area or move container to a well-ventilated area.

Environmental Precautions. Prevent waste from contaminating the surrounding environment. Keep personnel away. Discard any product, residue, disposable container, or liner in an environmentally acceptable manner, in full compliance with federal, state, and local regulations. If necessary, call your local supplier for assistance.

7. Handling and Storage

PRECAUTIONS TO BE TAKEN IN HANDLING: Do not get liquid in eyes, on skin, or on clothing. ***Keep away from heat, flame, and sparks.*** Never allow any unprotected part of your body to touch uninsulated pipes or vessels containing cryogenic fluids. Flesh will stick to the extremely cold metal and will tear when you try to pull free. For liquid withdrawal, wear face shield and cryogenic gloves (see section 8). ***Air will condense on exposed liquid or cold-gas surfaces such as vaporizers and piping.*** Nitrogen, which has a lower boiling point than oxygen, will evaporate first, leaving oxygen-enriched condensation on the surface. To prevent possible ignition of grease, oil, or other combustibles, keep all areas of potential condensation free of these substances. Use only spark-proof tools and explosion-proof equipment.

Use a suitable hand truck for container movement. Cryogenic containers must be handled and stored in an upright position. Do not drop or tip containers, or roll them on their sides. ***Hydrogen is the lightest known gas.*** It may leak out of systems that are air-tight for other gases and may collect in poorly ventilated upper reaches of buildings. ***All piped hydrogen systems and associated equipment must be grounded.*** Electrical equipment must be non-sparking or explosion-proof. Leak check system with soapy water; never use a flame. If valve is hard to open, discontinue use and contact your supplier. For other precautions in using hydrogen, see section 16.

PRECAUTIONS TO BE TAKEN IN STORAGE: ***Store and use with adequate ventilation.*** Store only where cylinder temperatures will not exceed 125°F (52°C). Do not store in a confined space. Cryogenic containers are equipped with a pressure relief device and a pressure controlling valve. Under normal conditions, these containers will periodically vent product. Use adequate pressure relief devices in systems and piping to prevent pressure buildup; entrapped liquid can generate extremely high pressures when vaporized by warming. ***Separate hydrogen containers from oxygen, chlorine, and other oxidizers*** by at least 20 ft (6.1 m), or use a barricade of noncombustible material. This barricade should be at least 5 ft (1.53 m) high and have a fire resistance rating of at least ½ hour. ***Post "No Smoking or Open Flames" signs in storage and use areas.*** There must be no sources of ignition. All electrical equipment in storage areas must be explosion-proof. Storage areas must meet national electric codes for Class 1 hazardous areas.

RECOMMENDED PUBLICATIONS: For further information on storage, handling, and use, see Praxair publication P-14-153, *Guidelines for Handling Gas Cylinders and Containers*. Obtain from your local supplier. For further information specific to hydrogen, see NFPA 50A, *Standard for Gaseous Hydrogen Systems at Consumer Sites*, published by the National Fire Protection Association, 1 Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101; 1-800-344-3555; www.nfpa.org.

8. Exposure Controls/Personal Protection

COMPONENT	OSHA PEL	ACGIH TLV-TWA (2007)
Hydrogen	N.E.*	Simple Asphyxiant

* N.E.–Not Established.

IDLH = Not available.

ENGINEERING CONTROLS:

Local Exhaust. An explosion-proof local exhaust system is acceptable. See SPECIAL.

Mechanical (General). Inadequate; see SPECIAL.

Special. Use only in a closed system.

Other. See SPECIAL.

PERSONAL PROTECTIVE EQUIPMENT:

Skin Protection. Wear loose-fitting, cryogenic gloves, metatarsal shoes for container handling, and protective clothing where needed. Cuffless trousers should be worn outside the shoes. Select in accordance with OSHA 29 CFR 1910.132 and 1910.133. Regardless of protective equipment, never touch live electrical parts.

Eye/Face Protection. Safety glasses and a full face shield are recommended. Select in accordance with OSHA 29 CFR 1910.133.

Respiratory Protection. None required under normal use. An air-supplied respirator must be used in confined spaces. Respiratory protection must conform to OSHA rules as specified in 29 CFR 1910.134. Select per OSHA 29 CFR 1910.134 and ANSI Z88.2.

9. Physical and Chemical Properties

APPEARANCE:	Colorless liquid		
ODOR:	Odorless		
ODOR THRESHOLD:	Not applicable.		
PHYSICAL STATE:	Cryogenic liquid		
pH:	Not applicable.		
MELTING POINT at 1 atm**:**	-434.56°F (-259.2°C)		
BOILING POINT at 1 atm**:**	-422.97°F (-252.76°C)		
FLASH POINT (test method)**:**	Not available.		
EXPANSION RATIO for liquid at boiling point to gas at 70°F (21.1°C)**:**	1 to 850.3		
EVAPORATION RATE (Butyl Acetate = 1)**:**	Not available.		
FLAMMABILITY:	Flammable		
FLAMMABLE LIMITS IN AIR, % by volume**:**	**LOWER:** 4.0%	**UPPER:** 75.0%	
LIQUID DENSITY at boiling point and 1 atm**:**	4.43 lb/ft^3 (70.96 kg/m^3)		
VAPOR PRESSURE at 68°F (20°C)**:**	Not applicable.		
VAPOR DENSITY at 70°F (21.1°C) and 1 atm**:**	0.0052 lb/ft^3 (0.083 kg/m^3)		
SPECIFIC GRAVITY (H_2O = 1) at 19.4°F (-7°C)**:**	Not available.		
SPECIFIC GRAVITY (Air = 1) at 32°F (0°C) and 1 atm**:**	0.07		
SOLUBILITY IN WATER, vol/vol at 60°F (15.6°C) and 1 atm**:**	0.019		
PARTITION COEFFICIENT: n-octanol/water:	Not available.		
AUTOIGNITION TEMPERATURE:	932°F (500°C)		
DECOMPOSITION TEMPERATURE:	Not available.		
PERCENT VOLATILES BY VOLUME:	100		
MOLECULAR WEIGHT:	2.016		
MOLECULAR FORMULA:	H_2		

10. Stability and Reactivity

CHEMICAL STABILITY: ☐ Unstable ☒ Stable

CONDITIONS TO AVOID: None known.

INCOMPATIBLE MATERIALS: Oxidizing agents, lithium, halogens

HAZARDOUS DECOMPOSITION PRODUCTS: None.

POSSIBILITY OF HAZARDOUS REACTIONS: ☒ May Occur ☐ Will Not Occur

Flammable gas. Forms explosive mixtures with air and oxidizer agents.

11. Toxicological Information

ACUTE DOSE EFFECTS: Hydrogen is a simple asphyxiant.

STUDY RESULTS: None known.

12. Ecological Information

ECOTOXICITY: No adverse ecological effects expected.

OTHER ADVERSE EFFECTS: Hydrogen does not contain any Class I or Class II ozone-depleting chemicals.

13. Disposal Considerations

WASTE DISPOSAL METHOD: Do not attempt to dispose of residual or unused quantities. Return container to supplier.

14. Transport Information

DOT/IMO SHIPPING NAME: Hydrogen, refrigerated liquid

HAZARD CLASS:	2.1	**PACKING GROUP/Zone:**	NA*	**IDENTIFICATION NUMBER:**	UN1966	**PRODUCT RQ:**	None

SHIPPING LABEL(s): FLAMMABLE GAS

PLACARD (when required): FLAMMABLE GAS

*NA–Not applicable.

SPECIAL SHIPPING INFORMATION: Cylinders should be transported in a secure position, in a well-ventilated vehicle. Cylinders transported in an enclosed, nonventilated compartment of a vehicle can present serious safety hazards.

Shipment of compressed gas cylinders that have been filled without the owner's consent is a violation of federal law [49 CFR 173.301(b)].

MARINE POLLUTANTS: Hydrogen is not listed as a marine pollutant by DOT.

15. Regulatory Information

The following selected regulatory requirements may apply to this product. Not all such requirements are identified. Users of this product are solely responsible for compliance with all applicable federal, state, and local regulations.

U.S. FEDERAL REGULATIONS:

EPA (ENVIRONMENTAL PROTECTION AGENCY)

CERCLA: COMPREHENSIVE ENVIRONMENTAL RESPONSE, COMPENSATION, AND LIABILITY ACT OF 1980 (40 CFR Parts 117 and 302):

Reportable Quantity (RQ): None

SARA: SUPERFUND AMENDMENT AND REAUTHORIZATION ACT:

SECTIONS 302/304: Require emergency planning based on Threshold Planning Quantity (TPQ) and release reporting based on Reportable Quantities (RQ) of Extremely Hazardous Substances (EHS) (40 CFR Part 355):

TPQ: None
EHS RQ (40 CFR 355): None

SECTIONS 311/312: Require submission of MSDSs and reporting of chemical inventories with identification of EPA hazard categories. The hazard categories for this product are as follows:

IMMEDIATE: Yes	**PRESSURE:** Yes
DELAYED: No	**REACTIVITY:** No
	FIRE: Yes

SECTION 313: Requires submission of annual reports of release of toxic chemicals that appear in 40 CFR Part 372.

Hydrogen is not subject to reporting under Section 313.

40 CFR 68: RISK MANAGEMENT PROGRAM FOR CHEMICAL ACCIDENTAL RELEASE PREVENTION: Requires development and implementation of risk management programs at facilities that manufacture, use, store, or otherwise handle regulated substances in quantities that exceed specified thresholds.

Hydrogen is listed as a regulated substance in quantities of 10,000 lb (4536 kg) or greater.

TSCA: TOXIC SUBSTANCES CONTROL ACT: Hydrogen is listed on the TSCA inventory.

OSHA: OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION:

29 CFR 1910.119: PROCESS SAFETY MANAGEMENT OF HIGHLY HAZARDOUS CHEMICALS: Requires facilities to develop a process safety management program based on Threshold Quantities (TQ) of highly hazardous chemicals.

Hydrogen is not listed in Appendix A as a highly hazardous chemical. However, any process that involves a flammable gas on site in one location in quantities of 10,000 lb (4536 kg) or greater is covered under this regulation unless the gas is used as a fuel.

STATE REGULATIONS:

CALIFORNIA: Hydrogen is not listed by California under the SAFE DRINKING WATER AND TOXIC ENFORCEMENT ACT OF 1986 (Proposition 65).

PENNSYLVANIA: Hydrogen is subject to the PENNSYLVANIA WORKER AND COMMUNITY RIGHT-TO-KNOW ACT (35 P.S. Sections 7301-7320).

16. Other Information

Be sure to read and understand all labels and instructions supplied with all containers of this product.

OTHER HAZARDOUS CONDITIONS OF HANDLING, STORAGE, AND USE: ***Extremely cold, flammable liquid and gas under pressure. Use only in a closed system. Use piping and equipment adequately designed to withstand pressures and temperatures to be encountered.*** Avoid materials incompatible with cryogenic use; some metals such as carbon steel may fracture easily at low temperature. Use insulated hoses and piping to avoid condensation of oxygen-rich liquid air. See container manufacturer's operating instructions to avoid freezing air in vent lines. Do not change or force fit connections.

Use only transfer lines designed for cryogenic liquids. ***Prevent liquid or cold gas from being trapped in piping between valves.*** Equip the piping with pressure relief devices. Use a backflow prevention device in the piping.

Gas can cause rapid suffocation due to oxygen deficiency. Store and use with adequate ventilation. Close container valve after each use; keep closed even when empty. Praxair recommends piping all vents to the exterior of the building. ***Never work on a pressurized system.*** If there is a leak, close the container valve. Blow the system down in a safe and environmentally sound manner in compliance with all federal, state, and local laws; then repair the leak. ***Never place a compressed gas container where it may become part of an electrical circuit.***

Mixtures. When you mix two or more gases or liquefied gases, you can create additional, unexpected hazards. Obtain and evaluate the safety information for each component before you produce the mixture. Consult an industrial hygienist or other trained person when you evaluate the end product. Remember, gases and liquids have properties that can cause serious injury or death.

HAZARD RATING SYSTEMS:

NFPA RATINGS:

HEALTH = 3
FLAMMABILITY = 4
INSTABILITY = 0
SPECIAL = None

HMIS RATINGS:

HEALTH = 3
FLAMMABILITY = 4
PHYSICAL HAZARD = 1

STANDARD VALVE CONNECTIONS FOR U.S. AND CANADA:

THREADED:	CGA-795 (cryogenic liquid withdrawal, for pressures up to 140 psig)
PIN-INDEXED YOKE:	Not applicable.
ULTRA-HIGH-INTEGRITY CONNECTION:	Not applicable.

Use the proper CGA connections. **DO NOT USE ADAPTERS.** Additional limited-standard connections may apply. See CGA pamphlet V-1 listed below.

Ask your supplier about free Praxair safety literature as referred to in this MSDS and on the label for this product. Further information can be found in the following materials published by the Compressed Gas Association, Inc. (CGA), 4221 Walney Road, 5th Floor, Chantilly, VA 20151-2923, Telephone (703) 788-2700, http://www.cganet.com/Publication.asp.

AV-1	*Safe Handling and Storage of Compressed Gases*
G-5	*Hydrogen*
G-5.3	*Commodity Specification for Hydrogen*
P-1	*Safe Handling of Compressed Gases in Containers*
P-12	*Safe Handling of Cryogenic Liquids*
SB-2	*Oxygen-Deficient Atmospheres*
V-1	*Compressed Gas Cylinder Valve Inlet and Outlet Connections*
—	*Handbook of Compressed Gases, Fourth Edition*

Praxair asks users of this product to study this MSDS and become aware of product hazards and safety information. To promote safe use of this product, a user should (1) notify employees, agents, and contractors of the information in this MSDS and of any other known product hazards and safety information, (2) furnish this information to each purchaser of the product, and (3) ask each purchaser to notify its employees and customers of the product hazards and safety information.

The opinions expressed herein are those of qualified experts within Praxair, Inc. We believe that the information contained herein is current as of the date of this Material Safety Data Sheet. Since the use of this information and the conditions of use of the product are not within the control of Praxair, Inc., it is the user's obligation to determine the conditions of safe use of the product.

Praxair MSDSs are furnished on sale or delivery by Praxair or the independent distributors and suppliers who package and sell our products. To obtain current MSDSs for these products, contact your Praxair sales representative or local distributor or supplier, or download from www.praxair.com. If you have questions regarding Praxair MSDSs, would like the form number and date of the latest MSDS, or would like the names of the Praxair suppliers in your area, phone or write the Praxair Call Center (**Phone:** 1-800-PRAXAIR; **Address:** Praxair Call Center, Praxair, Inc., PO Box 44, Tonawanda, NY 14151-0044).

Praxair, Inc.
39 Old Ridgebury Road
Danbury, CT 06810-5113

ConocoPhillips

Natural Gas

Safety Data Sheet

Section 1: Identification of the substance or mixture and of the supplier

Product Name:	Natural Gas
SDS Number:	724330
Synonyms/Other Means of Identification:	Fuel Gas Residue Gas Processed Gas Natural Gas, Dry Compressed Natural Gas
Intended Use:	Fuel
Manufacturer:	ConocoPhillips 600 N. Dairy Ashford Houston, Texas 77079-1175
Emergency Health and Safety Number:	Chemtrec: 800-424-9300 (24 Hours)
Technical Information:	855-244-0762
SDS Information:	Phone: 800-762-0942 Email: MSDS@conocophillips.com URL: www.conocophillips.com

Section 2: Hazard(s) Identification

DANGER

Extremely flammable gas. (H220)*
Contains gas under pressure. May explode if heated. (H280)*
Gas may reduce oxygen in confined spaces.

NFPA

Precautionary Statement(s):
Do not handle until all safety precautions have been read and understood. (P202)*
Use personal protective equipment as required. (P281)*
Keep away from heat/sparks/open flames/hot surfaces. - No smoking. (P210)*
Take precautionary measures against static discharge. (P243)*
Leaking gas fire: Do not extinguish, unless leak can be stopped safely. (P377)*
Eliminate all ignition sources if safe to do so. (P381)*
Protect from sunlight. Store in a well ventilated place. (P410+P403)*

** (Applicable GHS hazard code.)*

Section 3: Composition / Information on Ingredients

Component	CASRN	Concentration[1]
Natural gas, dried	68410-63-9	100

[1] All concentrations are percent by weight unless ingredient is a gas. Gas concentrations are in percent by volume.

Section 4: First Aid Measures

Eye Contact: If irritation or redness develops from exposure, flush eyes with clean water. If symptoms persist, seek medical attention.

Skin Contact: First aid is not normally required. However, it is good practice to wash any chemical from the skin.

Inhalation (Breathing): If respiratory symptoms develop, move victim away from source of exposure and into fresh air in a position comfortable for breathing. If breathing is difficult, oxygen or artificial respiration should be administered by qualified personnel. If symptoms persist, seek medical attention.

Ingestion (Swallowing): This material is a gas under normal atmospheric conditions and ingestion is unlikely.

Notes to Physician: Epinephrine and other sympathomimetic drugs may initiate cardiac arrhythmias in persons exposed to high concentrations of hydrocarbon solvents (e.g., in enclosed spaces or with deliberate abuse). The use of other drugs with less arrhythmogenic potential should be considered. If sympathomimetic drugs are administered, observe for the development of cardiac arrhythmias.

Medical Conditions Aggravated by Exposure: Exposure to high concentrations of this material may increase the sensitivity of the heart to certain drugs. Persons with pre-existing heart disorders may be more susceptible to this effect (see Section 4 - Note to Physicians).

Section 5: Fire-Fighting Measures

NFPA 704 Hazard Class

Health: 1 **Flammability:** 4 **Instability:** 0 (0-Minimal, 1-Slight, 2-Moderate, 3-Serious, 4-Severe)

Unusual Fire & Explosion Hazards: Extremely flammable. This material can be ignited by heat, sparks, flames, or other sources of ignition (e.g., static electricity, pilot lights, mechanical/electrical equipment, and electronic devices such as cell phones, computers, calculators, and pagers which have not been certified as intrinsically safe). Vapors may travel considerable distances to a source of ignition where they can ignite, flash back, or explode. May create vapor/air explosion hazard indoors, in confined spaces, outdoors, or in sewers. If container is not properly cooled, it can rupture in the heat of a fire. Contents under pressure.

Extinguishing Media: Dry chemical or carbon dioxide is recommended. Carbon dioxide can displace oxygen. Use caution when applying carbon dioxide in confined spaces.

Fire Fighting Instructions: For fires beyond the initial stage, emergency responders in the immediate hazard area should wear protective clothing. When the potential chemical hazard is unknown, in enclosed or confined spaces, a self contained breathing apparatus should be worn. In addition, wear other appropriate protective equipment as conditions warrant (see Section 8).

Isolate immediate hazard area and keep unauthorized personnel out. Stop spill/release if it can be done safely. If this cannot be done, allow fire to burn. Move undamaged containers from immediate hazard area if it can be done safely. Stay away from ends of container. Water spray may be useful in minimizing or dispersing vapors and to protect personnel. Cool equipment exposed to fire with water, if it can be done safely.

Hazardous Combustion Products: Combustion may yield smoke, carbon monoxide, and other products of incomplete combustion. Oxides of nitrogen and sulfur may also be formed.

See Section 9 for Flammable Properties including Flash Point and Flammable (Explosive) Limits

Section 6: Accidental Release Measures

Personal Precautions: Extremely flammable. Spillages of liquid product will create a fire hazard and may form an explosive atmosphere. Keep all sources of ignition and hot metal surfaces away from spill/release if safe to do so. The use of explosion-proof electrical equipment is recommended. Beware of accumulation of gas in low areas or contained areas, where explosive concentrations may occur. Prevent from entering drains or any place where accumulation may occur. Ventilate area and allow to evaporate. Stay upwind and away from spill/release. Avoid direct contact with material. For large spillages, notify persons down wind of the spill/release, isolate immediate hazard area and keep unauthorized personnel out. Wear appropriate protective equipment, including respiratory protection, as conditions warrant (see Section 8). See Sections 2 and 7 for additional information on hazards and precautionary measures.

Environmental Precautions: Stop spill/release if it can be done safely. Water spray may be useful in minimizing or dispersing vapors. If spill occurs on water notify appropriate authorities and advise shipping of any hazard.

Methods for Containment and Clean-Up: Notify relevant authorities in accordance with all applicable regulations.

Recommended measures are based on the most likely spillage scenarios for this material; however local conditions and regulations may influence or limit the choice of appropriate actions to be taken.

Section 7: Handling and Storage

Precautions for safe handling: Keep away from ignition sources such as heat/sparks/open flame – No smoking. Take precautionary measures against static discharge. Use good personal hygiene practices and wear appropriate personal protective equipment (see section 8).

Contents under pressure. Gas can accumulate in confined spaces and limit oxygen available for breathing. Use only with adequate ventilation. The use of explosion-proof electrical equipment is recommended and may be required (see appropriate fire codes). Refer to NFPA-70 and/or API RP 2003 for specific bonding/grounding requirements. Electrostatic charge may accumulate and create a hazardous condition when handling or processing this material. To avoid fire or explosion, dissipate static electricity during transfer by grounding and bonding containers and equipment before transferring material. Do not enter confined spaces such as tanks or pits without following proper entry procedures such as ASTM D-4276 and 29CFR 1910.146. Cold burns may occur during filling operations. Containers and delivery lines may become cold enough to present cold burn hazard.

The use of hydrocarbon fuel in an area without adequate ventilation may result in hazardous levels of incomplete combustion products (e.g. carbon monoxide, oxides of sulfur and nitrogen, benzene and other hydrocarbons) and/or dangerously low oxygen levels.

Conditions for safe storage: Keep container(s) tightly closed and properly labeled. Use and store this material in cool, dry, well-ventilated areas away from heat, direct sunlight, hot metal surfaces, and all sources of ignition. Store only in approved containers. Post area "No Smoking or Open Flame." Keep away from any incompatible material (see Section 10). Protect container(s) against physical damage. Outdoor or detached storage is preferred. Indoor storage should meet OSHA standards and appropriate fire codes.

"Empty" containers retain residue and may be dangerous. Do not pressurize, cut, weld, braze, solder, drill, grind, or expose such containers to heat, flame, sparks, or other sources of ignition. They may explode and cause injury or death. Avoid exposing any part of a compressed-gas cylinder to temperatures above 125F(51.6C). Gas cylinders should be stored outdoors or in well ventilated storerooms at no lower than ground level and should be quickly removable in an emergency.

Section 8: Exposure Controls / Personal Protection

Component	ACGIH	OSHA	Other
Natural gas, dried	1000 ppm TWA as Aliphatic Hydrocarbons C1-4	---	---

Note: State, local or other agencies or advisory groups may have established more stringent limits. Consult an industrial hygienist or similar professional, or your local agencies, for further information.

Engineering controls: If current ventilation practices are not adequate to maintain airborne concentrations below the established exposure limits, additional engineering controls may be required.

Eye/Face Protection: The use of eye/face protection is not normally required; however, good industrial hygiene practice suggests the use of eye protection that meets or exceeds ANSI Z.87.1 whenever working with chemicals.

Skin/Hand Protection: The use of skin protection is not normally required; however, good industrial hygiene practice suggests the use of gloves or other appropriate skin protection whenever working with chemicals.

Respiratory Protection: A NIOSH approved, self-contained breathing apparatus (SCBA) or equivalent operated in a pressure demand or other positive pressure mode should be used in situations of oxygen deficiency (oxygen content less than 19.5 percent), unknown exposure concentrations, or situations that are immediately dangerous to life or health (IDLH).

A respiratory protection program that meets or is equivalent to OSHA 29 CFR 1910.134 and ANSI Z88.2 should be followed whenever workplace conditions warrant a respirator's use.

Suggestions provided in this section for exposure control and specific types of protective equipment are based on readily available information. Users should consult with the specific manufacturer to confirm the performance of their protective equipment. Specific situations may require consultation with industrial hygiene, safety, or engineering professionals.

Section 9: Physical and Chemical Properties

Note: Unless otherwise stated, values are determined at 20°C (68°F) and 760 mm Hg (1 atm). Data represent typical values and are not intended to be specifications.

Appearance:	Colorless
Physical Form:	Compressed Gas
Odor:	Slight hydrocarbon
Odor Threshold:	No data
pH:	Not applicable
Vapor Density (air=1):	0.5
Initial Boiling Point/Range:	No data
Melting/Freezing Point:	No data
Solubility in Water:	Slight
Partition Coefficient (n-octanol/water) (Kow):	No data
Percent Volatile:	100%
Flammability (solid, gas):	Extremely Flammable
Evaporation Rate (nBuAc=1):	No data
Flash Point:	-299 °F / -184 °C
Test Method:	(estimate)
Lower Explosive Limits (vol % in air):	2.0
Upper Explosive Limits (vol % in air):	10.0
Auto-ignition Temperature:	999 °F / 537 °C

Section 10: Stability and Reactivity

Stability: Stable under normal ambient and anticipated conditions of use.

Conditions to Avoid: Avoid all possible sources of ignition. Heat will increase pressure in the storage tank.

Materials to Avoid (Incompatible Materials): Avoid contact with acids, aluminum chloride, chlorine, chlorine dioxide, halogens and oxidizing agents.

Hazardous Decomposition Products: Not anticipated under normal conditions of use.

Hazardous Polymerization: Not known to occur.

Section 11: Toxicological Information

Information on Toxicological Effects of Substance/Mixture

Acute Toxicity	Hazard	Additional Information	LC50/LD50 Data
Inhalation	Unlikely to be harmful	Asphyxiant. High concentrations in confined spaces may limit oxygen available for breathing. See Signs and Symptoms.	> 20,000 ppm (gas)
Skin Absorption	Skin absorption is not anticipated		Not Applicable
Ingestion (Swallowing)	Ingestion is not anticipated		Not Applicable

Aspiration Hazard: Not applicable

Skin Corrosion/Irritation: Skin exposure is not anticipated.

Serious Eye Damage/Irritation: Not expected to be irritating.

Signs and Symptoms: Light hydrocarbon gases are simple asphyxiants and can cause anesthetic effects at high concentrations. Symptoms of overexposure, which are reversible if exposure is stopped, can include shortness of breath, drowsiness, headaches, confusion, decreased coordination, visual disturbances and vomiting. Continued exposure can lead to hypoxia (inadequate oxygen), rapid breathing, cyanosis (bluish discoloration of the skin), numbness of the extremities, unconsciousness and death.

Skin Sensitization: Skin contact is not anticipated.

Respiratory Sensitization: Not expected to be a respiratory sensitizer.

Specific Target Organ Toxicity (Single Exposure): Not expected to cause organ effects from single exposure.

Specific Target Organ Toxicity (Repeated Exposure): Not expected to cause organ effects from repeated exposure.

Carcinogenicity: Not expected to cause cancer.

Germ Cell Mutagenicity: Not expected to cause heritable genetic effects.

Reproductive Toxicity: Not expected to cause reproductive toxicity.

Other Comments: High concentrations may reduce the amount of oxygen available for breathing, especially in confined spaces. Hypoxia (inadequate oxygen) during pregnancy may have adverse effects on the developing fetus.

Section 12: Ecological Information

Toxicity: Petroleum gases will readily evaporate from the surface and would not be expected to have significant adverse effects in the aquatic environment. Classification: No classified hazards.

Persistence and Degradability: The hydrocarbons in this material are expected to be inherently biodegradable. In practice, hydrocarbon gases are not likely to remain in solution long enough for biodegradation to be a significant loss process. Hydrogen sulfide, if present in refinery gas streams, will be rapidly oxidized in water and insoluble sulfides precipitated from water when metallic radicals are present.

Bioaccumulative Potential: Since the log Kow values measured for refinery gas constituents are below 3, they are not regarded as having the potential to bioaccumulate.

Mobility in Soil: Due to the extreme volatility of petroleum gases, air is the only environmental compartment in which they will be found. In air, these hydrocarbons undergo photodegradation by reaction with hydroxyl radicals with half-lives ranging from 3.2 days for n-butane to 7 days for propane.

Other Adverse Effects: None anticipated.

Section 13: Disposal Considerations

This material is a gas and would not typically be managed as a waste.

Section 14: Transport Information

U.S. Department of Transportation (DOT)

Shipping Description:	UN1971, Natural gas, compressed, 2.1
Non-Bulk Package Marking:	Natural gas, compressed, UN1971
Non-Bulk Package Labeling:	Flammable gas
Bulk Package/Placard Marking:	Flammable gas / 1971
Packaging - References:	49 CFR 173.306; 173.302; 173.302 *(Exceptions; Non-bulk; Bulk)*
Hazardous Substance:	See Section 15 for RQ`s
Emergency Response Guide:	115

International Maritime Dangerous Goods (IMDG)

Shipping Description:	UN1971, Natural gas, compressed, 2.1
Non-Bulk Package Marking:	Natural gas, compressed, UN1971
Labels:	Flammable gas
Placards/Marking (Bulk):	Flammable gas / 1971

Packaging - Non-Bulk:	P200
EMS:	F-D, S-U

International Civil Aviation Org. / International Air Transport Assoc. (ICAO/IATA)

UN/ID #:	UN1971
Proper Shipping Name:	Natural gas, compressed
Hazard Class/Division:	2.1
Subsidiary risk:	None
Packing Group:	None
Non-Bulk Package Marking:	Natural gas, compressed, UN1971
Labels:	Flammable gas , Cargo Aircraft Only
ERG Code:	10L

	LTD. QTY	**Passenger Aircraft**	**Cargo Aircraft Only**
Packaging Instruction #:	*Forbidden*	*Forbidden*	200
Max. Net Qty. Per Package:	*Forbidden*	*Forbidden*	150 kg

Section 15: Regulatory Information

CERCLA/SARA - Section 302 Extremely Hazardous Substances and TPQs (in pounds):

This material does not contain any chemicals subject to the reporting requirements of SARA 302 and 40 CFR 372.

CERCLA/SARA - Section 311/312 (Title III Hazard Categories)

Acute Health:	Yes
Chronic Health:	No
Fire Hazard:	Yes
Pressure Hazard:	Yes
Reactive Hazard:	No

CERCLA/SARA - Section 313 and 40 CFR 372:

This material does not contain any chemicals subject to the reporting requirements of SARA 313 and 40 CFR 372.

EPA (CERCLA) Reportable Quantity (in pounds):

EPA's Petroleum Exclusion applies to this material - (CERCLA 101(14)).

California Proposition 65:

This material does not contain any chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm at concentrations that trigger the warning requirements of California Proposition 65.

International Hazard Classification

GHS Classification
H220 -- Flammable gases -- Category 1
H280 -- Gases under pressure -- Compressed gas

Canada:

This product has been classified in accordance with the hazard criteria of the Controlled Products Regulations (CPR) and the MSDS contains all the information required by the Regulations.

WHMIS Hazard Class:
A - Compressed Gas
B1 - Flammable Gases

National Chemical Inventories
All components are either listed on the US TSCA Inventory, or are not regulated under TSCA
All components are either on the DSL, or are exempt from DSL listing requirements

U.S. Export Control Classification Number: EAR99

Section 16: Other Information

Date of Issue:	09-Feb-2012
Status:	FINAL
Previous Issue Date:	02-Sep-2009
Revised Sections or Basis for Revision:	Format change Identified Hazards (Section 2) NFPA ratings (Sections 2&5) Toxicological (Section 11)
SDS Number:	724330

Guide to Abbreviations:
ACGIH = American Conference of Governmental Industrial Hygienists; CASRN = Chemical Abstracts Service Registry Number; CEILING = Ceiling Limit (15 minutes); CERCLA = The Comprehensive Environmental Response, Compensation, and Liability Act; EPA = Environmental Protection Agency; GHS = Globally Harmonized System; IARC = International Agency for Research on Cancer; INSHT = National Institute for Health and Safety at Work; IOPC = International Oil Pollution Compensation; LEL = Lower Explosive Limit; NE = Not Established; NFPA = National Fire Protection Association; NTP = National Toxicology Program; OSHA = Occupational Safety and Health Administration; PEL = Permissible Exposure Limit (OSHA); SARA = Superfund Amendments and Reauthorization Act; STEL = Short Term Exposure Limit (15 minutes); TLV = Threshold Limit Value (ACGIH); TWA = Time Weighted Average (8 hours); UEL = Upper Explosive Limit; WHMIS = Worker Hazardous Materials Information System (Canada)

Disclaimer of Expressed and implied Warranties:
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NATIONAL
REFRIGERANTS™

Material Safety Data Sheet

R-134A

1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

PRODUCT NAME:	R-134A
DISTRIBUTOR:	National Refrigerants, Inc. 661 Kenyon Avenue Bridgeton, New Jersey 08302

FOR MORE INFORMATION CALL:
(Monday-Friday, 8:00am-5:00pm)
1-800-262-0012

IN CASE OF EMERGENCY CALL:
CHEMTREC: 1-800-424-9300

2. COMPOSITION / INFORMATION ON INGREDIENTS

INGREDIENT NAME	CAS NUMBER	WEIGHT %
1,1,1,2-Tetrafluoroethane	811-97-2	100

Trace impurities and additional material names not listed above may also appear in Section 15 toward the end of the MSDS. These materials may be listed for local “Right-To-Know” compliance and for other reasons.

3. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW: Colorless, volatile liquid with ethereal and faint sweetish odor. Non-flammable material. Overexposure may cause dizziness and loss of concentration. At higher levels, CNS depression and cardiac arrhythmia may result from exposure. Vapors displace air and can cause asphyxiation in confined spaces. At higher temperatures, (>250°C), decomposition products may include Hydrofluoric Acid (HF) and carbonyl halides.

POTENTIAL HEALTH HAZARDS

SKIN: Irritation would result from a defatting action on tissue. Liquid contact could cause frostbite.

EYES: Liquid contact can cause severe irritation and frostbite. Mist may irritate.

INHALATION: R-134A is low in acute toxicity in animals. When oxygen levels in air are reduced to 12-14% by displacement, symptoms of asphyxiation, loss of coordination, increased pulse rate and deeper respiration will occur. At high levels, cardiac arrhythmia may occur.

INGESTION: Ingestion is unlikely because of the low boiling point of the material. Should it occur, discomfort in the gastrointestinal tract from rapid evaporation of the material and consequent evolution of gas would result. Some effects of inhalation and skin exposure would be expected.

DELAYED EFFECTS: None Known

Ingredients found on one of the OSHA designated carcinogen lists are listed below.

INGREDIENT NAME	NTP STATUS	IARC STATUS	OSHA LIST
No ingredients listed in this section			

4. FIRST AID MEASURES

SKIN: Promptly flush skin with water until all chemical is removed. If there is evidence of frostbite, bathe (do not rub) with lukewarm (not hot) water. If water is not available, cover with a clean, soft cloth or similar covering. Get medical attention if symptoms persist.

EYES: Immediately flush eyes with large amounts of water for at least 15 minutes (in case of frostbite, water should be lukewarm, not hot) lifting eyelids occasionally to facilitate irrigation. Get medical attention if symptoms persist.

INHALATION: Immediately remove to fresh air. If breathing has stopped, give artificial respiration. Use oxygen as required, provided a qualified operator is available. Get medical attention immediately. DO NOT give epinephrine (adrenaline).

INGESTION: Ingestion is unlikely because of the physical properties and is not expected to be hazardous. DO NOT induce vomiting unless instructed to do so by a physician.

ADVICE TO PHYSICIAN: Because of the possible disturbances of cardiac rhythm, catecholamine drugs, such as epinephrine, should be used with special caution and only in situations of emergency life support. Treatment of overexposure should be directed at the control of symptoms and the clinical conditions.

5. FIRE FIGHTING MEASURES

FLAMMABLE PROPERTIES

FLASH POINT:	Gas, not applicable per DOT regulations
FLASH POINT METHOD:	Not applicable
AUTOIGNITION TEMPERATURE:	>750°C
UPPER FLAME LIMIT (volume % in air):	None*
LOWER FLAME LIMIT (volume % in air):	None* *Based on ASHRAE Standard 34 with match ignition
FLAME PROPAGATION RATE (solids):	Not applicable
OSHA FLAMMABILITY CLASS:	Not applicable

EXTINGUISHING MEDIA:

Use any standard agent – choose the one most appropriate for type of surrounding fire (material itself is not flammable)

UNUSUAL FIRE AND EXPLOSION HAZARDS:

R-134A is not flammable at ambient temperatures and atmospheric pressure. However, this material will become combustible when mixed with air under pressure and exposed to strong ignition sources.

Contact with certain reactive metals may result in formation of explosive or exothermic reactions under specific conditions (e.g. very high temperatures and/or appropriate pressures).

SPECIAL FIRE FIGHTING PRECAUTIONS/INSTRUCTIONS:

Firefighters should wear self-contained, NIOSH-approved breathing apparatus for protection against possible toxic decomposition products. Proper eye and skin protection should be provided. Use water spray to keep fire-exposed containers cool.

6. ACCIDENTAL RELEASE MEASURES

IN CASE OF SPILL OR OTHER RELEASE: (Always wear recommended personal protective equipment.)

Evacuate unprotected personnel. Protected personnel should remove ignition sources and shut off leak, if without risk, and provide ventilation. Unprotected personnel should not return until air has been tested and determined safe, including low-lying areas.

Spills and releases may have to be reported to Federal and/or local authorities. See Section 15 regarding reporting requirements.

7. HANDLING AND STORAGE

NORMAL HANDLING: (Always wear recommended personal protective equipment.)

Avoid breathing vapors and liquid contact with eyes, skin or clothing. Do not puncture or drop cylinders, expose them to open flame or excessive heat. Use authorized cylinders only. Follow standard safety precautions for handling and use of compressed gas cylinders.

R-134A should not be mixed with air above atmospheric pressure for leak testing or any other purpose.

STORAGE RECOMMENDATIONS:

Store in a cool, well-ventilated area of low fire risk and out of direct sunlight. Protect cylinder and its fittings from physical damage. Storage in subsurface locations should be avoided. Close valve tightly after use and when empty.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

ENGINEERING CONTROLS:

Provide local ventilation at filling zones and areas where leakage is probable. Mechanical (general) ventilation may be adequate for other operating and storage areas.

PERSONAL PROTECTIVE EQUIPMENT

SKIN PROTECTION:

Skin contact with refrigerant may cause frostbite. General work clothing and gloves (leather) should provide adequate protection. If prolonged contact with liquid or gas is anticipated, insulated gloves constructed of PVA, neoprene or butyl rubber should be used. Any contaminated clothing should be promptly removed and washed before reuse.

EYE PROTECTION:

For normal conditions, wear safety glasses. Where there is reasonable probability of liquid contact, wear chemical safety goggles.

RESPIRATORY PROTECTION:

None generally required for adequately ventilated work situations. For accidental release or non-ventilated situations, or release into confined space, where the concentration may be above the PEL of 1,000 ppm, use a self-contained, NIOSH approved breathing apparatus or supplied air respirator. For escape: use the former or a NIOSH approved gas mask with organic vapor canister.

ADDITIONAL RECOMMENDATIONS:

Where contact with liquid is likely, such as in a spill or leak, impervious boots and clothing should be worn. High dose-level warning signs are recommended for areas of principle exposure. Provide eyewash stations and quick-drench shower facilities at convenient locations. For tank cleaning operations, see OSHA regulations, 29 CFR 1910.132 and 29 CFR 1910.133.

EXPOSURE GUIDELINES

INGREDIENT NAME	ACGIH TLV	OSHA PEL	OTHER LIMIT
1,1,1,2-Tetrafluoroethane	None	None	*1000 ppm TWA (8hr)

* = Workplace Environmental Exposure Level (AIHA)

OTHER EXPOSURE LIMITS FOR POTENTIAL DECOMPOSITION PRODUCTS:
Hydrogen Fluoride: ACGIH TLV: 2 ppm ceiling, 0.5 ppm TLV-TWA

9. PHYSICAL AND CHEMICAL PROPERTIES

APPEARANCE:	Clear, colorless liquid and vapor	
PHYSICAL STATE:	Gas at ambient temperatures	
MOLECULAR WEIGHT:	102	
CHEMICAL FORMULA:	F_3CCH_2F	
ODOR:	Faint ethereal odor	
SPECIFIC GRAVITY (water = 1.0):	<1.22	
SOLUBILITY IN WATER (weight %):	0.15 wt%	
pH:	Neutral	
BOILING POINT:	-26.2°C (-15.1°F)	
FREEZING POINT:	-92.5°C (-141.9°F)	
VAPOR PRESSURE:	85.8 psia @ 70°F 213.4 psia @ 130°F	
VAPOR DENSITY (air = 1.0):	3.5	
EVAPORATION RATE:	>1	**COMPARED TO:** $CC1_4 = 1$
% VOLATILES:	100	
FLASH POINT:	Not applicable	

(Flash point method and additional flammability data are found in Section 5.)

10. STABILITY AND REACTIVITY

NORMALLY STABLE? (CONDITIONS TO AVOID):

The product is stable.

Do not mix with oxygen or air above atmospheric pressure. Any source of high temperatures, such as lighted cigarettes, flames, hot spots or welding may yield toxic and/or corrosive decomposition products.

INCOMPATIBILITIES:

(Under specific conditions: e.g. very high temperatures and/or appropriate pressures) – Freshly abraded aluminum surfaces (may cause strong exothermic reaction). Chemically reactive metals: potassium, calcium, powdered aluminum, magnesium, and zinc.

HAZARDOUS DECOMPOSITION PRODUCTS:

Halogens, halogen acids and possibly carbonyl halides.

HAZARDOUS POLYMERIZATION:

Will not occur.

11. TOXICOLOGICAL INFORMATION

IMMEDIATE (ACUTE) EFFECTS:

LC_{50} : 4 hr. (rat) - > 500,000 ppm / Cardiac Sensitization threshold (dog) 80,000 ppm. NOEL – 50,000 ppm

DELAYED (SUBCHRONIC AND CHRONIC) EFFECTS:

Not mutagenic in four tests
Teratogenic NOEL (rat and rabbit) – 40,000 ppm
Subchronic inhalation (rat) NOEL – 50,000 ppm
Chronic NOEL – 10,000 ppm

OTHER DATA:

Metabolism <0.5% as CO_2 in tests at 50,000 ppm, late developing benign tumors were found.

12. ECOLOGICAL INFORMATION

Degradability (BOD): R-134A is a gas at room temperature; therefore, it is unlikely to remain in water.
Octanol Water Partition Coefficient: Log $P_{ow} = 1.06$

13. DISPOSAL CONSIDERATIONS

<u>RCRA</u>

Is the unused product a RCRA hazardous waste if discarded?	Not a hazardous waste
If yes, the RCRA ID number is:	Not applicable

OTHER DISPOSAL CONSIDERATIONS:

Disposal must comply with federal, state, and local disposal or discharge laws. R-134A is subject to U.S. Environmental Protection Agency Clean Air Act Regulations Section 608 in 40 CFR Part 82 regarding refrigerant recycling.

The information offered here is for the product as shipped. Use and/or alterations to the product such as mixing with other materials may significantly change the characteristics of the material and alter the RCRA classification and the proper disposal method.

14. TRANSPORT INFORMATION

US DOT PROPER SHIPPING NAME:	1,1,1,2-Tetrafluoroethane
US DOT HAZARD CLASS:	2.2
US DOT PACKING GROUP:	Not applicable
US DOT ID NUMBER:	UN3159

For additional information on shipping regulations affecting this material, contact the information number found in Section 1.

15. REGULATORY INFORMATION

TOXIC SUBSTANCES CONTROL ACT (TSCA)

TSCA INVENTORY STATUS:	Listed on the TSCA inventory
OTHER TSCA ISSUES:	None

SARA TITLE III / CERCLA

"Reportable Quantities" (RQs) and/or "Threshold Planning Quantities" (TPQs) exist for the following ingredients.

INGREDIENT NAME	SARA / CERCLA RQ (lb.)	SARA EHS TPQ (lb.)
No ingredients listed in this section		

Spills or releases resulting in the loss of any ingredient at or above its RQ requires immediate notification to the National Response Center [(800) 424-8802] and to your Local Emergency Planning Committee.

SECTION 311 HAZARD CLASS: IMMEDIATE
PRESSURE

SARA 313 TOXIC CHEMICALS:

The following ingredients are SARA 313 "Toxic Chemicals". CAS numbers and weight percents are found in Section 2.

INGREDIENT NAME	COMMENT
No ingredients listed in this section	

STATE RIGHT-TO-KNOW

In addition to the ingredients found in Section 2, the following are listed for state right-to-know purposes.

INGREDIENT NAME	WEIGHT %	COMMENT
No ingredients listed in this section		

ADDITIONAL REGULATORY INFORMATION:

R-134A is subject to U.S. Environmental Protection Agency Clean Air Act Regulations at 40 CFR Part 82.

WARNING: DO NOT vent to the atmosphere. To comply with provisions of the U.S. Clean Air Act, any residual must be recovered. **Contains 1,1,1,2-Tetrafluoroethane (HFC-134a),** a greenhouse gas which may contribute to global warming.

WHMIS CLASSIFICATION (CANADA):

This product has been evaluated in accordance with the hazard criteria of the CPR and the MSDS contains all the information required by the CPR.

FOREIGN INVENTORY STATUS:

Canada – Listed on DSL
EU - EINECS # 223770

16. OTHER INFORMATION

CURRENT ISSUE DATE:	December, 2008
PREVIOUS ISSUE DATE:	August, 2007

OTHER INFORMATION:

HMIS Classification: Health – 1, Flammability – 1, Reactivity – 0
NFPA Classification: Health – 2, Flammability – 1, Reactivity – 0
ANSI/ASHRAE 34 Safety Group – A1
UL Classified

Regulatory Standards:

1. OSHA regulations for compressed gases: 29 CFR 1910.101
2. DOT classification per 49 CFR 172.101

Toxicity information per PAFT Testing

17. DISCLAIMER

National Refrigerants, Inc. believes that the information and recommendations contained herein (including data and statements are accurate as of the date hereof. NO WARRANTY OF FITNESS FOR ANY PARTICULAR PURPOSE, WARRANTY OF MERCHANTABILITY, OR ANY OTHER WARRANTY, EXPRESSED OR IMPLIED, IS MADE CONCERNING THE INFORMATION PROVIDED HEREIN. The information provided herein relates only to the specific product designated and may not be valid where such product is used in combination with any other methods of use of the product and of the information referred to herein are beyond the control of National Refrigerants. National Refrigerants expressly disclaims any and all liability as to any results obtained or arising from any use of the product or reliance on such information.

MATERIAL SAFETY DATA SHEET
UNICAT SR-109, SR-110, SR111

Revision : 10/2006

1.1 IDENTIFICATION OF PRODUCT.

Designation: SR-109, SR-110, SR-111. Sulphur absorption catalyst.

1.2 COMPANY.

UNICAT CATALYST, INC.
1600 East Hwy 6, Suite 320
ALVIN, TX 77511, USA

Phone:	(281) 331-2231
Fax:	(281) 331-2281
Emergency Phone:	(281) 331-2231

2 HAZARDOUS AND OTHER INGREDIENTS.

Exposure limits may vary. It is recommended that information about locally applicable exposure limits be obtained.

%w/w	Compound		CAS No	MAK mg/m^3 (Germany)	TLV mg/m^3 (ACGIH)	PEL mg/m^3 (OSHA)
92-98	Zinc oxide	ZnO	1314-13-2	5 (fume)	10 (dust) 5 10 STEL(fume)	10 (dust) 5 (resp & vapor) 10 STEL(vapor)

3 PHYSICAL DATA.

State:	Solid
Appearance and odour:	White.Extruded pellets.Odourless.
pH:	Not applicable.
Boiling point or range:	Not applicable.
Melting point or range:	Above 1900°C / 3450 °F.
Vapour pressure:	Not applicable.
Vapour density:	Not applicable.
Density relative to water:	Above 1.
Solubility in water:	Negligible.
Partition coefficient (n-octanol/water):	Not applicable.
Other data:	

4 FIRE AND EXPLOSION HAZARD DATA.

Fire, explosion and reactivity hazards:	Not applicable.
Flammability and flammability limits:	Non flammable.
Autoflammability:	Not applicable.
Explosive properties:	Non explosive.
Oxidizing properties:	Non oxidizing.

Fire fighting measures:
Product is compatible with standard firefighting agents. Check runoff for metals.

5 STABILITY AND REACTIVITY DATA.

The product is stable under normal handling and storage conditions.

Conditions to avoid:	not relevant.
Materials to avoid:	not relevant.
Hazardous decomposition products:	none known.

6 HEALTH HAZARDS.

Routes of entry:	Inhalation, eye and skin contact, ingestion.

Health hazards:

Acute:	Inhalation of excessive amounts of dust may cause irritation of the respiratory system; symptoms may include coughing and difficulty in breathing. Exposure to fumes and dusts of some metal oxides may result in metal fume fever, with flu-like symptons occuring in 4-12 hours. May cause physical irritation of eyes. May irritate skin.
Chronic:	None known.
Synergistic effects:	None known.

Toxicological data:

Compound	RTECS No	Toxicity data
Zinc oxide:	ZH4810000	Oral Human LDLo 500 mg/kg. Oral mouse LD50 7950 mg/kg. Inhalation mouse LC50 2500 mg/m^3. Intraperitoneal rat LD50 240 mg/kg. Human TCLo 600 mg/m^3

Chronic effects as listed by OSHA, IARC, NTP, MAK:

Carcinogenic:	not listed.
Teratogenic:	not listed.
Mutagenic:	not listed.

7 PREVENTIVE MEASURES.

Avoid handling methods creating excessive dust. Use mechanical ventilation when appropriate. Use good housekeeping and personal hygiene practices. Do not eat, drink or smoke when handling materials. Wash hands thoroughly after handling.

Personal protection:

Respiratory protection:	Use approved respirator when exposure may exceed recommended limits.
Hand protection:	Gloves recommended.
Eye protection:	Goggles recommended.
Other protection:	Change work clothing daily. Safety shoes recommended when handling heavy containers.

Accidental release measures.

Personal precautions:	Avoid inhalation of dust.
Environmental precautions:	Do not wash spills into water ways or public treatment systems.
Methods for cleaning up:	Collect by vacuuming or sweeping (minimizing dust) and place in labelled container.

Disposal considerations
May be reclaimed. Dispose of in accordance with applicable federal, state and local regulations. Unused product is not an EPA hazardous waste. UNICAT Inc. makes no claim for the classification of used or contaminated material.

Handling and storage.

Handling:	Avoid excessive dust formation.
Storage:	Product may be damaged by water.

Transport Information

Not classified as hazardous under:	IMO/IMDG ADR-RID IATA DOT TDG

8 FIRST-AID MEASURES.

Inhalation:	If dust is inhaled, move to fresh air. For significant inhalation: If breathing is difficult, give oxygen if available. If not breathing, give artificial respiration. Seek medical attention.
Eye contact:	Immediately flush eyes with water. If irritation persists, seek medical attention.
Skin contact:	Wash with soap and water. Remove contaminated clothing.
Ingestion:	In case of substantial ingestion, drink plenty of water and induce vomiting. Seek medical attention.

9 OTHER INFORMATION.

Regulatory information:

All components are included in TSCA (USA), DSL (Canada) and EINECS (EEC) inventories.

Chemical release reporting (SARA section 313, as codified in 40 CFR part 372):
Reporting required due to content of zinc compounds.

Canadian WHMIS classification: Class D, Division 2.B.

EEC label for product following directive 88/379/EEC:

Not applicable.

References and additional information:
RTECS (Registry of Toxic Effects of Chemical Substances, National Institute for Occupational Safety and Health, 4676 Columbia Pkwy., Cincinnati, Ohio 45226, USA).