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Abstract

The proposed Alaskan natural gas to liquids (GTL) plant utilizes microchannel technology for both steam-methane reforming and Fischer-Tropsch synthesis. A natural gas feed of 21.8 million standard cubic feet per hour is sent to a microchannel steam reformer, where it reacts with steam to produce a mixture comprised mainly of carbon monoxide and hydrogen, or syngas. The syngas proceeds to another microchannel reactor, in which the Fischer-Tropsch reaction converts it to hydrocarbons. Approximately 117,600 bbl/day of C_5+ liquid hydrocarbons (25.86% gasoline, 24.78% diesel, 21.40% naphtha, 21.72% C_{20+}, 6.25% other) are recovered and fed to the Trans-Alaskan Pipeline System for delivery to the North American market. The product contains little wax and few impurities and has an above average quality.

Using a 13% discount rate, the project yields a positive 25-year Net Present Value of $708 million in 2009 and a 14.96% Internal Rate of Return, suggesting that the project has the potential to be an attractive investment. The most promising alternative to the GTL project is the construction of a natural gas pipeline, which would commence operation no sooner than 2019.

The project's economic feasibility depends most strongly on the product's selling price, which is tied to the price of oil. The project is also capital-intensive and therefore sensitive to the final capital investment. Sensitivity analysis has been done on both of these factors.

Alaskan Natural Gas to Liquids (GTL) Using Microchannel Reactors

Jeffrey Hammond

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Sophie Weiss

Advisor: *Dr. Stuart Churchill*

Project Originator: *John Wismer*

April 14, 2009

Professor Stuart Churchill
Professor Leonard Fabiano
Mr. John Wismer
Department of Chemical Engineering
University of Pennsylvania
Philadelphia, PA 19104

April 14th, 2009

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

The following report consists of our Senior Design Project, "Alaskan Natural Gas to Liquid (GTL) using Microchannel Reactors," proposed by Mr. John Wismer. The plant design utilizes microchannel reactors for both steam reforming and Fischer-Tropsch synthesis to convert Alaskan natural gas to liquid fuels. The GTL products can be shipped to North American markets via the Trans-Alaskan Pipeline System.

The report primarily focuses on a preliminary plant design and profitability analysis. The plant has an estimated life of 25 years and utilizes 2.0 trillion standard cubic feet of Alaskan natural gas. Alaska's total proven natural gas reserves stand at around 12 trillion standard cubic feet. The output of the plant is proposed to be 117,600 barrels per day. The plant would require a total capital investment of $7.17B. The profitability of this process depends primarily on the price of oil and the total capital expenditure. Using the Energy Information Administration's Annual Energy Outlook for 2009 base case oil price projections and a discount rate of 13%, the plant has an IRR of 14.96% and an NPV of $708MM.

Based on this analysis, it is recommended that further design work be undertaken to obtain a more precise initial investment figure. The next step for this project would be to work with a microchannel reactor vendor in order to better assess the technical and economic feasibility of this technology.

Sincerely,

Jeffrey Hammond	Jared Lee
Mohd. Shayaan Nadeem	Sophie Weiss

Table of Contents

Section 1 - Abstract

Abstract

The proposed Alaskan natural gas to liquids (GTL) plant utilizes microchannel technology for both steam-methane reforming and Fischer-Tropsch synthesis. A natural gas feed of 21.8 million standard cubic feet per hour is sent to a microchannel steam reformer, where it reacts with steam to produce a mixture comprised mainly of carbon monoxide and hydrogen, or syngas. The syngas proceeds to another microchannel reactor, in which the Fischer-Tropsch reaction converts it to hydrocarbons. Approximately 117,600 bbl/day of C_5+ liquid hydrocarbons (25.86% gasoline, 24.78% diesel, 21.40% naphtha, 21.72% C_{20+}, 6.25% other) are recovered and fed to the Trans-Alaskan Pipeline System for delivery to the North American market. The product contains little wax and few impurities and has an above average quality.

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Section 2 - Introduction

Introduction

Enormous natural gas reserves on Alaska's North Slope exist; however, they remain untapped due to their remote and extreme location. A high premium is placed on finding a way to tap into these reserves because of the increasing world market demand for energy. One potentially attractive method of monetizing the stranded gas reserves involves converting them to useful hydrocarbons such as gasoline, diesel fuel, and naphtha. This is also a more economically and environmentally sensible alternative to the current practices of flaring the natural gas or re-injecting it back into the oil wells. The conversion technology is termed Gas to Liquids (GTL).

In Alaska, oil and gas companies have abandoned the conversion technology because of poor economic feasibility and instead are exploring the idea of a trans-continental gas pipeline stretching from the North Slope to North American markets. If, however, the GTL technology can be shown to be more attractive than the pipeline, the products could be pumped into the existing Trans-Alaskan Pipeline Systems (TAPS) with crude oil. One of the most promising GTL technologies involves the use of microchannel reactors, which simultaneously function as miniature reactors and heat exchangers. Microchannels are small channels, which at less than 2.0 millimeters across, improve heat transfer. The goal of this project is to design a GTL plant utilizing microchannel technology and evaluate its economic potential.

Emerging studies have found that microchannel reactors enhance the heat transfer necessary for chemical reactions and provide superior reaction control due to their small size of their channels. These channels are most often between 0.10 mm and 0.30 mm in diameter, rather than the 10+mm tubes in traditional reactors. Moreover, the scale reduces mass transfer resistance, enabling the catalysts to accelerate the reaction much more efficiently. It also allows the reactor wall to be coated with catalyst, rather than functioning as a packed bed. Faster reaction rates result in smaller reactors achieving the same product yield, reducing the overall reactor scale without compromising capacity. Microchannel technology reduces the plant footprint, and eases plant construction and operation.

The GTL process consists of two major steps. First, natural gas (methane, CH_4) undergoes steam methane reforming (SMR). This is a highly endothermic reaction in which steam reacts with methane to yield synthesis gas (syngas), which is a mixture of CO and H_2:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H = +206 \text{ kJ/mol}$$

This reaction is coupled with an undesirable water-gas shift reaction, through which CO reacts with water to form CO_2 and H_2:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41 \text{ kJ/mol}$$

The rate of the water-gas shift reaction can be adjusted to control the amount and composition of syngas produced from the steam methane reforming (SMR).

Second, the syngas reacts by the Fischer-Tropsch (FT) process to produce aliphatic hydrocarbons:

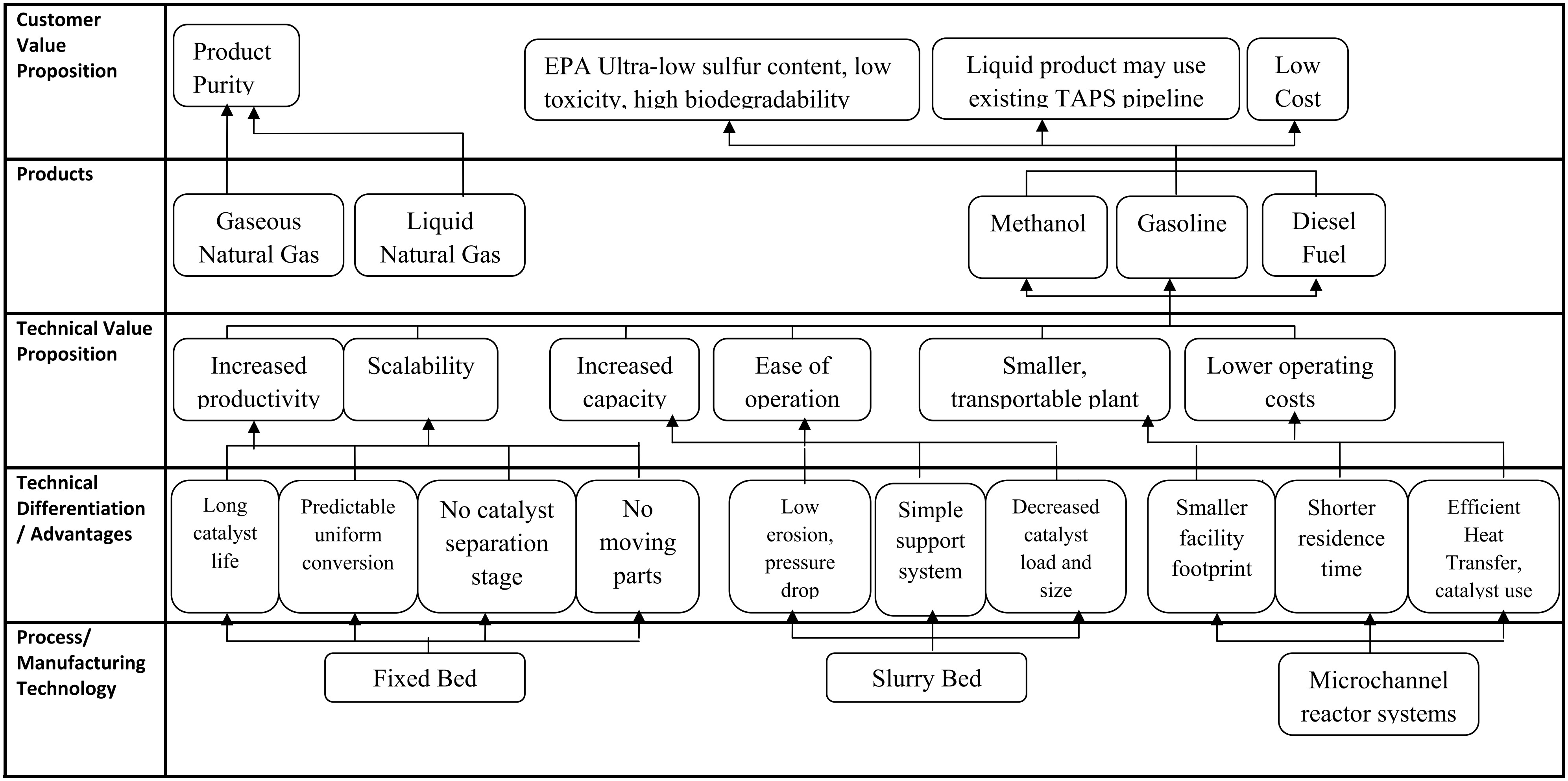
$$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + H_2O \qquad \Delta H < 0$$

The resulting mixture of hydrocarbons is composed of chains of varying length depending on reactor conditions. The most useful products include diesel fuel ($C_{12}H_{23}$, an average of molecules ranging from approximately $C_{10}H_{20}$ to $C_{15}H_{28}$), gasoline (C_8H_{18}, ranging from C_5H_{12} to $C_{10}H_{22}$), and naphtha (ranging from $C_{12}H_{26}$ to $C_{20}H_{42}$). These long-chain hydrocarbon products are in the liquid state and can therefore be blended with crude oil in the TAPS pipeline.

The microchannel reactor GTL plant will produce 117,599 barrels per day. This level of production will distinguish the project as one that seeks to take advantage of a large gas field far from market, similar to the GTL projects in Qatar. The plant will contain two sets of microchannel reactors, one for SMR, and one for the FT reaction, both a CO_2 and a CO separation system, and a power plant, as well as all equipment necessary for associated processing. The economic analysis accounts for the challenges of the location, namely extreme environmental conditions such as low temperatures, high wind-speeds, and remoteness. These challenges affect the cost of construction, supply, staffing, and product delivery.

The primary reasons for entering the Alaskan GTL market at this time are high natural gas and oil prices. Most economists believe that high prices for natural gas and oil will be sustained for the long term. However, even with more moderate price projections, the plant is still economical. Thus, microchannel technology could allow unprecedented access to the North Slope's natural gas reserves with competitive economics.

Section 3 - Innovation Map



Innovation Map: The benefits of microchannel technology for SMR and FT compared to conventional fixed and slurry bed reactors

Section 4 - Market and Competitive Analysis

Market and Competitive Analysis

The market for oil and natural gas products worldwide is enormous. The average demand in 2008 in the United States alone for crude products was just over 19.4MM barrels per day. The GTL project proposes to produce 117.6kbpd (thousand barrels per day). This low increase in supply is unlikely to affect overall price levels.

Alaska contains over 12 trillion cubic feet of proven reserves of natural gas (EIA). At the proposed production levels, the GTL plant and associated power plant, will consume 2.0 trillion cubic feet of this gas over 25 years of production. This is about 17% of the total gas available. Unfortunately, Alaska's natural gas is far from market and difficult to monetize. GTL promises a way to monetize this valuable resource. Thus, the two primary market drivers of GTL are high oil prices and the increased ability via new technology to bring this stranded gas to market.

There are many sources of competition to a potential GTL plant in the region. One source of competition is a proposed natural gas pipeline stretching from Alaska to central Alberta, where it would tie into the existing North American natural gas pipeline network. This alternative is explored in detail in Section 14.9. Another potential source of competition for GTL is liquefied natural gas (LNG). This involves chilling, liquefying, and shipping the natural gas via LNG container ships. There are also competing GTL technologies. Several oil and gas conglomerates have examined the possibility of GTL on the North Slope, but currently all have abandoned the idea, citing unfavorable economics. However, all of the previous examinations of GTL economics have relied on traditional GTL reactor technology, and none have specifically examined microchannel technology.

Significant players in the GTL market include British Petroleum (BP), ExxonMobil (Exxon), Shell Oil (Shell) and Sasol (Chevron). These companies have pursued large -scale opportunities using traditional GTL technology. However, many have recently pulled back after announcing new projects in the early 2000s. In February of 2007, Exxon in partnership with Qatar Petroleum cancelled a GTL plant which had an estimated capacity of 154kbpd at a capital cost of $7B. The plant would have begun production in 2011. Exxon cited desire to instead pursue a traditional Qatar gas project (Gill). Recently, Shell explored compact reformer technology at a demonstration plant in Nikiski, south of Anchorage. The $86MM plant produces 300 barrels per day. In 2004, Shell dismissed the idea of GTL for North Slope gas, stating that, "a long-distance pipeline would hold more promise for such large reserves" (GasandOil.com). Shell, however, has continued to develop a project nicknamed "Pearl," a 140kbpd GTL project in Qatar. In 2003, Shell projected a capital cost of between $4B and $6B, but in 2007, estimated that the project would cost between $12B and $18B (Gill). Qatar has seen much GTL interest due to its distance from market and enormous gas reserves. Shell also owns and operates a 14kbpd conventional plant in Malaysia that has been in operation since the early 1990s. Oryx also began production in 2007 at their Qatar GTL plant which has a 34kbpd capacity. Finally, Chevron has been operating GTL plants in South Africa since the 1970s. The largest Chevron plant has a 124kbpd capacity (Mazanec "Synthetic Fuels").

The primary technology company exploring microchannel reactor technology is Velocys, a Cincinnati-based Battelle spinoff. Velocys claims that their microchannel reactors result in a 90% size reduction, a 33% capital cost reduction and 100% increase in profit margin (Mazanec "The Future"). They claim the technology provides superior heat transfer capability as well as superior safety since reactions take place under more controlled conditions.

While Velocys has made bold claims, specific performance and cost information remains proprietary and it is difficult to evaluate the validity of their claims. Velocys has partnered with Oxford Catalysts Group to develop the best catalyst for their reactor technology. Nextant Inc. conducted an independent review of both Velocys' and Oxford Catalyst's claims regarding microchannel reactor technology. This report, entitled, "Oxford Catalysts Group PLC: Technical Expert's Report on the Velocys Technology," is the basis for much of the project analysis.

Other companies such as CompactGTL PLC and Rentech INC are exploring 'compact' reactor technology, which would compete with microchannel technology. CompactGTL has partnered with Brazilian oil conglomerate Petrobras and built a pilot plant that produces 20 barrels per day. Rentech constructed a pilot plant in Colorado to explore GTL and is currently attempting to commercialize coal to liquids and biomass to liquids in Mississippi.

Section 5 - Reactor Design

Reactor Design

5.1 Steam Methane Reformer Design

The steam-methane reforming (SMR) reaction is carried out in an Integrated Combustion Reactor (ICR) which utilizes this Microchannel Process Technology (MPT), as described by Tonkovich et al., U.S. Patent 7,250,151 B2.

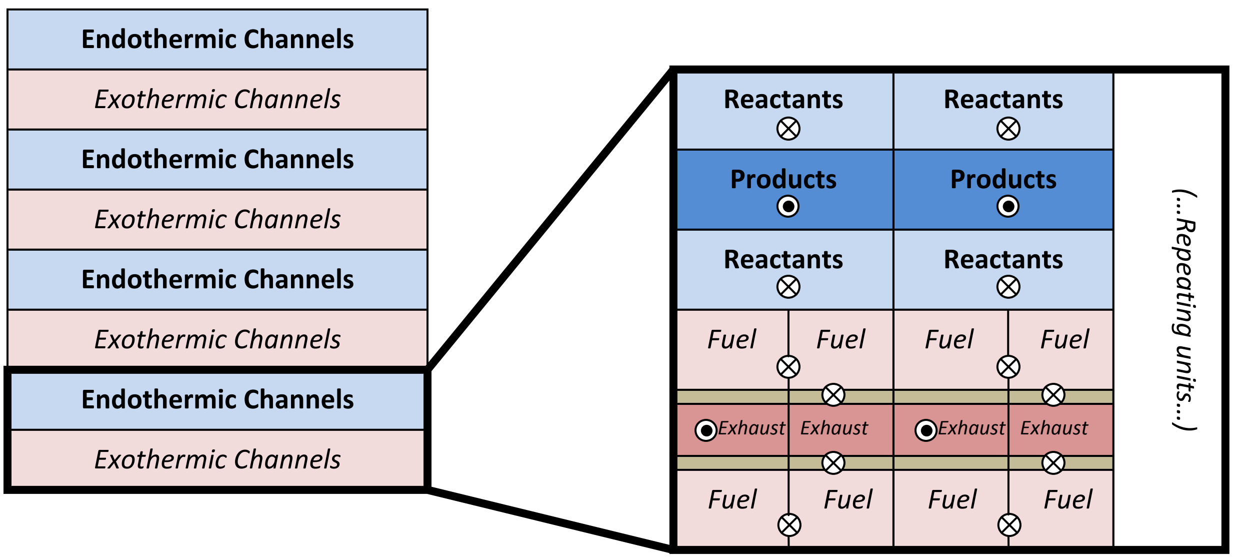


Figure 1 - Cross-section of a typical Integrated Combustion SMR microchannel reactor, based on U.S. Patent 7,250,151 B2. The enlarged portion represents one set of exothermic and endothermic channels.

Table 1 - Channel Dimensions

	Length	Width	Thickness
Endothermic	530 mm	9.70 mm	0.25 mm
Product	443 mm	4.1 mm	0.41 mm
Combustion	443 mm	4.1 mm	0.64 mm
Air	443 mm	4.1 mm	0.64 mm
Exhaust	443 mm	4.1 mm	0.36 mm

In an ICR, the SMR reaction occurs in endothermic reaction channels that are adjacent to exothermic reaction channels, where combustion fuel is burnt with air. The flow arrangement of the channels is shown in Figure 1 and Figure 2. Each microchannel has at least one internal dimension of 2 mm or less; the dimensions of each type of channel in this reactor are given in Table 1, and a schematic of a typical channel is shown in Figure 3. Microchannel reactors can be assembled in modules, which, in this particular application, are 1.5 m high, 1 m in width and 60 cm long. Each module consists of 4,469 sets of exothermic and endothermic channels (one set

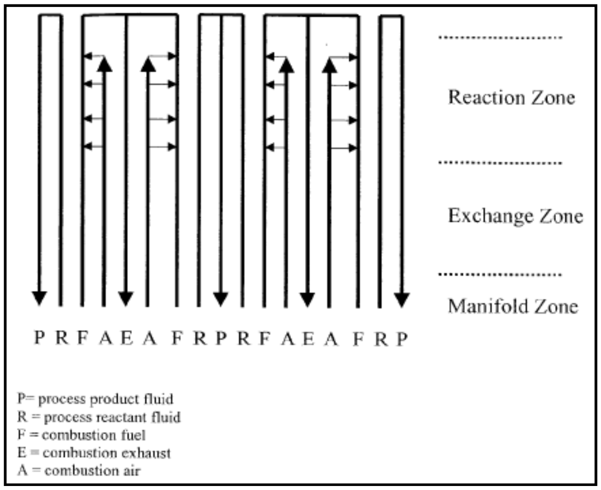


Figure 2- Flow orientation of streams within the reactor. The reactant feed is heated by the warm product feed, which is reciprocally cooled to 401°C (Source: U.S. Patent 7,250,151 B2).

equals two reactant channels, two product channels, four fuel channels, four air channels and two exhaust channels). 3,298 such modules are required to match the capacity of this plant, which processes 4,152 lb/hr of methane with approximately 90% conversion.

As described in the patent, the reactor is manufactured as a stack of welded *shims*, stainless steel plates with microchannels etched into them. Each shim generally contains at least one endothermic reactant channel or a multiple of two product/exothermic/air/exhaust channels with spacers of varying width in between. Detailed design information of these shims can be found in the patent and in the Appendix on page A19.

A gaseous mixture of methane, steam and carbon dioxide (recycled from the product stream) at 225 psi enters the reactant channels (Figure 1), where it is heated by the counter-currently flowing products (Figure 2). Even though the length of the endothermic reactant channel is 53 cm, the reactants only come into contact with catalyst in the last 18 cm of the channel, where they react using the energy evolved from fuel combustion. The reactants have a contact time with the catalyst (in the 18 cm reaction zone) of 6.0 ms. The reactor core can reach temperatures of up to 900°C; but more typically, the temperature will be close to 834°C (1,533°F). The warm products will enter the product channels through U-bends in the reactor, and proceed to lose thermal energy as they preheat the reactants in the adjacent reactant channels (Figure 2). The products exit the reactor at 401°C (754°F). A 2.99 mol H_2 to mol CO ratio in the product stream is obtained.

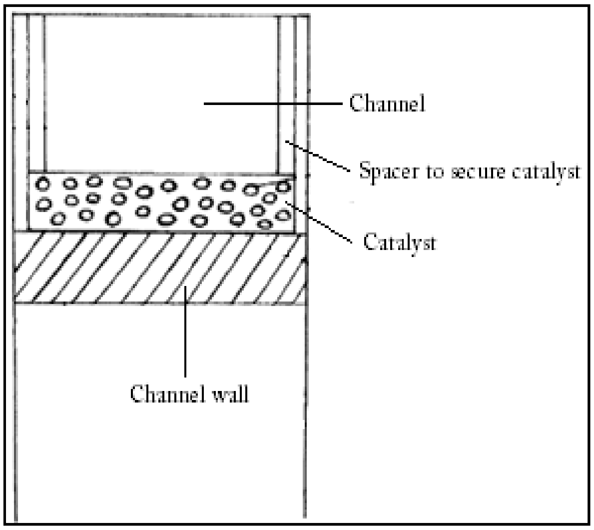


Figure 3 - Schematic of the internal structure of a typical microchannel (Source: U.S. Patent 7,250,151)

The 18 cm long reaction zone in the endothermic reaction channels is adjacent to a catalyst insert 9.4 mm wide and 0.25 mm thick. The catalyst is 10 wt% Rh/4.5 wt% MgO/85.5 wt% Al_2O_3 on spinel support with FeCrAlY felt coating (method of preparation is described in the patent).

On the combustion side, a mixture of methane, recycled hydrogen, excess air and heavier hydrocarbons (primarily gaseous hydrocarbons below C4 recycled from the Fischer-Tropsch Synthesis in reactor FTR-101 through stream RECYCLE) is fed (307 lb/hr fuel and 38 MMSCF/hr air) and combusted to provide energy for the reforming reaction.

SMR is highly endothermic, consuming approximately 1.34×10^{10} Btu/hr; combustion of the fuel provides this energy through a heat exchange surface of 1.07×10^{9} cm^2, resulting in a heat transfer rate of 12.48 Btu/hr-cm^2 or 3.66 W/cm^2. Detailed description of the design and costing of these modular reactors is presented in the Appendix on page A16; complete quantitative specifications are presented on page 66.

5.2 Fischer-Tropsch Reactor Design

The Fischer-Tropsch (FT) reaction, through which syngas ($CO + H_2$) is converted to hydrocarbons, is carried out in a microchannel reactor. In the microchannel reactor, heat is removed from the exothermic FT reaction through a co-current cooling water stream adjacent to the process/reaction channels (see Figure 4). The method for conducting this reaction using Microchannel Process Technology (MPT) is described in U.S. Patent 7,084,180 B2.

The FT reactor is a stack of 1mm thick parallel plates with spacers between them to form microchannels. Therefore, each channel has a rectangular cross-section. The reactor is organized in *pairs* of one reaction layer and one cooling layer stacked vertically per pair. Each pair consists of 70 reaction channels and 280 cooling channels along the reactor's width. A reactor module measures 1m high, 1m wide and 1.5m long and contains 225 plate pairs.

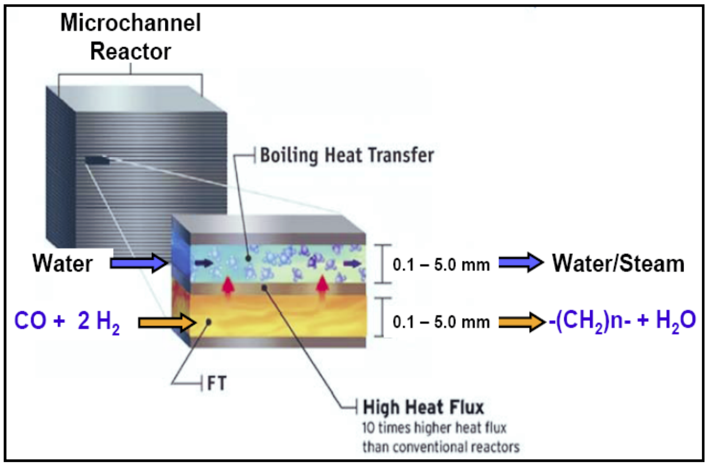


Figure 4 - Image from a Velocys presentation of its FT Microchannel technology. This image summarizes the functioning of the reactor.

Reaction channels are 0.95mm thick, 17mm wide and 1.4m long, arranged side-by-side at a 20mm pitch; cooling channels are 1.5mm thick and 3mm wide, with a 5mm pitch. The cooling and reaction layers are separated by 1mm thick plates. A diagram of such a reactor is shown in Figure 5. To meet the capacity of this particular plant, 3,987 such modules are required.

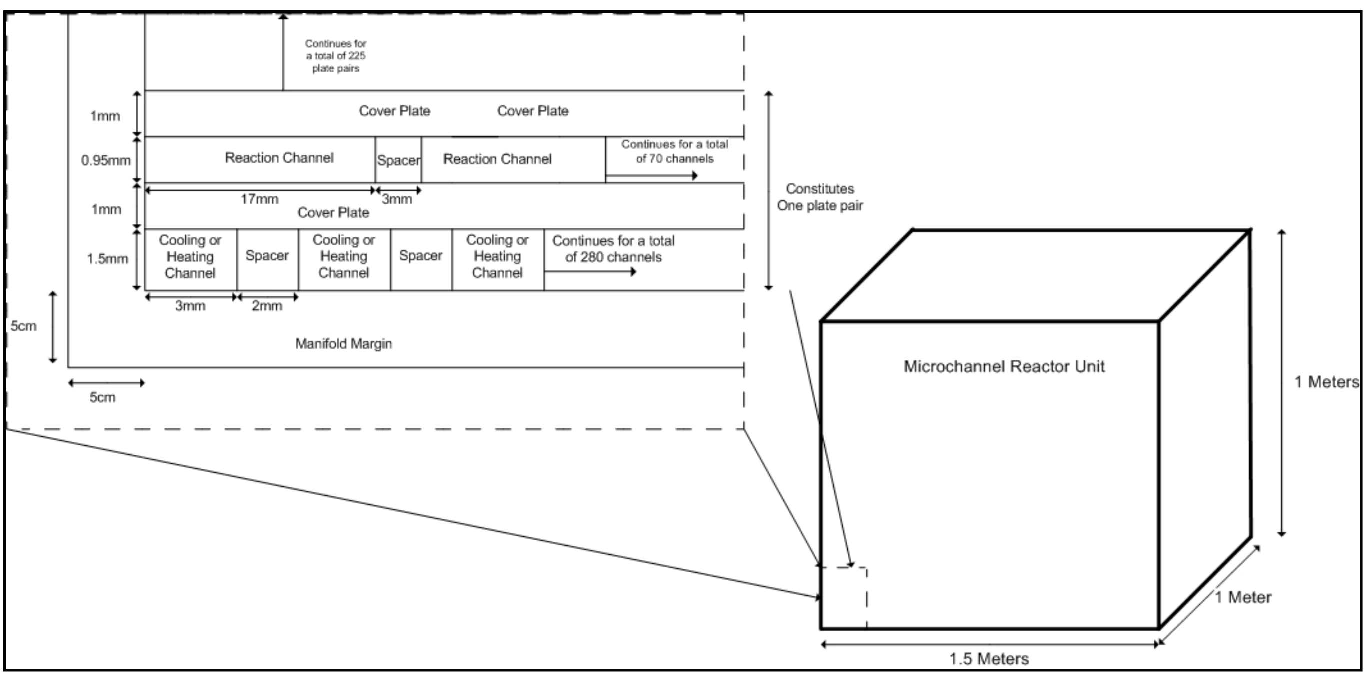


Figure 5 - The detailed internal dimensions of the Fischer-Tropsch reactor. The enlarged portion represents one plate pair; there are 225 plate pairs per 1m x 1m x 1.5m module.

The feed to the reactor is syngas produced by SMR-101, including a recycled CO feed from the FT product stream at 437°F and 517 psi. An H_2/CO ratio of 2.1 is maintained in the feed stream, since this is the recommended feed composition described by the patent. In this process, 4,149,000 lb/hr of CO and 647,300 lb/hr H_2 are reacted in the parallel modules. The reactants are allowed a contact time of 0.26 seconds in the reactor. As a result, 192,000 bbl/day of hydrocarbons are produced, of which 54,300 bbl/day are methane and 13,700 bbl/day are gaseous C_2-C_4 hydrocarbons. The reaction yields approximately 124,000 bbl/day of C_5+ products. The product stream, of course, contains large amounts of water, a byproduct of the reaction, as well as unreacted hydrogen, carbon monoxide and carbon dioxide. Before the effluent can be added to the TAPS pipeline, H_2, CO_2, CO and H_2O must be removed. A pressure drop of approximately 75psi occurs across the reactor.

1.16×10^7 lb/hr of partially vaporized water pass through the cooling channels, entering the reactor at 363°F and 150 psi from HX-201. As a result of heat transfer between the cooling and process channels, this water is completely vaporized, and exits at 401°F. This steam may then be used as feed for the Steam-Methane Reforming reactor. The highly exothermic FT reaction liberates 7.31×10^9 Btu/hr of heat is removed at a heat transfer rate of 0.38 Btu/hr-cm^2 or 0.11 W/cm^2.

The catalyst used to conduct the Fischer-Tropsch reaction is a fixed bed of particulate solid, containing Co/Re catalyst in a molar ratio of 21 with a metal dispersion of 5.4%. Each particle is 177-250 microns in diameter. One gram of catalyst per 800ml/hr of flow is packed into each reaction channel; at the flow rates in this particular embodiment (80,500 ml/hr), approximately 0.11g of catalyst (0.032g Co, 0.0048g Re) is loaded per channel.

The rate of reaction is enhanced in this reactor since cooling water rapidly removes heat from the reaction channels. As a result, approximately 70% conversion per pass of CO is achieved. The product distribution of the FT reaction is given by the Anderson-Schulz-Flory distribution, a key parameter of which is α, the chain growth probability. Conventional FT processes have an alpha equal to less than 0.89; however, owing to the rapid heat removal and low mass transfer limitations in the small microchannels, an alpha of at least 0.905 is obtained (it may be as high as 0.93). Increasing α results in lower selectivity of the FT reaction towards methane, a favorable result. Figure 6 shows a comparison of the product distribution obtained from a process with alpha equal to 89% versus alpha equal to 90.5%.

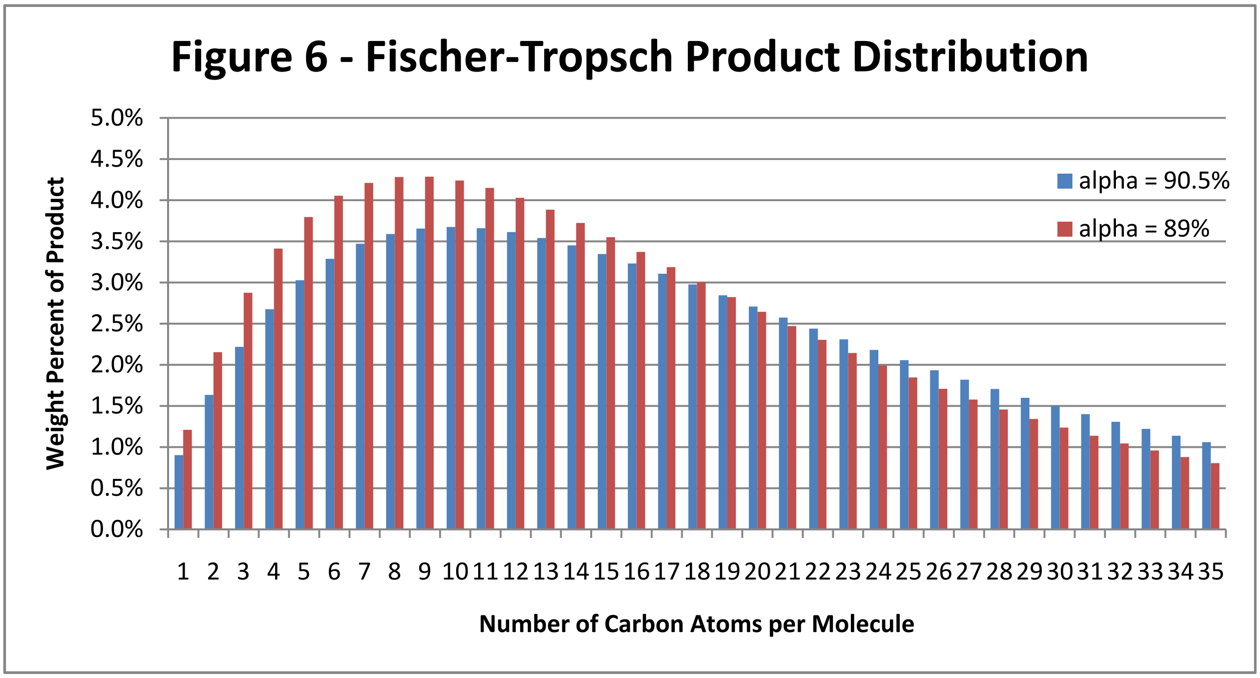


Figure 6 – Fischer-Tropsch Product Distribution as dictated by the Anderson-Shultz Flory Distribution. A comparison is given between alpha values of 0.89 (conventional FT) versus 90.5% (microchannel technology).

It is evident from the graph that, for higher values of alpha, less methane and more long-chain hydrocarbons are produced, improving product quality.

Section 6 - Process Flow Diagram

6.1 Process Block Overview

The process flow diagram is divided into three sections for simplicity. An overview of the process flow diagram is presented in Figure 7. Figure 8 contains the complete process flow diagram, while Figures 9, 10 and 11 contain the details for each section of the complete process flow diagram. Tables 2, 3 and 4 contain the stream results for each respective section of the process flow diagram.

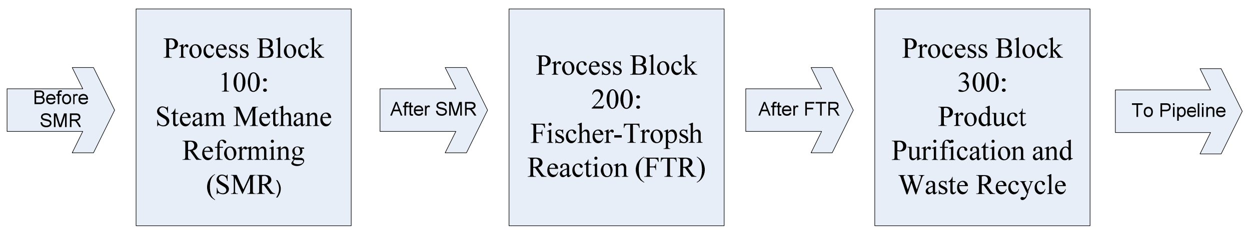


Figure 7 - Overview of the Process Flow Diagram

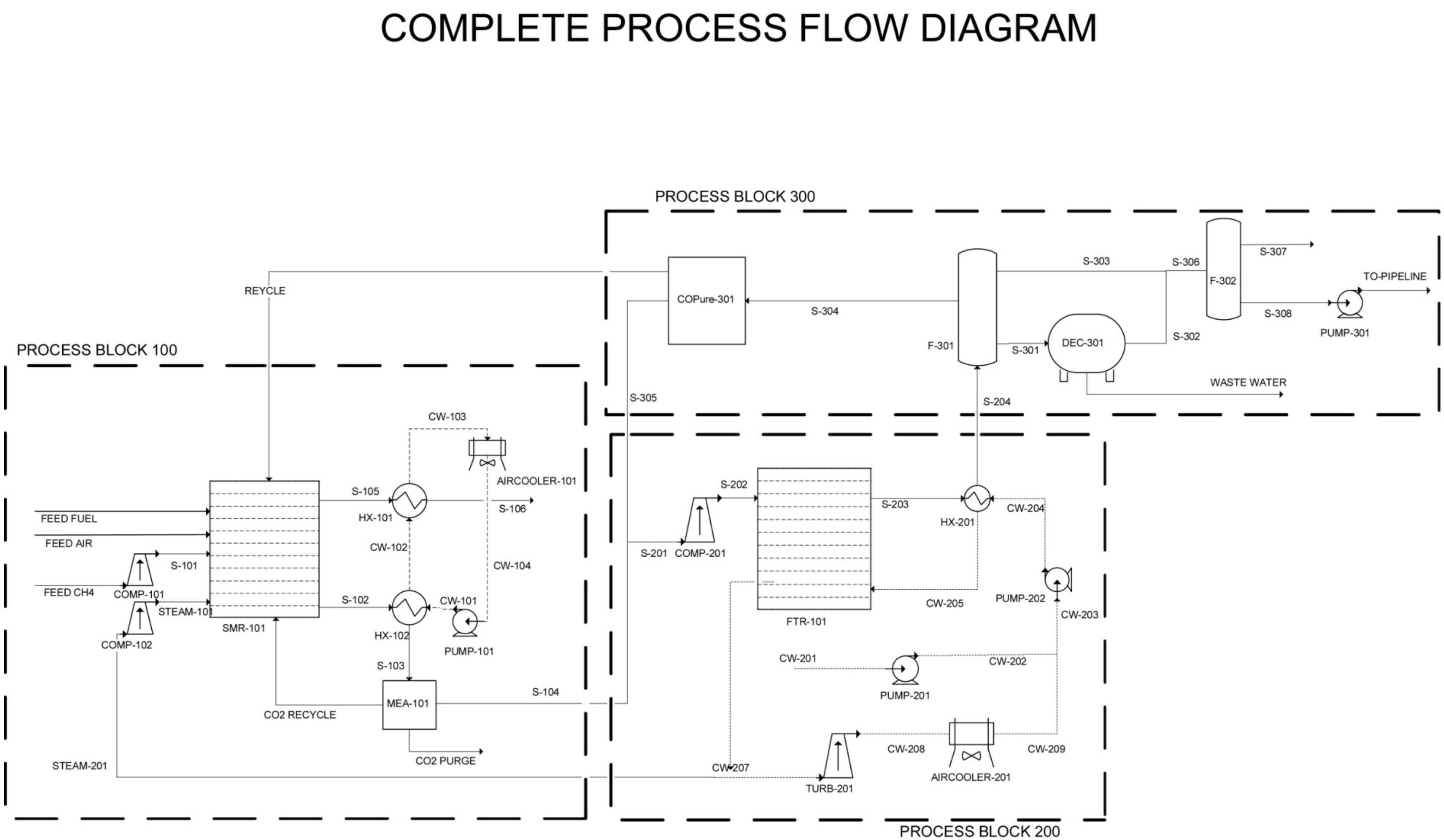


Figure 8 - Complete plant process flow diagram

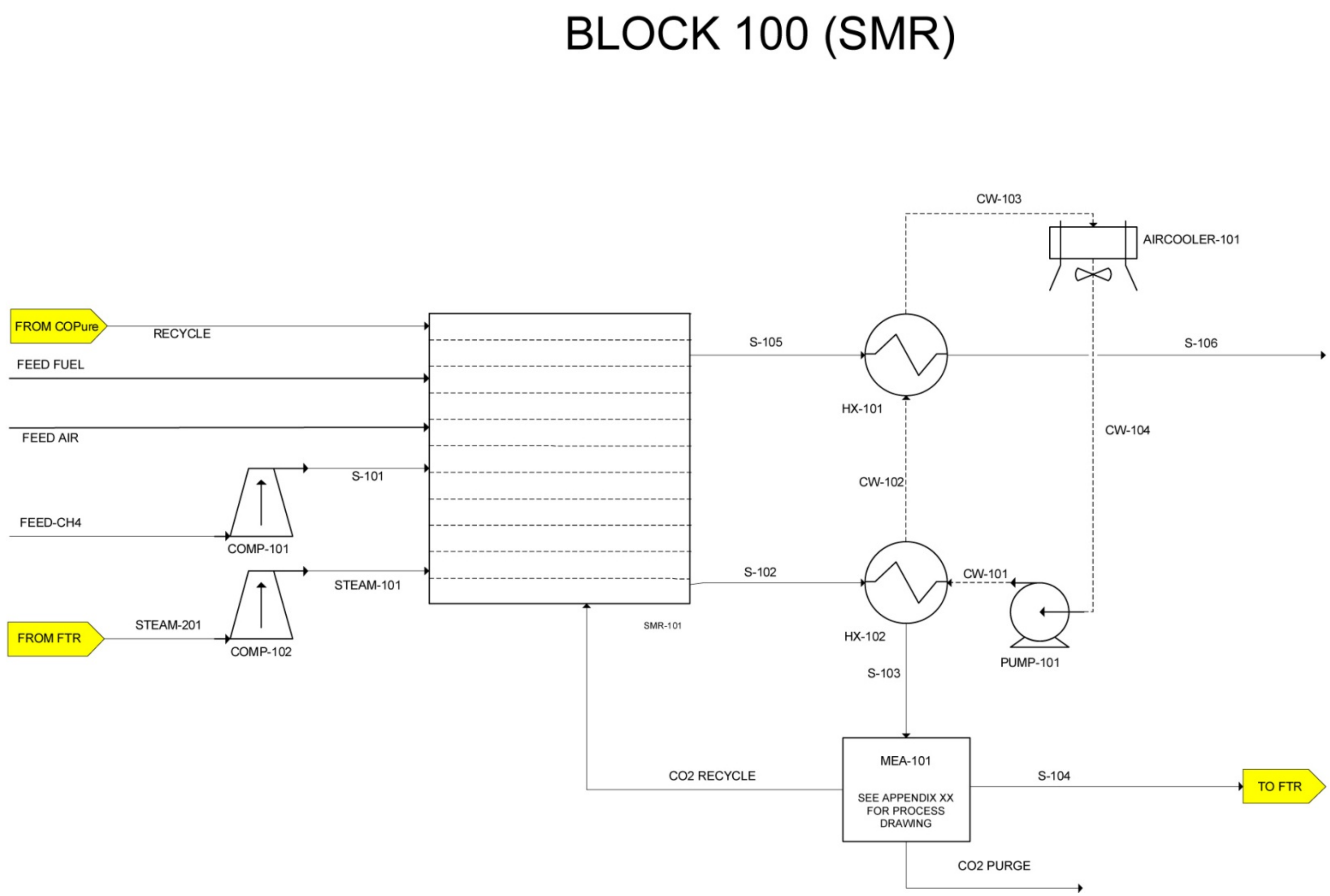


Figure 9 - Process Block 100

Stream	CO2 PURGE	CO2 RECYLCLE	CW-101	CW-102	CW-103	CW-104	FEED AIR	FEED CH4	FEED FUEL	RECYCLE	S-101	S102	S-103	S-104	S-105	S-106	S-301	STEAM-101	STEAM-201
Temperature F	437	437	39.2	252.811	463.5637	463.5637	77	100.00004	77	80.32262	255.25	753.8	437	437	627.8	320	80.6	638.6	401
Pressure psi	232.2526	232.2526	29.19972	29.19972	22.04067	29.19972	14.69595	44.08785	14.69595	232.2526	232.253	232.253	232.2526	232.2526	14.69595	14.696	232.253	232.2526	159.7337
Mole Flow kmol/hr																			
CH4	0	0	0	0	0	0	0	72783.8	2136.281	4442.655	72783.8	6342.78	6342.778	6342.778	0	0	2251.36	0	0
H2O	0	0	62500	62500	62500	62500	0	0	0	168.7517	0	96565.2	96565.16	96565.16	61286.91	61286.9	1.44E+05	1.92E+05	1.92E+05
CO	0	0	0	0	0	0	0	0	0	185.2656	0	48709.3	48709.27	48709.27	0	0	1577.72	0	0
CO2	20380.55	848.471	0	0	0	0	0	0	0	2939.389	0	26536.3	26536.28	5307.255	10160.11	10160.1	2341.41	0	0
H2	0	0	0	0	0	0	0	0	0	47057.39	0	1.46E+05	145643.0	1.46E+05	0	0	4.46E-03	0	0
C2H6-C4H10	0	0	0	0	0	0	0	0	0	261.1125	0	0	0	0	0	0	739.152	0	0
C5H12-C10H22	0	0	0	0	0	0	0	0	0	334.5808	0	0	0	0	334.5808	334.581	30.6541	0	0
C11H24-C20H42	0	0	0	0	0	0	0	0	0	0.517995	0	0	0	0	0.517995	0.51799	409.184	0	0
C21H44+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	578.557	0	0
N2	0	0	0	0	0	0	1.83E+05	0	23188.76	0	0	0	0	0	2.06E+05	#######	0	0	0
OXYGE-01	0	0	0	0	0	0	48546	0	6195.216	0	0	0	0	0	16961.41	16961.4	0	0	0
Mass Frac																			
CH4	0	0	0	0	0	0	0	1	0.0388521	0.212329	1	0.0218	0.021802	0.027259	0	0	0.0114	0	0
H2O	0	0	1	1	1	1	0	0	0	9.06E-03	0	0.37274	0.372737	0.466027	0.139989	0.13999	0.81612	1	1
CO	0	0	0	0	0	0	0	0	0	0	0	0.29233	0.292329	0.365494	0	0	0.01395	0	0
CO2	1	1	0	0	0	0	0	0	0	0.385385	0	0.25023	0.250225	0.06257	0.056694	0.05669	0.03253	0	0
H2	0	0	0	0	0	0	0	0	0	0.282605	0	0.06291	0.062906	0.078651	0	0	2.84E-09	0	0
C2H6-C4H10	0	0	0	0	0	0	0	0	0	0.028387	0	0	0	0	0	0	0.01067	0	0
C5H12-C10H22	0	0	0	0	0	0	0	0	0	8.20E-02	0	0	0	0	0.003489	0.00349	0.00118	0	0
C11H24-C20H42	0	0	0	0	0	0	0	0	0	2.50E-04	0	0	0	0	1.06E-05	1.1E-05	0.0318	0	0
C21H44+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08235	0	0
N2	0	0	0	0	0	0	0.767079	0	0.7364144	0	0	0	0	0	0.731002	0.731	0	0	0
OXYGE-01	0	0	0	0	0	0	0.232922	0	0.2247335	0	0	0	0	0	0.068815	0.06881	0	0	0
Total Flow kmol/h	20380.55	848.471	62500	62500	62500	62500	2.31E+05	72783.8	31520.26	55204.39	72783.8	3.24E+05	3.24E+05	3.03E+05	2.95E+05	#######	1.51E+05	1.92E+05	1.92E+05
Total Flow lb/hr	1.98E+06	82322.9	2.48E+06	2.48E+06	2.48E+06	2.48E+06	1.47E+07	2.57E+06	1.94E+06	7.40E+05	2.57E+06	1.03E+07	1.03E+07	8.23E+06	1.74E+07	#######	6.98E+06	7.63E+06	7.63E+06
Total Flow cuft/hr	1.85E+06	76837.99	39214.04	1.73E+07	4.64E+07	4.64E+07	2.00E+08	2.18E+07	2.72E+07	3.06E+06	5.27E+06	4.02E+07	2.96E+07	2.76E+07	5.16E+08	#######	1.26E+05	2.08E+07	2.34E+07
Vapor Frac	1	1	0	0.486962	1	1	1	1	1	0.999978	1	1	1	1	1	1	0	1	1
Liquid Frac	0	0	1	0.513039	0	0	0	0	0	2.23E-05	0	0	0	0	0	0	1	0	0
Density lb/cuft	1.071383041	1.071383041	63.30145	0.143156	0.053452	0	0.073629	0.1182752	0.07142689	0.241724	0.48847	0.25627	0.348148	0.297922	0.033712	0.04704	55.5565	0.36633071	0.32687162

Table 2 - Process Block 100 Stream Results

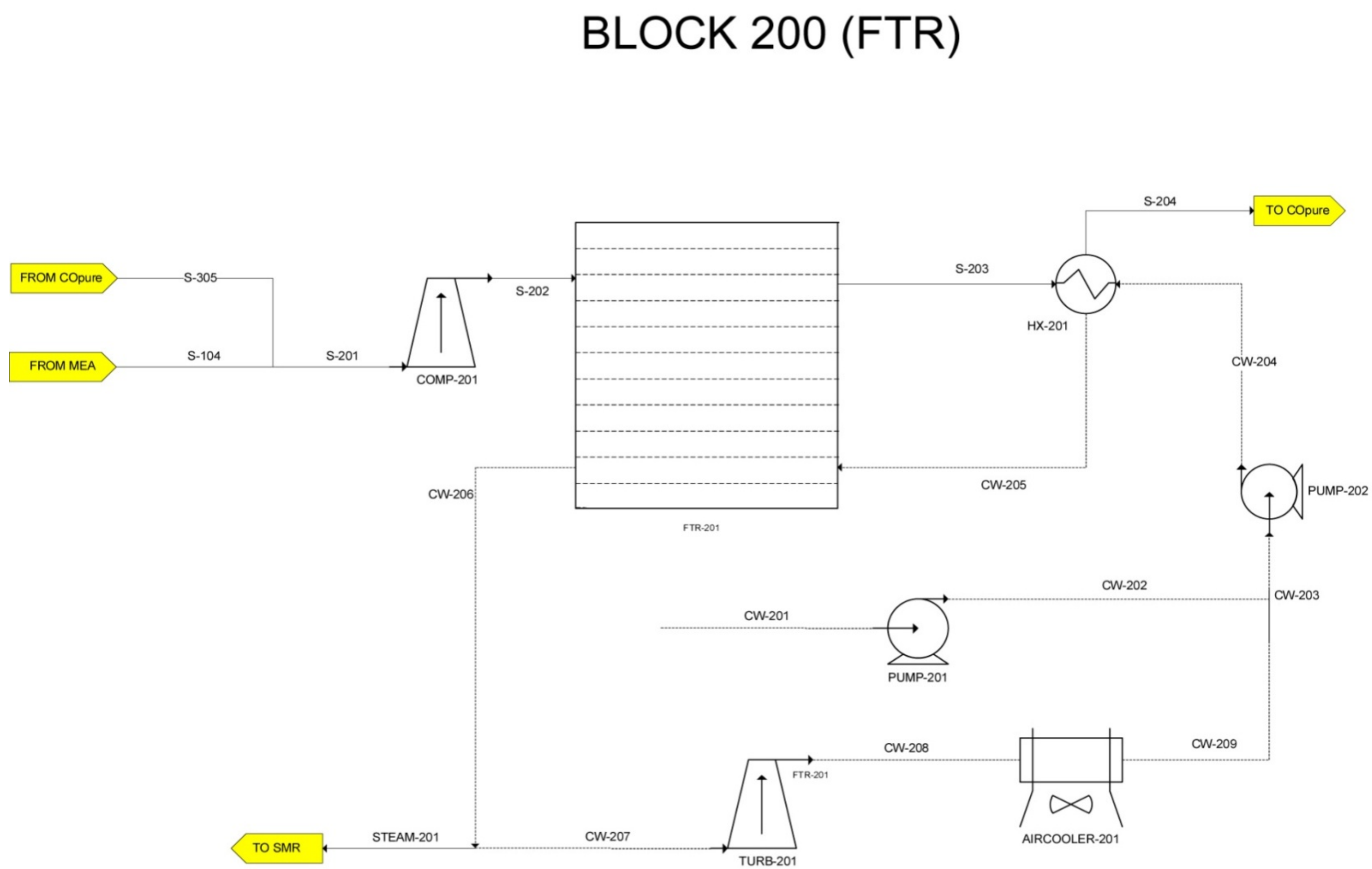


Figure 10- Process Block 200

Stream	CW-201	CW-202	CW-203	CW-204	CW-205	CW-206	CW-207	CW-208	CW-209	S-104	S-201	S-202	S-203	S-204	S-305	STEAM-201
Temperature F	39.2	39.22268	39.21494	39.2207	363.9969	401	401	369.563	39.2	437	417.8561	437	437	86	80.32262	401
Pressure psi	14.69595	130.7261	130.7261	159.7337	159.7337	159.7337	159.7337	130.7261	130.7261	232.2526	232.2526	514.3582	440.8785	440.8785	232.2526	159.7337
Mole Flow kmol/hr																
CH4	0	0	0	0	0	0	0	0	0	6342.778	6342.778	6342.778	6719.453	6719.453	0	0
H2O	1.92E+05	1.92E+05	2.93E+05	2.93E+05	2.93E+05	2.93E+05	1.01E+05	1.01E+05	1.01E+05	96565.16	96565.16	96565.16	1.44E+05	1.44E+05	0	1.92E+05
CO	0	0	0	0	0	0	0	0	0	48709.27	67235.82	67235.82	20122.09	20122.09	18526.56	0
CO2	0	0	0	0	0	0	0	0	0	5307.255	5307.255	5307.255	5307.255	5307.255	0	0
H2	0	0	0	0	0	0	0	0	0	1.46E+05	1.46E+05	1.46E+05	47057.36	47057.36	0	0
C2H6-C4H10	0	0	0	0	0	0	0	0	0	0	0	0	1008.703	1008.703	0	0
C5H12-C10H22	0	0	0	0	0	0	0	0	0	0	0	0	1342.434	1342.434	0	0
C11H24-C20H42	0	0	0	0	0	0	0	0	0	0	0	0	1044.75	1044.75	0	0
C21H44+	0	0	0	0	0	0	0	0	0	0	0	0	585.0937	585.0937	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OXYGE-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mass Frac																
CH4	0	0	0	0	0	0	0	0	0	0.027259	0.023932	0.023932	0.025353	0.025353	0	0
H2O	1	1	1	1	1	1	1	1	1	0.466027	0.409149	0.409149	0.60877	0.60877	0	1
CO	0	0	0	0	0	0	0	0	0	0.365494	0.442935	0.442935	0.13256	0.13256	1	0
CO2	0	0	0	0	0	0	0	0	0	0.06257	0.054934	0.054934	0.054934	0.054934	0	0
H2	0	0	0	0	0	0	0	0	0	0.078651	0.069051	0.069051	0.022311	0.022311	0	0
C2H6-C4H10	0	0	0	0	0	0	0	0	0	0	0	0	0.010278	0.010278	0	0
C5H12-C10H22	0	0	0	0	0	0	0	0	0	0	0	0	0.032606	0.032606	0	0
C11H24-C20H42	0	0	0	0	0	0	0	0	0	0	0	0	0.051144	0.051144	0	0
C21H44+	0	0	0	0	0	0	0	0	0	0	0	0	0.062044	0.062044	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OXYGE-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Flow kmol/hr	1.92E+05	1.92E+05	2.93E+05	2.93E+05	2.93E+05	2.93E+05	1.01E+05	1.01E+05	1.01E+05	3.03E+05	3.21E+05	3.21E+05	2.27E+05	2.27E+05	18526.56	1.92E+05
Total Flow lb/hr	7.63E+06	7.63E+06	1.16E+07	1.16E+07	1.16E+07	1.16E+07	4.01E+06	4.01E+06	4.01E+06	8.23E+06	9.37E+06	9.37E+06	9.37E+06	9.37E+06	1.14E+06	7.63E+06
Total Flow cuft/hr	1.21E+05	1.21E+05	1.84E+05	1.84E+05	1.11E+07	3.56E+07	1.23E+07	1.45E+07	63277.78	2.76E+07	2.87E+07	1.33E+07	1.04E+07	2.50E+06	1.02E+06	2.34E+07
Vapor Frac	0	0	0	0	0.324662	1	1	1	0	1	1	1	1	0.367144	1	1
Liquid Frac	1	1	1	1	0.675338	0	0	0	1	0	0	0	0	0.632856	0	0
Density lb/cuft	63.30145	63.3007	63.30095	63.30077	1.045113	0.326872	0.326872	0.276445	63.30145	0.297922	0.326679	0.707382	0.903188	3.74436	1.122416	0.32687162

Table 3- Process Block 200 Stream Results

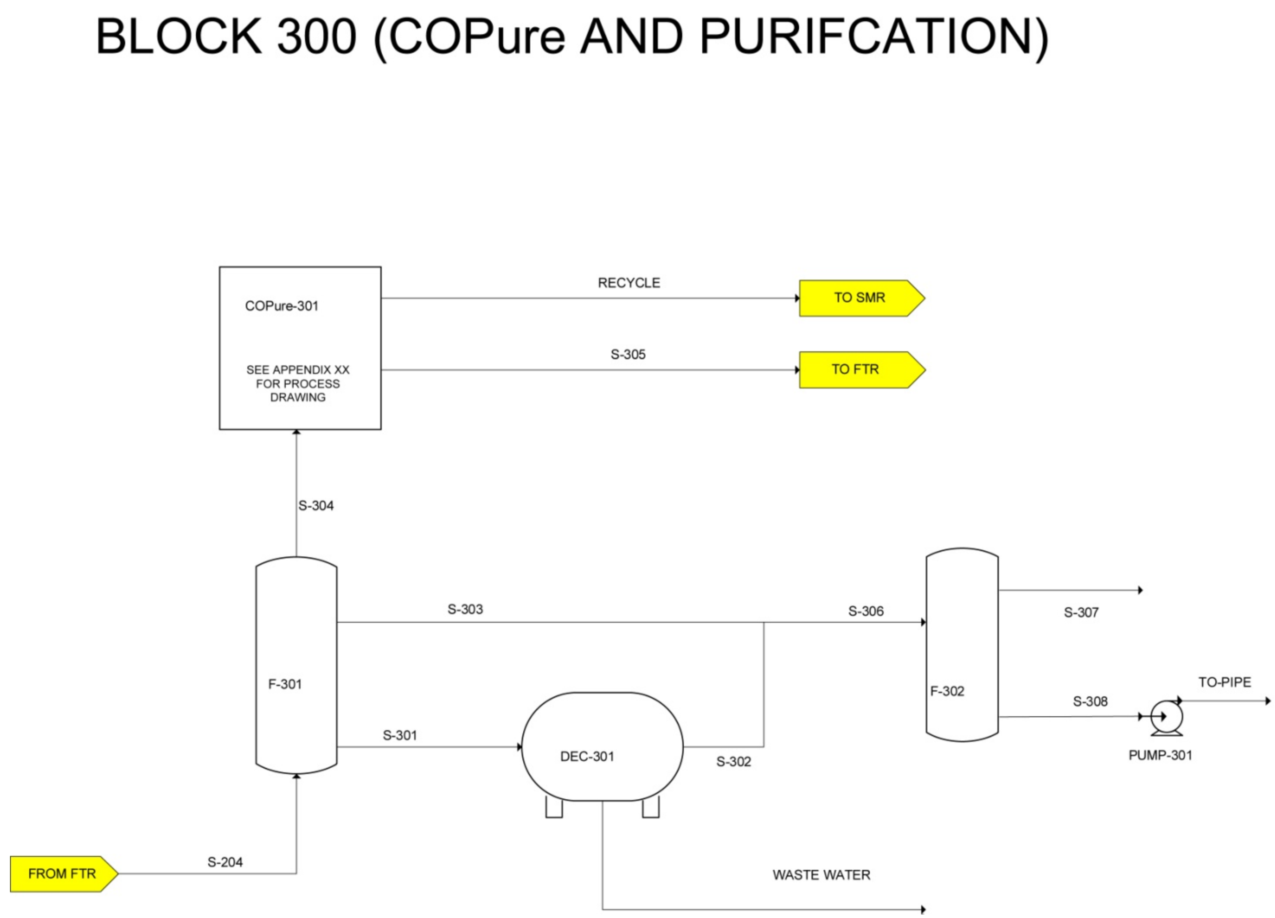


Figure 11 - Process Block 300

Stream	RECYCLE	S-204	S-301	S-302	S-303	S-304	S-305	S-306	S-307	S-308	TO-PIPE	WASTE WATER
Temperature F	80.3226	86	80.6	80.6	80.6	80.6	80.3226	80.65834	80.6	80.6	80.6464	80.6
Pressure psi	232.2526	440.8785	232.2526	290.2677	232.2526	232.2526	232.2526	290.2677	29.19972	29.19972	101.7186	290.2677
Mole Flow kmol/hr												
CH4	4442.655	6719.453	2251.362	2248.156	25.4371	4442.655	0	2273.593	2262.844	10.74948	10.74948	3.207227
H2O	168.7517	1.44E+05	1.44E+05	63.02164	3.738802	168.7517	0	66.76044	47.46744	19.293	19.293	1.43E+05
CO	185.2656	20122.09	1577.723	1577.303	17.82596	18526.56	18526.56	1595.129	1592.294	2.834803	2.834803	0.4198976
CO2	2939.389	5307.255	2341.413	2305.695	26.45454	2939.389	0	2332.15	2291.128	41.02154	41.02154	35.71873
H2	47057.39	47057.36	4.46E-03	4.45E-03	5.04E-05	47057.39	0	4.50E-03	4.50E-03	2.74E-06	2.74E-06	6.20E-06
C2H6-C4H10	261.1125	1008.703	739.1516	739.0737	8.438457	261.1125	0	747.5121	653.1298	94.38238	94.38238	0.078205103
C5H12-C10H22	334.58082	1342.434	30.6541	30.65411	977.199	334.5808	0	1007.853	111.0025	896.8504	896.8504	8.65508E-09
C11H24-C20H42	0.51799484	1044.75	409.1842	409.1844	635.0478	0.517995	0	1044.232	0.249919	1043.982	1043.982	0
C21H44+	0	585.0937	578.5567	578.5569	6.536844	6.49E-13	0	585.0938	1.86E-10	585.0938	585.0938	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
OXYGE-01	0	0	0	0	0	0	0	0	0	0	0	0
Mass Frac												
CH4	0.2123291	0.025353	0.011402	0.061972	1.78E-03	0.083398	0	0.04495	0.164194	2.92E-04	2.92E-04	1.99E-05
H2O	9.06E-03	0.60877	0.816124	1.95E-03	2.94E-04	3.56E-03	0	1.48E-03	3.87E-03	5.89E-04	5.89E-04	0.9993667
CO	0	0.13256	0.013951	0.075915	2.18E-03	0.607223	1	0.055062	0.201728	1.35E-04	1.35E-04	4.55E-06
CO2	0.3853845	0.054934	0.032529	0.174359	5.07E-03	0.15137	0	0.126485	0.456061	3.06E-03	3.06E-03	6.08E-04
H2	0.2826053	0.022311	2.84E-09	1.54E-08	4.43E-10	0.111001	0	1.12E-08	4.10E-08	9.35E-12	9.35E-12	4.84E-12
C2H6-C4H10	0.02838706	0.010278	0.010666	0.058051	0.001683	0.01115	0	0.04211	0.131752	0.008539	0.008539	9.31601E-07
C5H12-C10H22	0.08198718	0.032606	0.001184	0.006447	0.467857	0.032203	0	0.136933	0.042214	0.172405	0.172405	2.42232E-13
C11H24-C20H42	0.00024997	0.051144	0.031798	0.173081	0.508295	9.82E-05	0	0.267879	0.000183	0.368132	0.368132	0
C21H44+	0	0.062044	0.082347	0.448224	0.012843	3.42E-16	0	0.325099	3.79E-13	0.446849	0.446849	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
OXYGE-01	0	0	0	0	0	0	0	0	0	0	0	0
Total Flow kmol/hr	55204.39	2.27E+05	1.51E+05	7951.65	1700.678	73730.95	18526.56	9652.328	6958.12	2694.208	2694.208	1.43E+05
Total Flow lb/hr	7.40E+05	9.37E+06	6.98E+06	1.28E+06	5.06E+05	1.88E+06	1.14E+06	1.79E+06	4.87E+05	1.30E+06	1.30E+06	5.70E+06
Total Flow cuft/hr	3.06E+06	2.50E+06	1.26E+05	34788.8	11547.96	4.08E+06	1.02E+06	47048.73	3.03E+06	29307.25	29307.86	92042.61
Vapor Frac	0.9999777	0.367144	0	0	0	1	1	0	1	0	0	0
Liquid Frac	2.23E-05	0.632856	1	1	1	0	0	1	0	1	1	1
Density lb/cuft	0.24172369	3.74436	55.55655	36.88101	43.81004	0.46234	1.122416	38.02361	0.161013	44.40998	44.40905	61.93580977

Table 4 - Process Block 300 Stream Results

Section 7 - Product Evolution

Product Evolution:

7.1 Process Block 100

Properly proportioned feed is transformed into syngas by SMR:

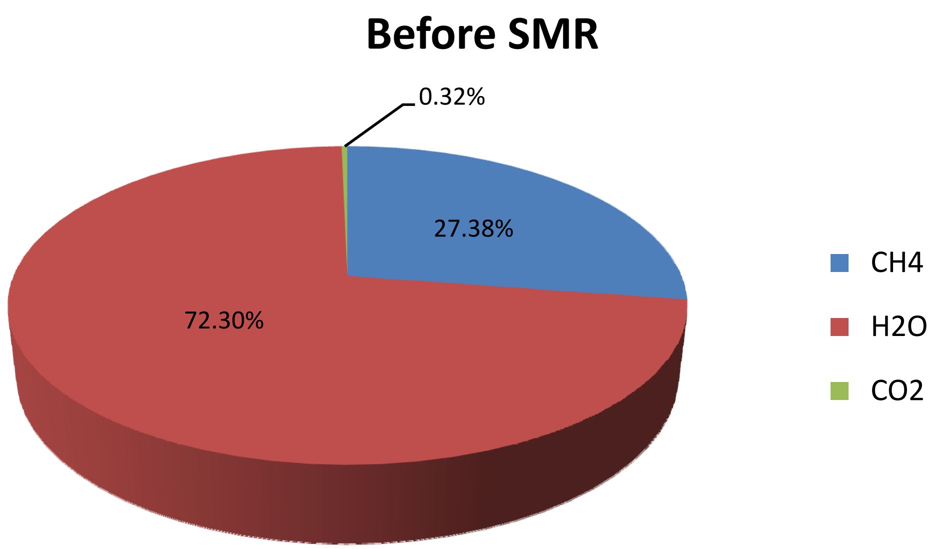


Figure 12 - Mole Fractions of Feed Stream to SMR

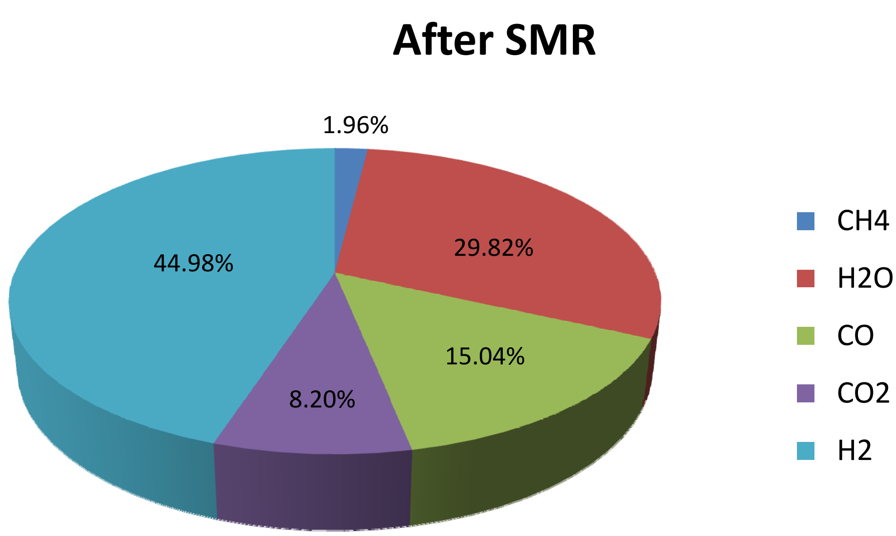


Figure 13 - Mole Fractions of Product Stream from SMR

Interim

CO_2 is removed and recycled to the SMR, H_2 is added for FT optimal 2.1:1 H_2:CO ratio:

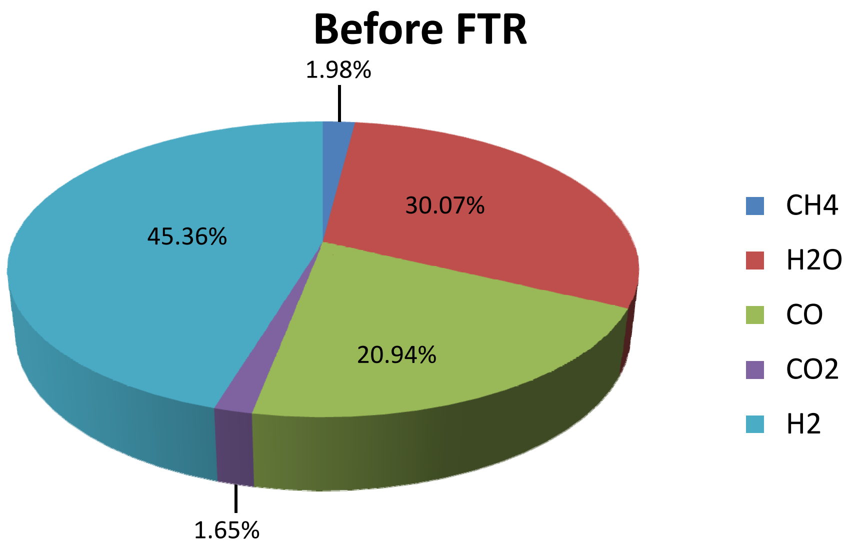
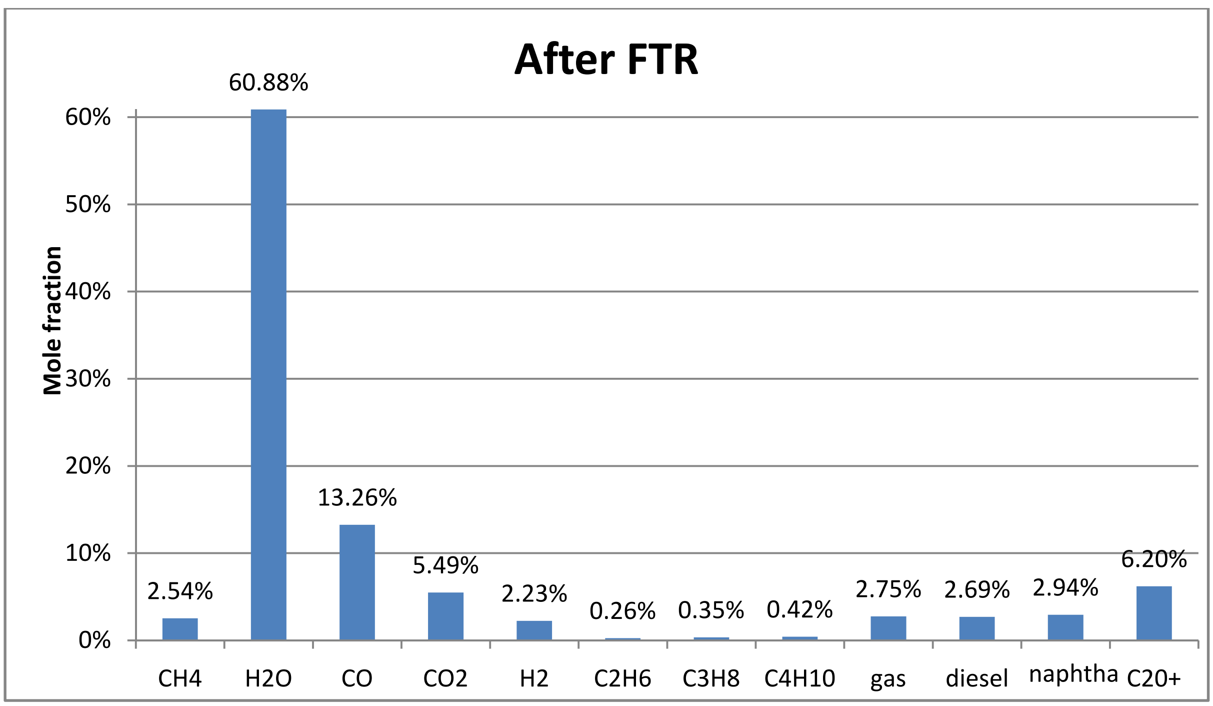


Figure 14 - Mole Fractions of Feed Stream to FTR

7.2 Process Block 200

Hydrocarbons are formed:



7.3 Process Block 300

Isolated product is sent to the pipeline:

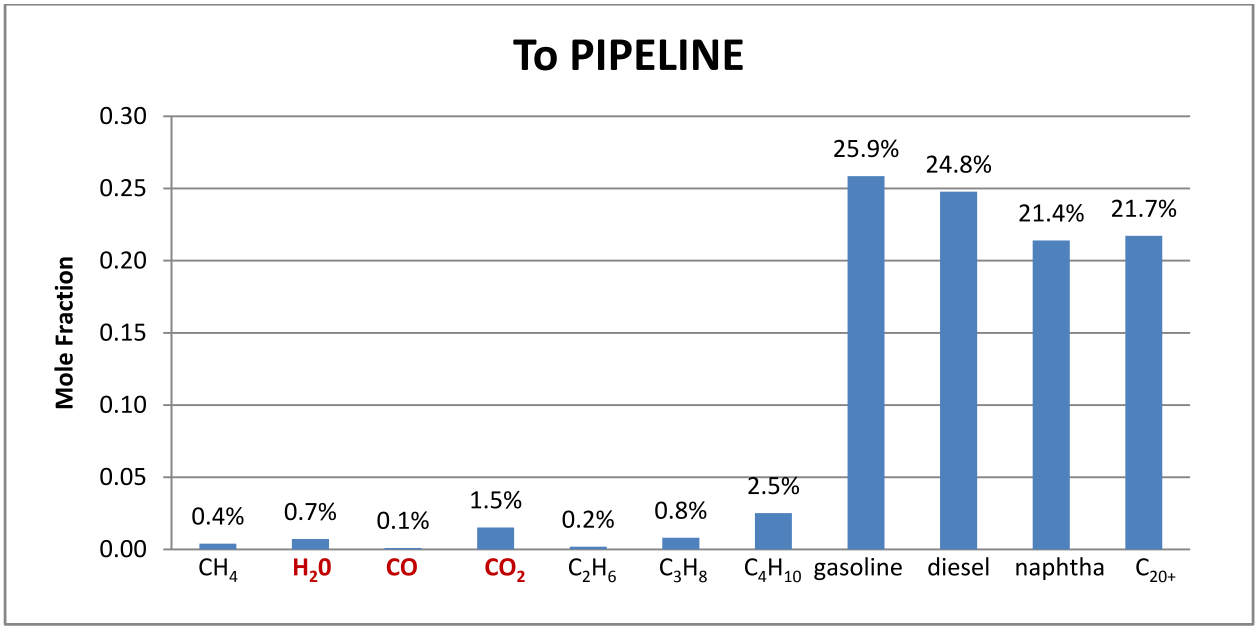


Figure 15 - Mass Fractions of the final product sent to the Trans-Alaskan Pipeline System (stream: "TO-PIPE"). The Hydrocarbons are classified as: gasoline (C_5H_{12} to $C_{10}H_{22}$), diesel fuel ($C_{10}H_{20}$ to $C_{15}H_{28}$), and naphtha ($C_{12}H_{26}$ - to $C_{20}H_{42}$). The components in red are undesirable, but are in low concentrations and therefore acceptable.

Section 8 - Process Description

Process Description

The production of liquid natural gas is accomplished in three major sections: the steam-methane reformer (Block 100), the Fischer-Tropsch reactor (Block 200), and product purification and waste recycle (Block 300). Many of the operating conditions in Blocks 100 and 200 are set by the optimal microchannel design developed by Velocys in U.S. Patents 7,250,151 B2 and 7,084,180, and the Nextant Technical Report. Stream compositions at crucial points in the process are shown in Section 7.

8.1 Block 100: Steam-Methane Reformer Section (Figure 9)

The main unit in this process is the steam-methane reforming reactor, SMR-101. SMR-101 is comprised of numerous microchannels that alternate between steam reforming channels and combustion heating channels.

This reaction is thermodynamically driven to produce the syngas products (H2 and CO) by combustion in an adjacent microchannel. Prior to entering the reactor, the SMR reactants, streams FEED-CH4 (comprised of gaseous methane) and STEAM-201 (comprised of water vapor), are compressed to the optimal pressure of 217.6psi. In SMR-101 these reactants undergo steam reforming and produce a mixture of syngas, unreacted methane, water and carbon dioxide. The combustion of natural gas, and recycled hydrogen and light hydrocarbons provides heat to the endothermic steam reforming reaction in the adjacent microchannels.

The adjacent SMR microchannels were simulated in ASPEN (see Appendix, page H2 for flowsheet) by simulating the two types of microchannels in adjacent reactors. The outlet temperatures of the reactors were simulated by “tricking” ASPEN. ASPEN initially yielded the resulting streams at the reactor temperature. This fails to account for the heat transfer the occurs within the microchannels, with the inlet temperatures being higher or lower than the entering temperatures depending on whether the stream is receiving or generating heat. On both the combustion and the reforming reactor, a heat stream run through a heater and recycled back to the reactor gave proper exit temperatures. The heat duties on the two heaters were set equal in magnitude, opposite in sign. This achieved an effective microchannel containing simultaneous SMR and combustion reactions.

A closed loop of cooling water is used to cool the reactor effluents due to the limited amount of useable water. Pump PUMP-101 is used to supply sufficient pressure for the cooling water to pass through heat exchangers HX-102 and HX-101. After the cooling water has passed through both heat exchangers, AIRCOOLER-101 reduces the temperature of the water back to 39.2°F. CW-104 then re-enters PUMP-101 and the cooling cycle is continued.

The effluent from the combustion channels, S-105, passes through HX-101 and is cooled to 320° F. After it is cooled, it is released into the atmosphere as flue gas. The effluent from the steam reforming channels, S-102, passes through HX-102 and is cooled to 437°F to meet the requirements for entry to the monoethanolamine separation block MEA-101. This block is clearly detailed in the unit descriptions and in the Appendix on page B2. MEA-101 effectively separates 80% of the carbon dioxide in S-103. Stream CO2 RECYCLE is a portion of the separated carbon dioxide that is to be mixed with the steam reforming reactants. This carbon dioxide feed provides the optimal feed concentrations for the steam reforming reaction specified by Velocys. The added carbon dioxide shifts the equilibrium-based water gas shift (WGS) reaction in the desired reverse direction, effectively preventing large amounts of carbon monoxide from being converted into carbon dioxide, and too much hydrogen from being formed. Stream CO2 PURGE is a product stream that contains excess carbon dioxide, which has potential to be transported and sold for enhanced oil recovery.

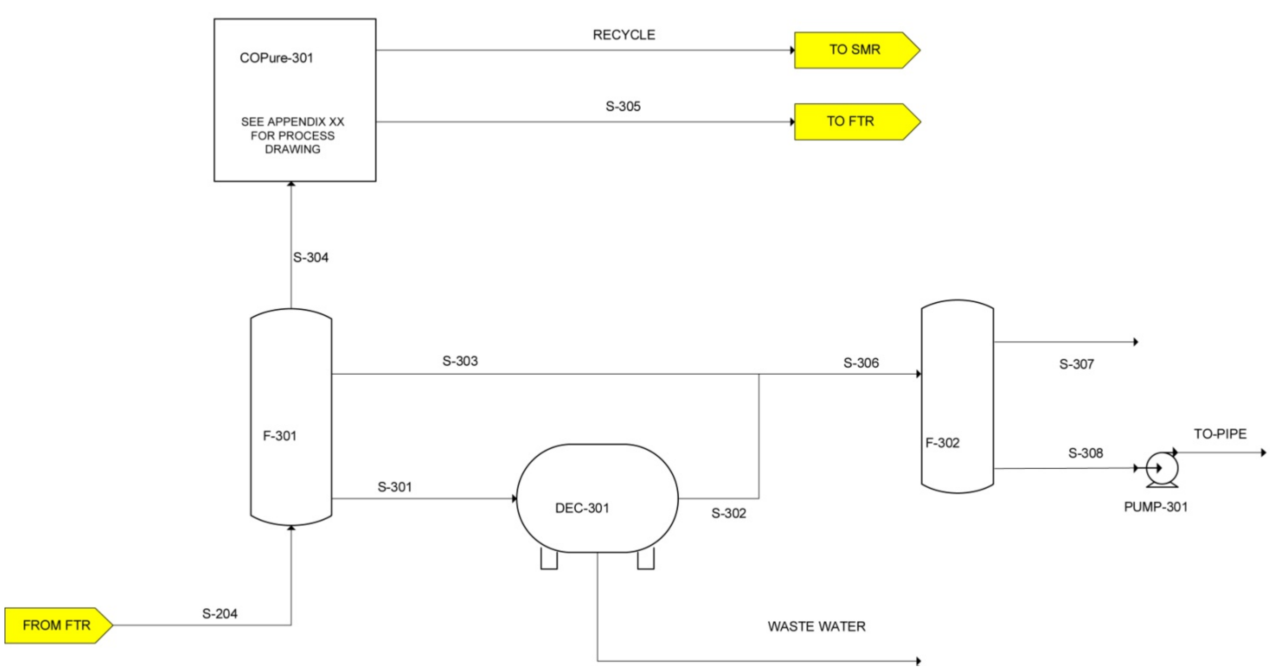
Stream S-104 is the product of process block 100 containing the syngas that will be fed to the process block 200 reactor.

8.2 Block 200: Fischer-Tropsch Reactor Section (Figure 10)

Stream S-305 is a recycle of pure carbon monoxide that is mixed with the syngas stream of S-104. This recycle stream is crucial in achieving the ideal 2.1 ratio of hydrogen to carbon monoxide that yields optimal Fischer-Tropsch products (Nextant). Compressor COMP-201 compresses stream S-201 to the reactor pressure of 440.9psi. Stream S-202 enters the microchannel reactor FTR-201 at 440.9psi and 437°F and proceeds to undergo the Fischer-Tropsch reaction, producing an array of hydrocarbons of varying length.

The Fischer-Tropsch reaction, unlike the steam reforming reaction, is exothermic and requires the removal of heat to maintain reactor conditions. Cooling water stream CW-205 passes through adjacent microchannels to remove the heat produced by the Fischer-Tropsch reaction. While cooling the reactor, CW-205 becomes fully vaporized and exits the reactor as steam in stream CW-206. 65.58% of stream CW-206 is sent back to process Block 100 to provide SMR-101 with its required steam feed. The remaining steam is passed through turbine TURB-201 to recover electricity. After the energy has been recovered from CW-207, it is air cooled to 39.7°F. Streams CW-209 and CW-202 are mixed and passed through pump PUMP-202 to achieve a pressure of 159.73psi. This pressurized water allows for a higher generation of electricity after it becomes vaporized. Stream CW-204 is then used to cool the effluent gas from FTR-101, stream S-203, to 86°F in preparation for process Block 300.

BLOCK 300 (COPure AND PURIFCATION)



8.3 Figure 11)

Stream S-204 enters process Block 300 as a gas comprised of long hydrocarbon products, unreacted methane, carbon monoxide, carbon dioxide, hydrogen and water. To separate these various components, S-204 is passed through the flash drum F-301. F-301 produces three streams: S-301 comprised of liquid water with small amounts of impurities, S-303 comprised of the desired longer liquid hydrocarbons product, and S-304, the effluent gas comprised mainly of hydrogen, carbon monoxide and methane. S-301 is sent to a decanter (DEC-301) where most of the remaining hydrocarbons that remain in the water are removed and returned to the product stream S-303. The bottoms from the decanter, stream WASTE WATER, will be sold at a low price for use in enhanced oil recovery. The gaseous stream S-304 is sent through the COPure-301 block, which is detailed in the Appendix on page B6. The COPure separation system allows for 99% separation of all carbon monoxide from S-304. This relatively pure stream of carbon monoxide is sent back to process block 200 where it is used in the FTR-201 reactor. The stream RECYCLE is sent to SMR-101 where it is burned as fuel to heat the reactor. S-303 is combined with the recovered hydrocarbons from DEC-301, and sent to F-302. This flash vessel removes dissolved CO_2 and CO from the hydrocarbon stream in S-307, which is subsequently flared. S-308 is re-pressurized as the final product stream, TOPIPE, and sent to the Trans-Alaska Pipeline System.

Section 9 - Equipment List and Descriptions

Equipment List and Unit Descriptions

9.1 CO_2 Separation

Overview

The SMR product contains 8.2% CO_2 to be removed before the FT process. The presence of other gases with similar molecular weight and polarity (CH_4, H_2, H_2O, and CO) makes this separation difficult. Aqueous monoethanolamine (MEA) exhibits selective reactivity towards CO_2, and hence provides the best separation option. It complexes with CO_2 to form the carbamate ion $MEACOO^-$ via equilibrium reactions:

$2H_20 \leftrightarrow H_30^+ + OH^-$

$C0_2 + 2H_20 \leftrightarrow H_30^+ + HCO_3^-$

$HCO_3^- + H_20 \leftrightarrow H_30^+ + CO_3^{2-}$

$C_2H_8NO^+ (MEAH^+) + H_20 \leftrightarrow H_30^+ + C_2H_7NO$ (MEA)

$C_3H_6NO_3^- (MEACOOH^-) + H_20 \leftrightarrow C_2H_7NO$ (MEA) $+ HCO_3^-$

MEA reacts with CO_2 in an absorption column, effectively separating it from the syngas. Then, MEA is regenerated in a stripping column as the carbamate ion breaks down to form MEA, released gaseous CO_2 and some vaporized H_20. The MEA is then re-circulated with the addition of water and ions to maintain the MEA concentration. The separated CO_2 is both recycled to the SMR and possibly sold. The product stream, with 80% CO_2 removed, is sent to the FT reactor microchannel.

CO_2 Separation - MEA-101

The SMR product passes through a flash vessel to remove some of the water and reduce the pressure for the absorption column. The amine absorber operates at 100^{o}F and atmospheric pressure to favor 80% CO_2-MEA complexation. It is built of stainless steel to resist MEA corrosion, and consists of 28 18ft towers. The use of more MEA and bigger equipment for more separation is not economically justified. The column consists of two packed beds modeled as equilibrium stages in which the syngas is contacted with a lean (3.7M) MEA solution. Because of the low operating pressure of the absorber and the high vapor pressure of MEA, there is a significant amount of MEA (over 500 ppmv) leaving the absorption section with the clean syngas. This is removed in a flash vessel, and the resulting MEA recycled back to the absorber. Some MEA in the column is taken out, cooled, and re-circulated to cool the column. The rich

MEA solution from the bottom of the absorber is then pumped through a mass/heat exchanger, where it undergoes rich/lean MEA exchange and is preheated by the hot lean amine before returning to the amine stripper for regeneration.

The absorbed CO_2 in STRFEED is separated from the aqueous MEA in 12 18ft stripping columns operating at 250^oF and 41psi to yield a lean amine solution consisting of 0.16 mol CO_2/mol MEA. Cooling is provided by seawater, the resulting CO_2 is flashed and compressed for recycle to the SMR or sold or used for enhanced oil recovery, and the lean amine is recycled. Both the inlet (S-103, also DRYGAS) and outlets (S-104, also VENT GAS and CO2 PURGE, also CO2 VENT) are at 437^oF and 232 psi. The costs of amine treating, preparation, reclamation, and storage away from air are included provided for. The total installed cost of the system is $960,315,790 (Thomas). See Page 53 for the unit specification sheet, and appendices A5, A12 for the design calculations.

9.2 CO Separation

Overview

The COPure separation utilizes similar reactions and unit operations as the MEA, except with a $CuAlCl_4$ complexing agent. For more details, see page 54 for the unit specification sheet, and the Appendix, page A5 for costing and further details.

CO Separation - COPure - 301

The gaseous product stream from F-301 is sent to a CO separation unit that is performed best using COPure technology. The major challenge to overcome is CO separation from CO_2 because of their molecular similarity. This is another chemical complexation process, differing only in that the solvent is $CuAlCl_4$ dissolved in an organic such as toluene. The inlet stream (S-305) at 80.3^oF and 160 psi goes through a dryer to remove water, which reacts adversely with $CuAlCl_4$, and a similar absorption/stripping process as MEA. The product stream RECYCLE exits the process at 80.6^oF and 225psi from the absorption column for combustion in the SMR, and the CO stream (S-305) leaves with 100% recovery from the top of the stripper, and after treatment, at 80.6^oF and 225psi for recycle to the FT. A lean/rich mass/heat exchanger in between the two columns plays the same role as in the MEA process. The total installed cost of

CO Pure technology is \$1,496,470,800 (R.C. Costello). See page 54 for the unit specification sheet, page A5 of the Appendix for the design calculations, and page B6 of the Appendix for vendor information and a sample flowsheet.

9.3 Steam-Methane Reformer - SMR-101

This unit performs the steam-methane reforming reaction in a custom-fabricated microchannel reactor. The reactor is modular in design; with 3,298 parallel modules measuring 1.5m high, 1m wide and 60cm in length. The reactor is operated at 1,652°F, with the reaction channels at 225psi pressure, and the combustion channels at atmospheric pressure. Since the reactor doubles as a heat exchanger, the product stream does not emerge at this high temperature, but instead loses heat to preheat the reactor feed. The reactor input is CH_4 and steam in a 2.64 molar ratio. The reactor effluent (S-102) emerges from SMR-101 at 753°F and 232psi. The catalyst used is 10 wt% Rh/4.5 wt% MgO/85.5 wt% Al_2O_3 on spinel support with FeCrAlY felt coating to achieve 90% conversion of methane. The reactor design is based on the information in U.S. Patent 7,250,151 B2; the cost of the reactor is estimated based on the amount of metal used in the construction of the reactor, and inflated by a factor of 5 to account for manufacturing costs. The bare module cost is estimated as \$128,892 per module, and \$425,084,912 for all 3,298 modules. Detailed design and costing calculations for this reactor are presented in the Appendix on page A16, and the unit specification sheet can be found on page 66.

9.4 Fischer-Tropsch Reactor - FTR-201

This unit is a custom-fabricated microchannel reactor that conducts the Fischer-Tropsch synthesis. The reactor is modular in design, with 3,987 parallel modules measuring 1m high, 1m wide and 1.5m in length. The feed to the reactor (S-203) contains syngas with an H_2/CO feed ratio of approximately 2.1:1, at a temperature of 437^{o}F and a pressure of 440.9psi. The reactor achieves 70% conversion of CO, yielding 192,000 bbl/day of hydrocarbons. The reactor is operated at 225°C, with the reaction channels at 525psi pressure, the cooling channels at 150psi, and a pressure drop of 75psi. The heat of reaction of the FT synthesis is transferred to the cooling channels, completely vaporizing the water, which is heated from 184°C to 205°C. The catalyst used to conduct Fischer-Tropsch is a fixed bed of particulate solid, with each particle

177-250 microns in diameter and containing Co/Re catalyst in a molar ratio of 2:1 with a metal dispersion of 5.4%. The reactor design is based on the information in U.S. Patent 7,084,180 B2 and reactor dimensions provided by Arkema, Inc.; the cost of the reactor is estimated by estimating the amount of metal used in the construction of the reactor, and inflated by a factor of 10 to account for manufacturing costs. The bare module cost is estimated as $186,408 per module, and $743,210,558 for all 3,987 modules. Detailed design and costing calculations for this reactor are presented in the Appendix on page A29, and the unit specification sheet can be found on page 58.

9.5 Flash Vessel - F-301

The V-L-L equilibrium vertical pressure vessel separates S-108 into product gas (S-109) for recycle to be burned in the SMR, desired liquid hydrocarbons for the pipeline (S-113), and liquid water for decanting (S-112). The flash vessel presumes equilibrium takes place at 80.6^{o}F and 225 psi. Due to the high total flow rate, F-301 is broken down into 22 carbon steel vessels, each with a flow of 1895 ft^3/min. The bare module cost per unit is $2,981,056 and the total indexed cost is $88,337,615 (Seider 2005). For additional information, see Aspen report for F-301 in the Appendix on page H29, costing calculations on page A12 of the Appendix, and specifications on page 56.

9.6 Flash Vessel – F-302

The V-L equilibrium vertical pressure vessel separates S-306 into a flared waste gas stream (S-307), and the final hydrocarbon mixture (S-308) to be pumped into the pipeline. The flash vessel presumes equilibrium takes place at 80.6^{o}F and 14.5 psi to remove dissolved CO2 in the product hydrocarbon mixture. F-302 is composed of 12 carbon steel vessels, with a 65.2 ft^3 capacity. The bare module cost per unit is $41,600 and the total indexed cost is $680,168 (Icarus Cost Charts). For additional information, see Aspen report for F-302 on page H31 of the Appendix, and specifications on page 57.

9.7 Decanter - DEC-301

The decanter is modeled as a single-stage flash vessel/settler and further separates the liquid water S-118 stream from F-301 into pure water with trace hydrocarbons (WASTEWATER), and hydrocarbons (S-114) for recombination into the final pipeline stream. The residence time is only 5 minutes, because the mixture separates readily, and the vertical pressure vessel operates at 80.6^oF and 225psi. Again due to the high total flow rate, DEC-301 is broken down into 30 carbon steel vessels, each with a flow of 69.84 ft^3/min. The bare module cost per unit is $135,200 and the total indexed cost is $5,526,365 (Icarus Cost Charts). For additional information, see Aspen report for DEC-301 on page H28 of the Appendix, costing calculations in the Appendix on page A12, and specifications on page 55.

9.8 Air Cooled Heat Exchanger - Aircool-101

Aircool-101 removes heat from the SMR cooling water recycle loop and is modeled as an air-cooled heat exchanger to take advantage of the average yearly North Slope temperature of 14^oF. Its heat duty is 8.345E7 Btu/hr and cools 2,482,306 lb/hr at atmospheric pressure from 463.6^oF (CW-11) to 39.2^oF (CW-12). Because of the large flow rate, it is modeled as 40 carbon steel heat exchangers with an area of 5,890ft^2. The individual unit bare module cost is $345,188 and the total installed cost is $18,598,099 (Seider 2005). For additional information, see costing calculations in the Appendix on page A14 and specifications on page 51.

9.9 Air Cooled Heat Exchanger - Aircool-201

Aircool-201 removes heat from the FT cooling water recycle loop and is modeled as an air-cooled heat exchanger due to the low Alaskan-air -temperatures. Its heat duty is 1.293E8 Btu/yr and cools 4.00E6 lb/hr at 120psi from 369.6^oF (CW-3) to 39.2^oF (CW-1). Because of the large flow rate, it is modeled as 40 carbon steel heat exchangers with an area of 91,769 ft^2. The individual unit bare module cost is $415,052 and the total installed cost is $22,254,487 (Seider 2005). For additional information, see costing calculations in the Appendix on page A15, and specifications on page 52.

9.10 Centrifugal Compressor- COMP-101

Compressor COMP-101 is a set of two two-stage compressors running in parallel used to pressurize the natural gas feed stream to the required pressure for steam reforming in SMR-101. Stream FEED-CH4 containing 3.63E5 scf/min, is compressed from 44.09 psi to 232.25 psi. Additionally, the temperature of FEED-CH4 increases from 100°F to 255.25°F while the compression achieved. It is constructed of carbon steel and consumes 4.5E8 Btu/hr. The bare module cost for both compressors, including electric motors, is $28,612,837 (H.P. Loh). For additional information, see costing calculations in the Appendix on page A6 and the specification sheet on page 48.

9.11 Centrifugal Compressor- COMP-102

Compressor COMP-101 is a set of two single-stage compressors running in parallel used to pressurize the recycled steam stream STEAM-201 to the required pressure for steam reforming in SMR-101. Stream STEAM-201containing 3.89E5 scf/min, is compressed from 159.73 psi to 232.25 psi. Additionally, the temperature of STEAM-201 increases from 401°F to 638.6°F while the compression achieved. It is constructed of carbon steel and consumes 3.75 Btu/hr. The total indexed cost for both compressors, including electric motors, is $26,650,814 (H.P. Loh). For additional information, see costing calculations in the Appendix on page A7 and specifications on page 49.

9.12 Centrifugal Compressor- COMP-201

Compressor COMP-101 is a set of three three-stage compressors running in parallel used to pressurize the syngas product stream from the process block 100 to the required pressure for the Fischer-Tropsch reactor FTR-201. Stream S-201 containing 4.78E5 scf/min, is compressed from 232.25 psi to 514.36 psi. Additionally, the temperature of FEED-CH4 increases from 232.25°F to 514.36°F while the compression achieved. It is constructed of carbon steel and consumes 1.822E9 Btu/hr. The total indexed cost for all three compressors, including electric motors, is $49,050,578 (H.P. Loh). For additional information, see costing calculations in the Appendix on A7 and specifications on page 50.

9.13 Centrifugal Pump- PUMP-101

PUMP-101 is a set of two centrifugal pumps running in parallel used to pressurize the cooling water stream CW-104 from 22.04 psi to 29.39 psi at 35°F. The volume of water pumped is 673.3 scf/min. This pressure will allow for the water to travel through the two heat exchangers that need cooling. An extra pump has been included to prevent problems that would occur, including plant shutdown, if one pump failed. PUMP-101 requires 63,875.76 Btu/hr and has a head of 17.22 ft. The pump is constructed out of stainless steel and has an rpm of 3600. The 3600 rpm electric motor that accompanies the pump features a totally enclosed, fan-cooled enclosure to prevent against moisture damage. The total indexed cost for both pump/motor units was $56,387 (Seider 2005). For additional information, see costing calculations in the Appendix on page A8. The specification sheet can be found on page 62.

9.14 Centrifugal Pump- PUMP-201

PUMP-201 is a set of five centrifugal pumps running in parallel used to pressurize the cooling water stream CW-201 from 14.7 psi to 130.73 psi at 39.2°F. The volume of water pumped is 2009.7 scf/min. This pressure will allow for the safe mixing of this water with CW-209. An extra pump has been included to prevent problems that would occur, including plant shutdown, if one pump failed. PUMP-201 requires 3.013E 6 Btu/hr and has a head of 236.95 ft. The pump is constructed out of stainless steel and has an rpm of 3600. The 3600 rpm electric motor that accompanies the pump features a totally enclosed, fan-cooled enclosure to prevent against moisture damage. The total indexed cost for all of the pump & motor units is $580,768 (Seider 2005). For additional information, see costing calculations in the Appendix on page A9. The specification sheet can be found on page 63.

9.15 Centrifugal Pump- PUMP-202

PUMP-202 is a set of three centrifugal pumps running in parallel used to pressurize the cooling water stream CW-203 from 130.73 psi to 159.73 psi at 39.2°F. The volume of water pumped is 3064.38.7 scf/min. The additional pressure in this water stream will allow for a higher recovery of electricity in TURB-201. An extra pump has been included to prevent problems that would occur, including plant shutdown, if one pump failed. PUMP-202 requires

1.1485E6 Btu/hr and has a head of 65.99 ft. The pump is constructed out of stainless steel and has an rpm of 3600. The 3600 rpm electric motor that accompanies the pump features a totally enclosed, fan-cooled enclosure to prevent against moisture damage. The total indexed cost for all of the pump & motor units is $229,369 (Seider 2005). For additional information, see costing calculations in the Appendix on page A10. The specification sheet can be found on page 64.

9.16 Centrifugal Pump- PUMP-301

PUMP-301 is a set of two centrifugal pumps running in parallel used to pressurize the final product stream for transportation to the Trans-Alaskan Pipeline. It pumps stream S-308 from 29.2 psi to 101.72 psi at 80.6°F. The volume of liquid pumped is 488.45 scf/min. An extra pump has been included to prevent problems that would occur, including plant shutdown, if one pump failed. PUMP-301 requires 4.64E5 Btu/hr and has a head of 235.14 ft. The pump is constructed out of stainless steel and has an rpm of 3600. The 3600 rpm electric motor that accompanies the pump features a totally enclosed, fan-cooled enclosure to prevent against moisture damage. The total indexed cost for all of the pump & motor units is $128,166 (Seider 2005). For additional information, see costing calculations in the Appendix on page A10. The specification sheet can be found on page 65.

9.17 Steam Turbine- Turb-201

Turb-201 is a turbine used to recover the energy from steam stream CW-207. CW-207 enters at 149.73 psi and 401°F and CW-208 exits at 130.73 psi and 369.56°F. The volume of steam entering is 204,237.99 scf/min and expands to 241,493.5 scf/min at exit. The turbine is constructed out of carbon steel and has a 3600 rpm motor. It has a power production capacity of 14.96 MW or 5.106E7 Btu/hr. After the TURB-201 has recovered the energy from the team, it exits as stream CW-208. The total indexed cost of the turbine is $2,180,026 (H.P. Loh). For additional information, see costing calculations in the Appendix on page A6 and the specification sheet on page 67.

9.18 Heat Exchanger - HX-102

HX-102 is a countercurrent floating head shell and tube heat exchanger that cools the primary products from the Steam-Methane Reformer (SMR) in S-102. S-102 contains primarily hydrogen, steam and carbon monoxide. The cooling water loop, which enters HX-102 as stream CW-101 is a closed loop that is kept at pressure by Pump-101. S-102 is cooled from a temperature of 753.8^{o}F to 437.0^{o}F. The shell side cooling water rises from a temperature of 39.2^{o}F to a temperature of 252.8^{o}F, where it partially vaporizes to a vapor fraction of 0.49. A heat transfer coefficient of 100Btu/hr-sqft-R was used (Perry). The unit uses 11,615 20ft tubes for a 1.82E09 Btu/hr heat duty, as calculated by Aspen's HeatX subroutine. The tubes have an ID of 0.625 in. while the shell has an ID of 110 in. The minimum baffle spacing is 22 in. and total area for heat transfer is 40,729 sqft. The total indexed cost is $408,683 (Seider 2005). For calculation details, please see page A3 of the Appendix. The specification sheet can be found on page 60.

9.19 Heat Exchanger - HX-101

HX-101 is system of countercurrent floating head shell and tube heat exchangers that cool the combustion products from the Steam-Methane Reformer (SMR) in S-105. There are a total of four identical exchangers in parallel. S-105 contains mostly nitrogen, water and unreacted oxygen. It enters at a temperature of 627.8^{o}F. Cooling water enters the exchanger via CW-102 at 252.8^{o}F and exits as stream CW-103 at 463.6^{o}F. The exit stream is labeled S-106 and is cooled to a temperature of 320.0^{o}F. The cooling water is on the shell side and enters partially vaporized, at a vapor fraction of 0.49. In the exchanger, the remaining liquid is completely vaporized. A heat transfer coefficient of 100Btu/hr-sqft-R has been postulated based on values obtained from the literature (Perry). Each of the four units uses 12,493 20ft tubes for a 3.79E08 Btu/hr heat duty, as calculated by Aspen's HeatX subroutine. The tubes have an ID of 0.625 in. while the shell has an ID of 114 in. The minimum baffle spacing is 23 in. and total area for heat transfer is 49,046 sqft. The total indexed cost for all four exchangers is $1,884,936 (Seider 2005). For calculation details, please see page A3 of the Appendix. The specification sheet can be found on page 59.

9.20 Heat Exchanger - HX-201

HX-201 is system of countercurrent floating head shell and tube heat exchangers that cools the Fischer-Tropsch Reactor (FTR) stream products, S-203. There are a total of 120 identical exchangers in parallel. S-203, containing crude products, including saturated hydrocarbons from methane to C_{20}+ and 61% mass steam and 13% mass CO, enters the exchangers at a temperature of 437^{o}F. The exit stream is labeled S-204 and is cooled to a temperature of 86^{o}F. Shell-side cooling water enters the exchanger via CW-204 at 39.2^{o}F and exits partially vaporized (vapor fraction 0.32) as stream CW-205 at 364.0^{o}F. A heat transfer coefficient of 100Btu/hr-sqft-R has been assumed based on values obtained from the literature (Perry). Each of the 120 units uses 13,469 24ft tubes for a 6.55E06 Btu/hr heat duty, as calculated by Aspen's HeatX subroutine. The tubes have an ID of 0.625 in. while the shell has an ID of 118 in. The minimum baffle spacing is 24 in. and total area for heat transfer is 63,455 sqft, nearly the maximum practical size of a shell and tube heat exchanger. The total indexed cost for all four exchangers is $74,196,004 (Seider 2005). For calculation details, please see page A3 of the Appendix. The specification sheet can be found on page 61.

Section 10 - Equipment Specification Sheets

Air Compressor			
Identification:	Item	Air Compressor	
	Item No.	COMP-101	
	No. Required	2	
Function:	Compress natural gas feed to the desired reactor pressure		
Operation:	Continuous		
Performance of Unit			
	Entry		Exit
Stream No.	Feed-CH4		S-101
Flow Rate (scf/min)	362746.47		362746.47
Flow Rate (lb/hr)	2574234.07		2574234.07
Temperature (F)	100		255.25
Pressure (psi)	44.09		232.25
Design Data:	Utility Used	Electricity	
	Power Consumption	4.4979E8 Btu/hr	
	Material	Carbon Steel	
	Number of Stages	2	
	Efficiency	72%	
Bare Module Cost Per Unit (1998 dollars CE=389.5):		$10,500,000	
Total Bare Module Cost:		$21,000,000 (Icarus 1998 Cost Charts)	
Total Indexed Cost:		$28,612,837	

Air Compressor			
Identification:	Item	Air Compressor	
	Item No.	COMP-102	
	No. Required	2	
Function:	Compress carbon dioxide recycle stream to the desired reactor pressure		
Operation:	Continuous		
Performance of Unit			
	Entry	Exit	
Stream No.	STEAM-201	STEAM-101	
Flow Rate (scf/mi	389190	389190	
Flow Rate (lb/hr)	7632910.68	7632910.68	
Temperature (F)	401	638.6	
Pressure (psi)	159.73	232.25	
Design Data:	Utility Used	Electricity	
	Power Consumption	3.7498E8 Btu/hr	
	Material	Carbon Steel	
	Number of Stages	1	
	Efficiency	72%	
Bare Module Cost Per Unit (1998 dollars CE=389.5):		$9,780,000	
Total Bare Module Cost :		$19,560,000	(Icarus 1998 Cost Charts)
Total Indexed Cost:		$26,650,814	

Air Compressor			
Identification:	Item	Air Compressor	
	Item No.	Comp-201	
	No. Required	3	
Function:	Compress synthetic gas to the desired reactor pressure		
Operation:	Continuous		
Performance of Unit			
	Entry		Exit
Stream No.	S-201		S-202
Flow Rate (scf/min)	478236.25		478236.25
Flow Rate (lb/hr)	9373779.93		9373779.93
Temperature (F)	417.86		437
Pressure (psi)	232.25		514.36
Design Data:	Utility Used	Electricity	
	Power Consumption	1.822 E9 Btu/hr	
	Material	Carbon Steel	
	Number of Stages	3	
	Efficiency	72%	
Bare Module Cost Per Unit (1998 dollars CE=389.5):		$12,000,000	
Total Bare Module Cost :		$36,000,000 (Icarus 1998 Cost Charts)	
Total Indexed Cost:		$49,050,578	

Air-Cooled Heat Exchanger				
Identification:	Item	Air Fin/Fan Heat Exchanger		
	Item No.	AIRCOOLER-101		
	No. Required	40		
Function:	Use Alaskan air to cool cooling water			
Operation:	Continuous			
Performance of Unit				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	CW-103	CW-104		
Flow Rate (lb/hr)	2482306	2482306	62057	62057
Vapor Fraction	1	0	1	1
Temperature (F)	463.6	39.2	14	173
Pressure (psi)	14.96	14.96	14.96	14.96

Design Data:				
	Flow Type:	CounterCurrent	No. of Fans	2
	Shell Type:	Four-Pass	Fan Diameter	11.2 ft
	U:	5.7 Btu/hr-sqft-F	Fan Pressure Drop	0.037 psi
	LMTD:	108.5	Fan Power	203,520 Btu/h
	Area:	5,890 sqft	Tube Inner Diameter	0.85 in.
	Duty:	8.345E7 Btu/h	Tube Outer Diameter	1 in.
	Tube Length:	40 ft	Material	Carbon Steel
	No. of Tubes:	264		

Bare Module Cost Per Unit (2000 dollars CE=394):	$	345,188	
Total Bare Module Cost:	$	13,807,520	(Erwin)
Total Indexed Cost:	$	18,598,099	
The heat exchanger uses 5/8 in high fins, 10 fins/in, a 2.5 in pitch, and 16BWG tubing			

Air-Cooled Heat Exchanger				
Identification:	Item	Air Fin/Fan Heat Exchanger		
	Item No.	AIRCOOLER-201		
	No. Required	40		
Function:	Use Alaskan air to cool cooling water			
Operation:	Continuous			
Performance of Unit				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	CW-208	CW-209		
Flow Rate (lb/hr)	4.006 E6	4.006 E6	100139	100139
Vapor Fraction	1	0	1	1
Temperature (F)	369.6	39.2	14	152.3
Pressure (psi)	120	120	14.7	14.7

Design Data:				
	Flow Type:	CounterCurrent	No. of Fans	2
	Shell Type:	Four-Pass	Fan Diameter	14 ft
	U:	7.32 Btu/hr-sqft-F	Fan Pressure Drop	0.037 psi
	LMTD:	220.6 F	Fan Power	253,350 Btu/h
	Area:	91,769 sqft	Tube Inner Diameter	0.85 in.
	Duty:	1.293E8 Btu/hr	Tube Outer Diameter	1 in.
	Tube Length:	40 ft	Material	Carbon Steel
	No. of Tubes:	412		

Bare Module Cost Per Unit (2000 dollars CE=394):	$413,052	
Total Bare Module Cost:	$ 16,522,080	(Erwin)
Total Indexed Cost:	$ 22,254,487	
The heat exchanger uses 5/8 in high fins, 10 fins/in, a 2.5 in pitch, and 16BWG tubing		

CO2 Separator					
Identification:	Item		Adsorber/Stripper		
	Item No.		MEA-101		
	No. Required		1		
Function:	Separate and recycle CO2 back to the SMR				
Operation:	Continuous				
Performance of Unit					
		IN	OUT		
		S-103	S-104	CO2 RECYCLE	CO2 PURGE
Quantity (lb/hr)		9.45E+06	7.558E+06	7.560E+04	1.816E+06
Phase		Vapor	Vapor	Vapor	Vapor
Composition		CH4, H20, H2, CO, CO2	CO2	Rest of chemicals in S-103	CO2
Temperature(F)		753.8	753.8	753.8	758.8
Pressure (psig)		225	225	225	225
Solvent:	Aqueous 85% wt monoethanolamine (MEA)				
Solvent Action:	Ionic chemical reaction equilibria with MEA-CO2				
Design Data:	Units:	Absorption followed by Stripping with appropriate temperature /pressure/separation units			
	CO2 recycled:	80%			
	Electricity:	178508.8 kw/y			
	Steam:	4.653E+7 Btu/y			
	Cooling Water:	5.18E+9 Btu/y			
	(For details see attachments)				
Total Plant Cost:		$967,315,790		(Thomas)	

CO Separator				
Identification:	Item		Adsorber/Stripper	
	Item No.		COPure-301	
	No. Required		1	
Function:	Separate and recycle CO back to the Fischer-Tropsh reactor from recycle stream			
Operation:	Continuous			
Performance of Unit				
		IN	OUT	
		S-304	S-305	RECYCLE
Quantity (lb/hr)		1.88E+06	1.144E+06	7.400E+06
Phase		Vapor	Liquid	Liquid
Composition		CH4, H20, H2, CO, CO2, Heavier hydrocarbons to C_{30}	CO	Rest of chemicals in S-109
Temperature(F)		80.6	80.6	80.6
Pressure (psig)		225	225	225
Solvent:	$CuAlCl_4$ dissolved in an organic solvent such as toluene			
Solvent Action:	Complexation			
Design Data:	Units:	Absorption followed by Stripping with appropriate temperature /pressure/separation units		
	Material:	Carbon Steel		
	Electricity:	783.75 kw/y		
	Reboiler:	1350615 Btu/y		
	Cooling Water:	7428382.5 Btu/y		
	(For details see attachments)			
Total Plant Cost:		$1,496,470,800		(R.C. Costello)

Decanter				
Identification:	Item	Vertical Pressure Vessel		
	Item No.	DEC-301		
	No. Required	30		
Function:	Separates hydrocarbons remaining in the water stream from the flash unit and combines them with the final product in the pipeline.			
Operation:	Continuous			
Performance of Unit				
		IN		OUT
		S-301	WASTE WATER	S-302
Quantity (lb/hr)		6.983E+06	5.700E+06	1.283E+06
Phase		Liquid	Liquid	Liquid
Composition (weight fraction)				
	CH4	1.1402-02	2.2353-05	0.2827
	H2O	0.8161	0.9997	7.9256-03
	CO	1.3951-02	2.9265-06	0.1984
	CO2	3.2529-02	2.4894-04	0.29
	H2	2.8381-09	4.3241-11	5.6009-07
	C2H6	1.8662-03	5.1754-07	2.4715-02
	C3H8	3.6318-03	2.6534-08	3.2811-02
	C4H10	5.1678-03	9.7916-10	3.5420-02
	N-HEX-01	4.8908-05	9.3735-16	2.2609-04
	N-NON-01	8.8053-04	0	2.7350-03
	N-UND-01	9.4645-05	0	2.4122-04
	N-DOD-01	9.6035-05	0	2.2460-04
	N-HEX-02	9.6745-05	0	1.7020-04
	N-PEN-01	2.6076-05	5.9386-14	1.4398-04
	N-HEP-01	5.0231-05	0	1.9970-04
	N-OCT-01	7.3013-05	0	2.5464-04
	N-TRI-01	9.7742-05	0	2.1120-04
	N-TET-01	9.8219-05	0	1.9723-04
	N-PEN-02	6.9949-03	0	1.3119-02
	N-HEP-02	6.4929-03	0	1.0756-02
	N-OCT-02	6.2217-03	0	9.7391-03
	N-NON-02	5.9434-03	0	8.8176-03
	N-EIC-01	5.6619-03	0	7.9829-03
	N-DEC-01	1.0562-04	0	2.9573-04
	N-DOT-01	8.2347-02	0	7.2759-02
Temperature (oF)		80.6	80.6	80.6
Design Data:	Unit Type:	Flash/Settler	Diameter:	7.63 ft
	Column Material:	Carbon Steel	Length:	7.63 ft
	Total Flow:	2095.09 ft^3/min	Capacity	349.2 ft^3
	Per Vessel:	69.84 ft^3/min	Residence Time:	5 min
Bare Module Cost Per Unit (1998 dollars CE=389.5):		$135,200		
Total Bare Module Cost:		$4,056,000	(Icarus Cost Charts)	
Total Indexed Cost:		$5,526,365		

Flash Vessel					
Identification:	Item	Vertical Pressure Vessel			
	Item No.	F-301			
	No. Required	22			
Function:	Separates Fischer-Tropsh products into liquid water for decanting, desired heavier hydrocarbons for the pipeline, and product gas for recycle.				
Operation:	Continuous				
Performance of Unit					
		IN	OUT		
		S-204	S-301	S-303	S-304
Quantity (lb/hr)		1884093	1884093	505913	1884093
Phase		Liquid	Liquid	Liquid	Vapor
Composition (weight fraction)	CH4	2.5353-02	1.1402-02	1.7783-03	8.3398-02
	H2O	0.61	0.82	2.9353-04	3.5574-03
	CO	0.13	1.3951-02	2.1758-03	0.61
	CO2	5.4934-02	3.2529-02	5.0735-03	0.15
	H2	2.2311-02	2.8381-09	4.4265-10	0.11
	C2H6	2.5724-03	1.8662-03	2.9106-04	5.8028-03
	C3H8	3.4921-03	3.6318-03	5.7527-04	3.7572-03
	C4H10	4.2138-03	5.1678-03	8.1645-04	1.5897-03
	N-HEX-01	5.1768-03	4.8908-05	5.6766-02	1.0332-02
	N-NON-01	5.7557-03	8.8053-04	9.2346-02	5.7521-04
	N-UND-01	5.7616-03	9.4645-05	0.11	6.6756-05
	N-DOD-01	5.6883-03	9.6035-05	0.10	2.1809-05
	N-HEX-02	5.0876-03	9.6745-05	9.2929-02	2.4061-07
	N-PEN-01	4.7668-03	2.6076-05	3.2743-02	1.4827-02
	N-HEP-01	5.4658-03	5.0231-05	8.4300-02	4.3713-03
	N-OCT-01	5.6532-03	7.3013-05	9.6699-02	1.8898-03
	N-TRI-01	5.5769-03	9.7742-05	0.10	7.0507-06
	N-TET-01	5.4353-03	9.8219-05	9.9343-02	2.3157-06
	N-PEN-02	5.2703-03	6.9949-03	1.0910-03	8.8195-09
	N-HEP-02	4.8921-03	6.4929-03	1.0127-03	8.7620-10
	N-OCT-02	4.6877-03	6.2217-03	9.7038-04	3.0214-10
	N-NON-02	4.4781-03	5.9434-03	9.2699-04	8.5325-11
	N-EIC-01	4.2660-03	5.6619-03	8.8307-04	2.5992-11
	N-DEC-01	5.7876-03	1.0562-04	0.11	2.0789-04
	N-DOT-01	6.2044-02	8.2347-02	1.2843-02	3.4231-16
Temperature (oF)		86	80.6	80.6	80.6
Design Data:	Flash Type:	V-L-L Equilibrium		Diameter:	23.87 ft
	Column Material:	Carbon Steel		Length:	45.88 ft
	Total Flow:	41690 ft^3/min		Thickness:	2.55 ft
	Per Vessel:	1895 ft^3/min		Residence Time:	5 min
Bare Module Cost Per Unit (2000 dollars CE=394):		$	2,981,056		
Total Bare Module Cost:		$	65,583,230	(Seider 2005)	
Total Indexed Cost:		$	88,337,615		

Flash Vessel					
Identification:	Item		Vertical Pressure Vessel		
	Item No.		F-302		
	No. Required		12		
Function:	Separates CO and CO2 from pipeline product				
Operation:	Continuous				
Performance of Unit					
		IN	OUT		
		S-306	S-308	S-307	
Quantity (lb/hr)		1,788,952	1,301,527	487,425	
Phase		Liquid	Liquid	Vapor	
Composition (mol fraction)	CH4	0.2355	0.0040	0.3252	
	H2O	0.0069	0.0072	0.0068	
	CO	0.1653	0.0011	0.2288	
	CO2	0.2416	0.0152	0.3293	
	H2	0.0000	0.0000	0.0000	
	C2H6	0.0206	0.0018	0.0278	
	C3H8	0.0273	0.0081	0.0348	
	C4H10	0.0295	0.0251	0.0312	
	N-HEX-01	0.0158	0.0438	0.0050	
	N-NON-01	0.0194	0.0688	0.0003	
	N-UND-01	0.0162	0.0580	0.0000	
	N-DOD-01	0.0147	0.0526	0.0000	
	N-HEX-02	0.0099	0.0355	0.0000	
	N-PEN-01	0.0109	0.0199	0.0074	
	N-HEP-01	0.0202	0.0661	0.0024	
	N-OCT-01	0.0203	0.0708	0.0008	
	N-TRI-01	0.0133	0.0477	0.0000	
	N-TET-01	0.0121	0.0432	0.0000	
	N-PEN-02	0.0109	0.0392	0.0000	
	N-HEP-02	0.0090	0.0321	0.0000	
	N-OCT-02	0.0081	0.0291	0.0000	
	N-NON-02	0.0073	0.0263	0.0000	
	N-EIC-01	0.0067	0.0238	0.0000	
	N-DEC-01	0.0178	0.0635	0.0001	
	N-DOT-01	0.0606	0.2172	0.0000	
Temperature (^oF)		80.6	80.6	80.6	
Design Data:	Flash Type:	V-L Equilibrium		Diameter:	7.46 ft
	Column Materi	Carbon Steel		Length:	14.93 ft
	Total Flow:	784.13 ft^3/min		Capacity:	488 gal
	Per Vessel:	65.34 ft^3/min		Residence Time:	5 min
Bare Module Cost Per Unit (1998 dollars CE=389.5):			$ 41,600		
Total Bare Module Cost:			$ 499,200	(Icarus 1998 Cost Charts)	
Total Indexed Cost:			$ 680,168		

Fischer Tropsch Reactor (FTR-201)				
Identification:	Item	Microchannel Reactor		
	Item No.	FTR-201		
	No. Required	3,987 modules		
Function:	Convert feed of syngas (H_2 and CO) to a distribution of hydrocarbons resulting from Fischer Tropsch hydrocarbon synthesis			
Operation:	Continuous			
Materials Handled				
Reaction channels	Inlet Stream S-202 (437˚F, 34.5 barg):	CO	4,149,081	lb/hr per module
		H_2	647,273	lb/hr per module
		H_2O	3,835,272	lb/hr per module
		CO_2	514,937	lb/hr per module
		CH_4	224,333	lb/hr per module
	Outlet Stream S-203 (437˚F, 29.4 barg):	CO	1,241,726	lb/hr per module
		H_2	209,439	lb/hr per module
		CO_2	3,835,272	lb/hr per module
		H_2O	5,705,178	lb/hr per module
		CH_4	237,646	lb/hr per module
		C_2H_6	24,097	lb/hr per module
		C_3H_8	32,711	lb/hr per module
		C_4H_{10}	39,471	lb/hr per module
		C_5H_{12}	44,652	lb/hr per module
		C_6H_{14}	48,492	lb/hr per module
		C_7H_{16}	51,200	lb/hr per module
		C_8H_{18}	52,955	lb/hr per module
		C_9H_{20}	53,915	lb/hr per module
		$C_{10}H_{22}$	54,214	lb/hr per module
		$C_{11}H_{24}$	53,970	lb/hr per module
		$C_{12}H_{26}$	53,284	lb/hr per module
		$C_{13}H_{28}$	52,240	lb/hr per module
		$C_{14}H_{30}$	50,914	lb/hr per module
		$C_{15}H_{32}$	49,368	lb/hr per module
		$C_{16}H_{34}$	47,657	lb/hr per module
		$C_{17}H_{36}$	45,825	lb/hr per module
		$C_{18}H_{28}$	43,911	lb/hr per module
		$C_{19}H_{30}$	41,947	lb/hr per module
		$C_{20}H_{32}$	39,960	lb/hr per module
		C_{20}+	581,185	lb/hr per module
Cooling channels	Inlet Stream CW-205 (363˚F, 10 barg):	$H_2O_{(l)}$	7,855,450	lb/hr per module
		$H_2O_{(g)}$	3,744,815	lb/hr per module
	Outlet Stream CW-208 (401˚F, 10 barg):	Steam	#########	lb/hr per module
Design Data:	Flow Orientation:	Co-current flow		
	Channel Dimensions[1]:			
Bare Module Cost Per Unit		$186,408		
Total Indexed Cost:		$743,210,558		

Design Data (continued):

Channel Dimensions[1]	Length	Width	Thickness	Spacer
Reaction	1400 mm	17 mm	0.95 mm	3 mm
Cooling	1400 mm	3 mm	1.5 mm	3 mm

No. Channels:	(per plate pair)	(per module)
Reaction	70	15,750
Cooling	280	63,000

Module Dimensions: 1 m height, 1 m width, 1.5 m depth

Other Information:

- Catalyst: Fixed bed of particulate solid, containing Co/Re catalyst (molar ratio Co/Re = 21), 30% wt loading Co, 4.5% wt loading Re, supported on Al_2O_3; metal dispersion 5.4%; 177-250 microns diameter; 6.7 tons required
- Max. Pressure gradient between adjacent channels: 24.5 bar
- Average heat flux: 0.11 W/cm^2
- Reactor core temperature during operation: ~ 437^{0}F (225^{0}C)

[1] For detailed information on the internal structure of the module, see page A29 of the Appendix

Heat Exchanger				
Identification:	Item	Floating Head Shell-and-tube Heat Exchanger		
	Item No.	HX-101		
	No. Required	4		
Function:	Use cooling water to cool combustion SMR products			
Operation:	Continuous			
Performance of Unit				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	CW-102	CW-103	S-105	S-106
Flow Rate (lb/hr)	2482306	2482306	17387942	17387942
Vapor Fraction	0.4869	1	1	1
Temperature (F)	252.8	463.6	627.8	320
Pressure (psi)	29.2	29.2	14.7	14.7

Design Data:				
	Flow Type:	CounterCurrent	Ft	0.7116
	Shell Type:	One-Pass	Tube Inner Diameter	0.625 in.
	U:	100 Btu/hr-sqft-R	Tube Outer Diameter	0.75 in.
	LMTD:	108.6 F	Min. Baffle Spacing:	23 in.
	Area:	49046 sqft	Shell Outer Diameter:	116 in.
	Duty:	378953276 Btu/hr	Shell Inner Diameter	114 in.
	Tube Length:	20 ft	Material	Carbon Steel
	No. of Tubes:	12493	Pitch	0.9375 in (triangular)

Bare Module Cost Per Unit (2000 dollars CE=394):	$349,851	
Total Bare Module Cost:	$1,399,406	(Seider 2005)
Total Indexed Cost:	$1,884,936	

Heat Exchanger				
Identification:	Item	Floating Head Shell-and-tube Heat Exchanger		
	Item No.	HX-102		
	No. Required	1		
Function:	Use cooling water to cool SMR reforming products			
Operation:	Continuous			
Performance of Unit				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	CW-101	CW-102	S-102	S-103
Flow Rate (lb/hr)	2482306	2482306	10289470	10289470
Vapor Fraction	0	0.4869	1	1
Temperature (F)	39.2	252.8	753.8	437
Pressure (psi)	29.2	29.2	232.25	232.25

Design Data:				
	Flow Type:	CounterCurrent	Ft	0.9406
	Shell Type:	One-Pass	Tube Inner Diameter	0.625 in.
	U:	100 Btu/hr-sqft-R	Tube Outer Diameter	0.75 in.
	LMTD:	479.4 F	Min. Baffle Spacing:	22 in.
	Area:	40729 sqft	Shell Outer Diameter:	112 in.
	Duty:	1.822E09 Btu/hr	Shell Inner Diameter	110 in.
	Tube Length:	20 ft	Material	Carbon Steel
	No. of Tubes:	11615	Pitch	0.9375 in (triangular)

Bare Module Cost Per Unit (2000 dollars CE=394):	$303,413	
Total Bare Module Cost:	$303,413	(Seider 2005)
Total Indexed Cost:	$408,683	

Heat Exchanger				
Identification:	Item	Floating Head Shell-and-tube Heat Exchanger		
	Item No.	HX-201		
	No. Required	120		
Function:	Use cooling water to cool FTR products			
Operation:	Continuous			
Performance of Unit				
	Shell Side		Tube Side	
	Entry	Exit	Entry	Exit
Stream No.	CW-204	CW-205	S-203	S-204
Flow Rate (lb/hr)	11638488	11638488	9373780	9373780
Vapor Fraction	0	0.32	1	0.37
Temperature (F)	39.22	364	437	86
Pressure (psi)	159.73	159.73	440.88	440.88

Design Data:	Flow Type:	CounterCurrent	Ft	1
	Shell Type:	One-Pass	Tube Inner Diameter	0.625 in.
	U:	100 Btu/hr-sqft-R	Tube Outer Diameter	0.75 in.
	LMTD:	58.9 F	Min. Baffle Spacing:	24 in.
	Area:	63455 sqft	Shell Outer Diameter:	120 in.
	Duty:	6552747 Btu/hr	Shell Inner Diameter	118 in.
	Tube Length:	24 ft	Material	Carbon Steel
	No. of Tubes:	13469	Pitch	0.9375 in (triangular)

Bare Module Cost Per Unit (2000 dollars CE=394):	$459,036	
Total Bare Module Cost:	$55,084,276	(Seider 2005)
Total Indexed Cost:	$74,196,004	

Pump			
Identification:	Item	Centrifugal Pump and Electric Motor	
	Item No.	PUMP-101	
	No. Required	2	
Function:	Pump CW-13 to circulate the cooling water between heat exchangers		
Operation:	Continuous		
Performance of Unit			
	Entry		Exit
Stream No.	CW-104		CW-101
Flow Rate (scf/min)	673.3		673.3
Temperature (F)	35		35
Pressure (psi)	22.04		29.39
Design Data:	Utility Used	Electricity	
	Power Consumption	63875,76 Btu/hr	
	Head	17.22035 ft	
	Ft Steam Turbine Driver	2	
	Fm Stainless Steel	2	
	Electric Motor	3600 rpm	
	Ft Electric Motor	1.8	
	Number of Stages	1	
	Efficiency	86%	
Centrifugal Pumps			
Bare Module Cost Per Unit (2000 dollars CE=394):		$18,577	
Total Bare Module Cost For All Pumps		$37,154	
Electric Motors			
Bare Module Cost Per Unit (2000 dollars CE=394):		$2,354	
Total Bare Module Cost For All Units:		$4,709	
Total Bare Module Cost for Pumps and Motors		$41,862	(Seider 2005)
Total Indexed Cost:		$56,387	

Pump			
Identification:	Item	Centrifugal Pump and Electric Motor	
	Item No.	PUMP-201	
	No. Required	5	
Function:	Pump CW-4 to a pressure of 130.73psi		
Operation:	Continuous		
Performance of Unit			
	Entry		Exit
Stream No.	CW-201		CW-202
Flow Rate (scf/min)	2009.7		2009.7
Temperature (F)	39.2		39.2
Pressure (psi)	14.7		130.73
Design Data:	Utility Used	Electricity	
	Power Consumption	3.01275 E6 Btu/hr	
	Head	236.95 ft	
	Ft Steam Turbine Driver	2	
	Fm Stainless Steel	2	
	Electric Motor	3600 rpm	
	Ft Electric Motor	1.8	
	Number of Stages	1	
	Efficiency	86%	
Centrifugal Pumps			
Bare Module Cost Per Unit (2000 dollars CE=394):		$31,288	
Total Bare Module Cost:		$156,442	
Electric Motors			
Bare Module Cost Per Unit (2000 dollars CE=394):		$54,946	
Total Bare Module Cost :		$274,729	
Total Bare Module Cost for Pumps and Motors		$431,171	(Seider 2005)
Total Indexed Cost:		$580,768	

Pump			
Identification:	Item	Centrifugal Pump and Electric Motor	
	Item No.	PUMP-202	
	No. Required	3	
Function:	Pump CW-5 to a pressure of 159.73psi for turbine energy recovery		
Operation:	Continuous		
Performance of Unit			
	Entry	Exit	
Stream No.	CW-203	CW-204	
Flow Rate (scf/min)	3064.38	3064.38	
Temperature (F)	39.21	39.21	
Pressure (psi)	130.73	159.73	
Design Data:	Utility Used	Electricity	
	Power Consumption	1.1485 E6 Btu/hr	
	Head	65.99 ft	
	Ft Steam Turbine Driver	2	
	Fm Stainless Steel	2	
	Electric Motor	3600 rpm	
	Ft Electric Motor	1.8	
	Number of Stages	1	
	Efficiency	86%	
Centrifugal Pumps			
Bare Module Cost Per Unit (2000 dollars CE=394):		$31,518	
Total Bare Module Cost:		$94,554	
Electric Motors			
Bare Module Cost Per Unit (2000 dollars CE=394):		$38,186	
Total Bare Module Cost:		$114,557	
Total Bare Module Cost for Pumps and Motors		$209,111	(Seider 2005)
Total Indexed Cost:		$281,664	

Pump			
Identification:	Item	Centrifugal Pump and Electric Motor	
	Item No.	PUMP-301	
	No. Required	2	
Function:	Pump CW-13 to circulate the cooling water between heat exchangers		
Operation:	Continuous		
Performance of Unit			
	Entry	Exit	
Stream No.	S-308	TO-PIPE	
Flow Rate (scf/min)	488.45	488.45	
Temperature (F)	80.6	80.6	
Pressure (psi)	29.19972	101.7186	
Design Data:	Utility Used	Electricity	
	Power Consumption	4.64.E+05 Btu/hr	
	Head	235.14346 ft	
	Ft Steam Turbine Driver	2	
	Fm Stainless Steel	2	
	Electric Motor	3600 rpm	
	Ft Electric Motor	1.8	
	Number of Stages	1	
	Efficiency	86%	
Centrifugal Pumps			
Bare Module Cost Per Unit (2000 dollars CE=394):		$29,876	
Total Bare Module Cost For All Pumps		$59,751	
Electric Motors			
Bare Module Cost Per Unit (2000 dollars CE=394):		$17,701	
Total Bare Module Cost For All Units:		$35,401	
Total Bare Module Cost for Pumps and Motors		$95,152	(Seider 2005)
Total Indexed Cost:		$128,166	

Steam-Methane Reformer (SMR-101)			
Identification:	Item	Welded Integrated Combustion Microchannel Reactor - N3-type	
	Item No.	SMR-101	
	No. Required	3298 modules	
Function:	Convert steam and natural gas feed to syngas stream using energy from the combustion of methane and hydrocarbon fuel		
Operation:	Continuous		
Materials Handled			
Reformer Side	Inlet Streams S-101, STEAM-101, CO2 RECYCLE:	CH_4	4,152 lb/hr per module
		Steam	12,311 lb/hr per module
		CO_2	133 lb/hr per module
	Outlet Stream S-102 (401°C/754°F):	CH_4	362 lb/hr per module
		Steam	6,186 lb/hr per module
		CO_2	4,153 lb/hr per module
		CO	4,851 lb/hr per module
		H_2	1,044 lb/hr per module
Combustion Side	Inlet Streams FEED FUEL, FEED AIR:	Fuel[1]	307 lb/hr per module
		Air[2]	38 MMSCFT/hr per module
Design Data:	Flow Orientation: Two-stream loop (Fig. 2, US Patent 7,250,151 B2)		
	Channel Dimensions:	Length / Width / Thickness	
	Endothermic[3]	530 mm / 9.70 mm / 0.25 mm	
	Product[4]	443 mm / 4.1 mm / 0.41 mm	
	Combustion	443 mm / 4.1 mm / 0.64 mm	
	Air	443 mm / 4.1 mm / 0.64 mm	
	Exhaust[5]	443 mm / 4.1 mm / 0.36 mm	
	No. Channels per module:		
	Endothermic: 8938	Air: 8938	
	Product: 8938	Exhaust: 8938	
	Combustion: 17876		
	Module Dimensions: 1.5 m height, 1m width, 60 cm depth		
Other Information:	Catalyst:	10 wt% Rh/4.5 wt% MgO/85.5 wt% Al2O3 on spinel support with FeCrAlY felt coating (method of preparation in US Patent 0033455 A1)	
	Volume of catalyst:	0.14 ft^3	
	Pressure gradient between fuel and air channels:	19 bar	
	Average heat flux:	38.5 W/cm^2	
	Reactor core temperature during operation:	~ 1533°F	
	[1]Fuel is composed of 122 lb/hr CH_4 feed, in addition to the contents of stream RECYCLE,		
	[2]Air is assumed to be 21% O_2 and 79% N_2		
	[3]The length of the reaction zone is 180 mm		
	[4]The first 110 mm of the product channel is thicker than 0.41 mm, upto 0.91 mm thick		
	[5]The first 438 mm of the exhaust channel is thicker than 0.36 mm, upto 0.86 mm thick		
Bare Module Cost Per Unit	$128,892		
Total Indexed Cost:	$425,084,912		

Turbine			
Identification:	Item	Steam Turbine	
	Item No.	TURB-201	
	No. Required	1	
Function:	Generate electricity from cooling water that has been converted to steam		
Operation:	Continuous		
Performance of Unit			
	Entry	Exit	
Stream No.	CW-207	CW-208	
Flow Rate (scf/min)	204237.99	241493.48	
Temperature (F)	401	369.56	
Pressure (psi)	159.73	130.73	
Design Data:	Utility Produced	Electricity	
	Power Production	14.9634 MW	
	Power Production	5.106 E7 Btu/hr	
	Material	Carbon Steel	
	Speed	3600 RPM	
	Number of Stages	1	
	Efficiency	72%	
Centrifugal Pumps			
Bare Module Cost Per Unit (1998 dollars CE=389.5):			$1,600,000
Total Bare Module Cost:			$1,600,000 (Icarus Cost Charts)
Total Indexed Cost:			$2,180,026

Equipment Cost Summary

Equipment Type	Quantity	Indexed Cost	% of Total Cost
Heat Exchangers			
HX-101	4	$1,884,936	0.05%
HX-102	1	$408,683	0.01%
HX-201	120	$74,196,004	1.88%
AIRCOOLER-101	40	$18,598,099	0.47%
AIRCOOLER-201	40	$22,254,487	0.56%
MicroChannels			
SMR-101	620	$425,084,912	10.76%
FTR-101	11	$743,210,558	18.81%
Separators			
MEA-101	1	$967,315,790	24.48%
COPure-301	1	$1,496,470,800	37.87%
F-301	22	$88,606,163	2.24%
F-302	12	$680,168	0.02%
DEC-301	30	$5,526,365	0.14%
Pumps			
PUMP-201	5	$580,768	0.01%
PUMP-202	3	$281,664	0.01%
PUMP-101	2	$56,387	0.00%
PUMP-301	2	$128,166	0.00%
Compressors			
COMP-101	2	$28,612,837	0.72%
COMP-102	2	$26,650,814	0.67%
COMP-201	3	$49,050,578	1.24%
Turbines			
TURB-201	1	$2,180,026	0.06%
TOTAL		**$3,951,778,205**	**100.00%**

Section 11 - Energy Balance and Utility Requirements

Energy Balance and Utility Requirements

The operation of this plant requires processing water, cooling water, and natural gas as utilities. One of the main benefits in using microchannel reactors is the significant decrease in required utilities. For steam reforming, the high rate of heat transfer in the microchannels allows for the reaction to be sustained at the temperature of 753.8°F. This is very low when compared to conventional reactor temperatures of 1472°F. When compared with a conventional process sheet that was prepared, the natural gas required for combustion with microchannel reactors was reduced by 94%. Additionally, the cooling water utility required to cool these streams was significantly decreased. The following utility requirements are small in comparison to conventional gas-to-liquid processes.

11.1 Cooling Water

The streams cooling heat exchangers HX-101 and HX-102 form a closed loop using an air cooler, to lower the cooling water requirements. This cooling loop requires a flow rate of 7,152,457 gallons/hour. A makeup requirement of 3% of the total enclosed flow per year yields a requirement of 214,574 gallons of makeup/year.(Petrakis) Similarly the cooling water streams passing through the HX-201 cooling loop has a flow rate requirement of 11,541,573 gallons/hour and a makeup requirement of 346,247 gallons/year. The total amount of makeup cooling water that is required per year is 560,821gallons/year, which is equal to 0.131 gallons of makeup/bbl of product produced. The resulting cost of cooling water is $560.82/year. The initial purchase cost of cooling water is $18,964.

11.2 Process Water

The flow rate of stream CW-201 is the requirement of process water for the plant. This process water initially serves as cooling water for HX-201. In HX-201 the cooling water is vaporized into steam at 401°F. The steam produced from the process water will then serve as a feed to the steam reforming reaction. This method of producing steam from process water eliminates the need for steam as a purchased utility. The process water requirement is 901,769 gallons/hour at an annual cost of $7,697,700.

11.3 Natural Gas

Natural Gas is required to heat the SMR-101 reactor. Stream FUEL FEED has a natural gas requirement of 21,800,000 cubic feet per hour at an annual cost of $27,200. Other requirements of natural gas include the feed of natural gas that will undergo steam reforming and the natural gas power plant that will be operating on site. These natural gas requirements have been categorized under raw material costs.

11.4 Electricity

Electricity is a major requirement for the proposed project. The electricity requirement is summarized in Table 5 and is equal to an approximate total of 782.3MW plus ancillary demand. The GTL plant design includes a single turbine capable of producing just under 15MW. This leaves ~765MW of unmet demand. Unfortunately, currently, the largest power plant in the North Slope region is only capable of producing approximately 300MW. In order to meet the electricity requirement, a new power plant must be constructed. Due to the availability and low cost of natural gas, a plant utilizing this fuel makes the most economic sense. NG fired generation is also among the cheapest options from a capital cost standpoint. The current project proposes to construct a natural gas combined cycle (NGCC) plant using newer generation and emission controls technologies. The plant will have a capacity of between 800MW and 1000MW, depending on factors such as the demand for additional electricity in the area and the final needs of the GTL plant and supporting infrastructure.

Table 5 - Electricity Requirements

Block Name	Electricity(MW)
COMP-101	131.81
COMP-102	109.89
COMP-201	533.96
PUMP-101	0.018
PUMP-201	0.88
PUMP-202	0.33
PUMP-301	0.136
MEA-101	20.35
TURB-201	-14.96
Total	**782.30**

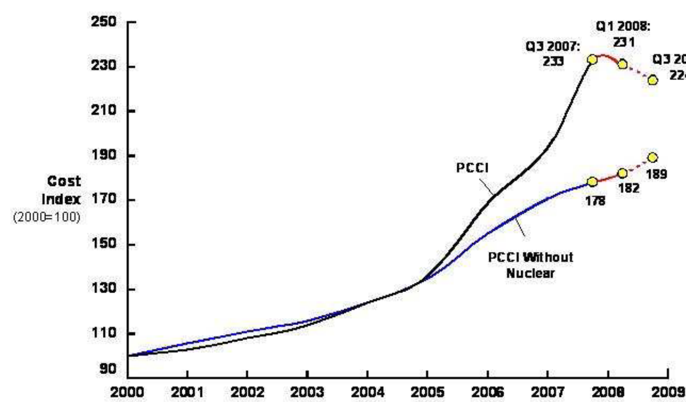


Figure 16 - Power Capital Cost Index

Capital costs for such a plant range from $500/kW to $1500/kW depending on numerous factors. At the low end of this range, a May 2007 NETL (DOE) model put the cost of a 560MW plant at $311MM, or $555/kW. In March of 2009, Idaho Power Company announced their Langley Gulch NGCC plant would cost $427MM and would be capable of producing 300MW. A 2008 comparison done by PJM put the capital cost of a NGCC plant at between $987/kW and $1131/kW in its region. The Northwest Power Planning Council estimated the cost in 2002 of an NGCC plant at $621/MW. The wide variance in costs can be attributed to geographic location, financing assumptions, capacity factor assumptions and other factors. Unfortunately, over the past five years, the cost of construction for power plants has escalated greatly. The PCCI or Power Capital Cost Index tracked by CERA (Cambridge Energy Research Associates) for 2008 can be found in Figure 17. In summer of 2008, FERC released a report estimating capital costs for new plants of various types. This information can be found in Figure 17.

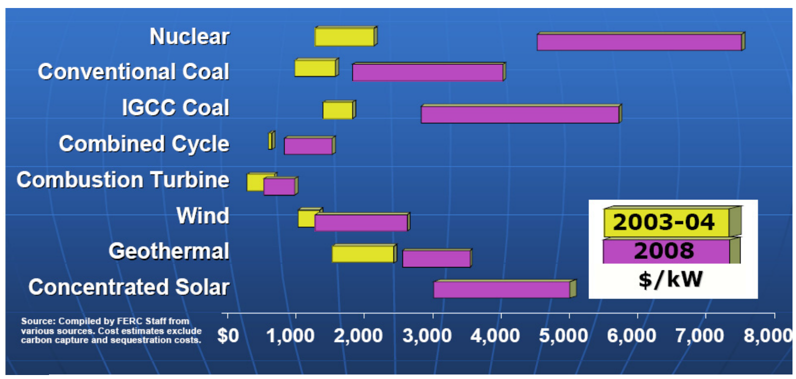


Figure 17 - FERC Estimated Cost of New Generation (June)

For the purposes of the proposed project, the capital cost for a new NGCC plant in Alaska has been estimated to be $1500/kW. This would yield a total capital cost of $1200MM to $1500MM depending on the final capacity. This estimate is based on escalating capital costs and an increased site factor for Alaska, including strict environmental regulations, harsh climate conditions and remoteness of location. Construction would begin in 2010, with completion scheduled for 2012.

Section 12 - Alternative Process Sequences

Alternative Process Sequences

There were many potential process sequences considered before arriving upon the final process design, mostly due to variations in the separation processes. Stream compositions at crucial points in the process are shown in Section 7. In an initial survey of the capital cost investments, the MEA and COPure separations seem costly. However, after further analysis, these separations have proven to be important if not crucial to the operation of the plant.

The MEA separation unit's current location in the sequence is ideal for several reasons. This separation removes CO_2 from the SMR products. The removal of 80% of the CO_2 from stream S-102 provides a decrease in capital cost for the numerous downstream process operations. More importantly, its recycle provides a source of carbon dioxide for the SMR, and a 10.9% dry basis volume of CO_2, as specified by the Nextant Technical Report. Furthermore, separation of CO_2 and C_2H_6 is difficult, as it often requires a liquid-liquid extraction. This makes placement of the MEA separation unit before the Fischer-Tropsch reaction important. The Velocys patent also specifies that CO_2 should be removed before the FT reactor. Additionally, the extra CO_2 that is produced can be sold to outside companies for various uses, the most relevant of which in Northern Alaska is supercritical CO_2 use in enhanced oil recovery (Austell 1).

Another possible source for carbon dioxide is stream S-106. However, placing the MEA system to separate this stream is not a good alternative. Stream S-106 is nearly equivalent in volume to S-103, but its CO_2 content is much lower. S-106 is also contaminated with inerts from the air inlet to SMR-101 on the combustion side of the microchannel. These inerts would require more separation equipment, and if allowed to circulate with the CO_2 would greatly increase downstream equipment size and price. Therefore, the separation of CO_2 in S-106 is not a good alternative.

MEA was chosen as the best CO_2 separation system because it has been extensively researched and has performed reliably for over 60 years. This is especially important in the harsh operating conditions in Alaska. It also provides high CO_2 recovery and purity potential, up to 95% depending on the amount of solvent circulated and operating conditions. It has significant disadvantages in that it may increase the footprint of the Alaskan plant by as much as

60% because it is very energy and equipment intensive. Amine degradation concerns are eased because the feed does not contain acids, nitrogen, or sulfur.

The best alternative separation method is membrane technology. This provides lower energy and equipment, and a competitive cost separation at the expense of CO_2 purity. While this option is extremely promising and has made rapid progress against MEA separation, large-scale operation is not yet being performed. Patents are pending, and this should be looked into again in a few years (Yang, et al.). Thus, although the MEA separation cost is $967 million and 33.7% of the total equipment cost, it is worth the investment.

The COPure separation unit's placement after S-304 is ideal for many reasons. The Nextant Technical Report specifies that the best feed for the Fischer-Tropsch microchannel reactor contains a H_2 to CO ratio of 2.1:1. The SMR produces a ratio of 2.99, which would lead to non-ideal FT conditions and decreased production of pipeline quality hydrocarbons. This leads to two options: H_2 removal from the effluent of the SMR, or CO recycle from the FTR product stream to its inlet stream.

The first option involves adding a H_2 separation unit before FTR-201 and is unfavorable for several reasons. Hydrogen separation from a gaseous stream is as difficult as a CO separation, and the resulting cost would be comparable to the COPure separation. More importantly, the H_2 separation would result in the lower limit of production capacity. Thus, CO separation and recycle allows maximum carbon monoxide usage to achieve the highest possible feed with produced materials, whereas H_2 removal results in wasting produced materials, as CO is the limiting reactant. When these two options were compared, an 18% increase in total sellable product resulted from former option. For the similarly priced H_2 and CO separations, it is apparent that CO recycle is best.

For CO separation, CO Pure technology provides the most reliable method of separating CO. High yields result (typical recovery is 98%, purity is 100%), no separation from H_2, N_2, CO_2, or CH_4 is required, no temperature or pressure extremes are required, and the solvent is non-corrosive and has a high absorption capacity. However, it is equipment intensive, requiring feed pre-treatment and regulation of potential tar buildup due to the presence of trace heavier hydrocarbons in the feed. It is an improvement over the alternative COSORB technology, which also uses copper salts. COPure copper salts do not degrade; there is indirect cooling and heating, a solid management system, a self-cleaning re-boiler, and seal-less pumps. All other processes require harsh chemicals, and high temperatures/pressures. This would demand even more equipment and energy intensive processes. The only other potential competitor is the emerging technology of membranes, which are cheaper and more cost efficient. However, their use has only been proven on small to moderate-scale plants, and they only achieve approximately 70% purity (Dutta, Paul). Membranes should be considered again in the future. Thus, the COPure process technology is the most suitable CO separation unit, in spite of its large capital cost of $1.48 billion, or 52% of the total equipment cost.

Section 13 - Fixed Capital Investment Summary

Fixed Capital Investment Summary

The total permanent investment (TPI) of $6.86B was calculated using the profitability analysis spreadsheet v2.0 provided by *Seider et al.* The total permanent investment is equal to the total capital investment minus the working capital. A breakdown of the components of Total Capital Investment is shown in Table 16.9 of *Seider et al*. Some important alterations were made to this spreadsheet in order to account for circumstances unique to this project.

The years of construction was assumed to be three due to the nature and scope of the project and limited yearly period suitable for construction in Alaska's cold climate.

A site factor of 1.4 was chosen due to the remoteness of the North Slope and extreme conditions. The site factor is based on costs in the US Gulf Coast, which has a site factor of 1.0. For comparison purposes, the US West Coast has the highest site factor, which is 1.25. The biggest contributor to an increased site factor is the extra cost associated with equipment design, transportation and installation, which quickly add up in Alaska. For instance, to prevent the cooling water streams from freezing, they must be jacketed with either steam or thermal electrical resistance. Additionally, the ground may have to be insulated from the plant to prevent the permafrost from melting. Other factors such as earthquake codes and additional environmental concerns also add to the cost. Thus a 1.4 site factor proves quite reasonable.

Additionally, certain other TPI costs were escalated. The cost of site preparation and startup were both adjusted. The cost of site preparation was escalated from 5% to 15% of total bare module costs to account for the difficulty and expense of transporting heavy construction equipment to the North Slope and the extra costs of construction of a grass-roots plant in an extraordinarily cold climate (Seider 2005). The cost of startup was adjusted from 10% to 15% of total depreciable capital to account for increased difficulty, and labor costs (Seider 2005).

On the contrary, land costs in Alaska are comparatively low and the cost of land was assumed to be just 1.0% of total depreciable capital. The cost of royalties was purposefully excluded here and the cost associated with potential royalties was rolled into annual licensing fees. Discussion of these annual licensing fees is included in the section on costs.

For cash flow purposes, the total depreciable capital expenditure was distributed evenly over the three years of construction. Total depreciable capital is equal to the TPI minus the cost of land, royalties and startup. The cost of land was included in the first year of construction while the cost of startup was included in the last year of construction.

A summary of the fixed capital investment components is shown in Table 6.

Table 6- Investment Summary

Alaskan Natural Gas to Liquids Using Microchannel Reactor

Bare Module Costs			
Fabricated Equipment			
SMR101		$84,877,200	
HX-101		$1,884,900	
HX-102		$408,700	
HX-201		$74,196,000	
AIRCOOLER-101		$18,598,100	
AIRCOOLER-201		$22,254,500	
MEA-101		$967,315,800	
FTR-201		$4,101,000	
TURB-201		$2,155,100	
FLASH-301		$88,606,200	
COPure-301		$1,496,470,800	
DEC-301		$5,463,200	
	Total Fabricated Equipment:	**$2,766,331,500**	
Process Machinery			
COMP-101		$28,612,800	
COMP-102		$26,650,800	
COMP-201		$49,050,600	
PUMP-201		$580,800	
PUMP-202		$229,400	
PUMP-101		$56,400	
	Total Process Machinery:	**$105,180,800**	
Catalysts			
SMR101 Catalyst		$5,000	
FTR-201 Reform Catalyst		$5,000	
FTR-201 Combustion Catalyst		$5,000	
	Total Catalysts:	**$15,000**	
		Total Bare Module Costs:	**$3,950,691,500**
Direct Permanent Investment			
Cost of Site Preparation:		$ 200,645,000	
Cost of Service Facilities:		$66,881,700	
Allocated Costs for Utility Plants and Related Facilities:		$1,500,000,000	

	Direct Permanent Investment:	**$5,718,218,200**
Total Depreciable Capital		
Cost of Contingencies and Contractor Fees:	$558,928,900	
	Total Depreciable Capital:	**$6,277,147,100**
Total Permanent Investment		
Cost of Land:	$36,640,900	
Cost of Royalties:	$0	
Cost of Plant Start-Up:	$549,613,400	
	Total Permanent Investment:	**$6,863,401,400**
Working Capital		
Accounts Receivable:	$242,918,200	
Cash Reserves:	$76,883,900	
Accounts Payable:	$ (8,387,000)	
Inventory		
Total Inventory:	**$0**	
Total Working Capital:		**$311,415,100**
TOTAL CAPITAL INVESTMENT		**$7,174,816,500**

Section 14 - Operating Cost and Economic Analysis

Operating Cost and Economic Analysis

14.1 Fixed Costs

The total annual fixed costs are $572MM (in year 1) and include operations, maintenance, overhead, property insurance and taxes, and annual licensing fees. Fixed costs escalate at the rate of inflation, 2.4% per year. Some important assumptions were made in the calculation of the fixed costs.

Twenty operators per shift were assumed based on information provided by Mr. David M. Kolesar and the rules of thumb provided by *Seider (2005)*. Operations wages were increased by 50% over Gulf Coast baseline salaries to account for the difficulty of attracting and keeping a talented labor force in northern Alaska.

Maintenance wages and benefits were increased from 3.5% to 4.75% of total depreciable capital (TDC). Property taxes and insurance was reduced from 2.0% of TDC to 1.0% of TDC to reflect the lower property tax rates in the state of Alaska (Seider 2005).

All other cost assumptions remained as described in *Seider's et al.* profitability analysis 2.0 and Chapter 17 (Seider). A summary of the fixed costs is shown in Table 7.

Table 7 - Fixed Cost Summary

Alaskan Natural Gas to Liquids Using Microchannel Reactor

Operations			
	Direct Wages and Benefits:	$39,312,000	
	Direct Salaries and Benefits:	$5,896,800	
	Operating Supplies and Services:	$2,358,720	
	Technical Assistance to Manufacturing:	$1,300,000	
	Control Laboratory:	$1,400,000	
	Total Operations:	**$50,267,520**	**$50,267,520**
Maintenance			
	Wages and Benefits:	$174,044,234	
	Salaries and Benefits:	$43,511,058	
	Materials and Services:	$174,044,234	
	Maintenance Overhead:	$8,702,212	
	Total Maintenance:	**$400,301,738**	**$450,569,258**
Operating Overhead			
	General Plant Overhead:	$18,656,251	
	Mechanical Department Services:	$6,306,338	
	Employee Relations Department:	$15,503,081	
	Business Services:	$19,444,543	
	Total Operating Overhead:	**$59,910,213**	**$510,479,471**
Property Insurance and Taxes			
-	Property Insurance and Taxes:	$36,640,891	
	Total Property Insurance and Taxes:	**$36,640,891**	**$547,120,362**
Other Annual Expenses			
-	Annual Licensing Fees:	$25,000,000	
Total Other Annual Expenses:		**$25,000,000**	**$572,120,362**
TOTAL			**$572,120,362**

14.2 Variable Costs

Variable costs are divided into two categories – variable costs that are based production level and variable costs that are based on the quantity of sales. If the plant were to run at 100% capacity, the total non-sales, or production-based, variable costs would be $106MM per year. For purposes of cash flows, the variable cost is the product of $106MM and the percent design capacity the plant is operating at in that year. The costs are escalated annually at the rate of inflation. These costs include utilities and raw materials for the production process. The MEA system solvents and reactants were calculated to cost $0.31 per barrel of GTL products produced while the COPure system solvents and reactants were calculated to cost $0.44 per barrel of GTL products produced. Details of these calculations can be found in the Appendix on page B6. Utility costs (process water and cooling water) were calculated using the inflation adjusted dollar values given in Table 17.1 of *Seider (2005)* multiplied by the amount of utility required as calculated using ASPEN PLUS. Finally, the natural gas will be supplied at a price of $0.80MCF, according to Energy Information Administration Report #SR-OIAF/2002-02. This price is justified based on the fact that the gas on the North Slope is stranded from market and is currently being compressed and sent back underground or otherwise being flared and thus has comparatively minimal current market value. The amount of natural gas required for the process was calculated using ASPEN PLUS, while the amount required for the natural gas combined cycle (NGCC) plant was calculated using a lower heating value of 50,100 kJ/kg. The NGCC plant has a capacity of 1000MW. It was assumed that the composition of the natural gas was 100% methane as the gas has already been processed by third parties.

The sales-based variable costs include selling/transfer expenses, direct research, allocated research, administrative expense and management incentive compensation. These costs were also adjusted as appropriate to this particular project. The selling/transfer expenses were reduced from 3% to 0.25% of sales since there is a ready market at the end of the Trans-Alaskan Pipeline (TAPS) for petroleum products and little expense would be associated with tapping that market. Direct research was set at 1.0% of sales (versus 4.8% as given by *Seider et al.*) to reflect low costs associated with quality control and minimal need for additional research. Allocated research would be covered by the parent company and was thus set to 0%. Other expense ratios remain as given by *Seider et al.* The sales-based variable costs total 4.5% of sales. In addition to these standard costs, the plant is charged a fee to pump its product through the TAPS oil pipeline. This tariff is $4.87 as of January 1, 2008, as reported by FERC (Federal Energy Regulation Commission). These sales-based costs are separated in the cash flow sheet for clarity. A summary of all the variable costs is shown in Table 8, except for the pipeline tariff.

Table 8 - Variable Cost Summary

Alaskan Natural Gas to Liquids Using Microchannel Reactor

Raw Materials				
	Process Natural Gas	$0.0225 per bbl of GTL Product	$925,100	
	Air	$0 per bbl of GTL Product	$0	
	MEA Solvents and Reactants	$0.3100 per bbl of GTL Product	$12,759,500	
	CO Separation Solvents and Reactants	$0.4400 per bbl of GTL Product	$18,110,200	
	Power Plant Feed Gas	$1.3304 per bbl of GTL Product	$66,053,000	
	Total Raw Materials:	**$2.1029 per bbl of GTL Product**	$97,847,800	**$97,847,800**
Utilities				
	Process Water	$0.1870 per bbl of GTL Product	$7,697,700	
	Cooling Water	$1.3066E-05 per bbl of GTL Product	$500	
	Natural Gas	$6.5968E-04 per bbl of GTL Product	$27,200	
	Total Utilities:	**$0.1877 per bbl of GTL Product**	$7,725,400.00	**$105,573,200**
General Expenses				
	Selling / Transfer:	0.25% of Sales		
	Direct Research:	1.00% of Sales		
	Allocated Research:	0.0% of Sales		
	Administrative Expense:	2.00% of Sales		
	Management Incentives:	1.25% of Sales		
	Total General Expenses:	**4.5% of Sales**		
TOTAL		**$2.2906 per bbl of GTL Product**		**$105,573,200**

14.3 Taxes

The tax situation of an oil and gas operation in Alaska is quite complicated. State taxable income is equal to sales minus costs minus depreciation. Alaska imposes a 9.4% corporate income tax. For oil and gas operation, Alaska also imposes a windfall profit tax. This tax is equal to 25% plus an escalation factor. The escalation only applies if the price of oil is above

$52 per barrel. The escalated tax rate is calculated by subtracting $52 from the market price of oil and multiplying this number by 0.10%. This result is then added to the 25% base rate. For example, if the price of oil is $102 per barrel, the escalation factor is equal to $50 x 0.10%, or 5.0%, for a total windfall tax rate of 30%. Total state taxes are then calculated by multiplying the state taxable income by the sum of the windfall tax rate and 9.4%.

Furthermore, the US federal government levies a corporate tax rate of 35% on taxable income above $18MM per year. However, state tax is deductible.

The effective tax rate was calculated on the cash flow sheet for informational purposes and was obtained by dividing the total income tax (the sum of all Alaskan and federal income taxes) by the state taxable income (equivalent to pretax earnings). The effective tax rate in the first year of production (Year 5) is equal to 60.46% with an oil price of $99.75 for the base case. The highest effective tax rate (62.88%) occurs in the final year of production and coincides with the highest price of oil ($136.93).

14.4 Sales

In order to estimate sales, a price per barrel of oil must be assumed. For the base case, the Energy Information Administration Annual Energy Outlook 2009 market price projections to 2030 were used. The prices quoted are the weighted average price of delivery to US refiners. These projections are included in the cash flow sheets. Since plant life extends beyond 2030, to 2037, additional price projection was required. The average yearly projected increase in crude price from 2025 to 2030 was used to project prices to 2037. It was felt that this gave a more accurate projection than using an average increase from the entire time period (2009 – 2037). This increase was 1.36%. Sensitivity analysis is discussed under the summary section by the same name.

14.5 Working Capital

Working capital is equal to accounts receivable minus accounts payable plus cash reserves. Since all product is immediately transported to the TAPS pipeline as it is produced, inventory does not factor into working capital. Accounts payable is assumed to be 30 days of the cost feedstock (raw materials and utilities) and accounts receivable is assumed to be 30 days of sales. Cash reserves are equal to 30 days of the cost of manufacture (raw materials, utilities, operations, maintenance, overhead, property taxes and insurance). As production increases to from 45% to 67.5% to 90% in years 5, 6 and 7 respectively, working capital will necessarily increase.

14.6 Overall Feasibility Summary

A discount rate of 13% was applied to the project to strike a balance between a typical discount rate of 15% and typical utility discount rate of approximately 10%. The project presents less risk than a typical project due to likely securitization of capital by the state and federal governments. Under this scenario, the project yields a positive NPV of $708MM after 25 years. The investor's rate of return or IRR, based on annual cash flow, is equal to 14.96%. The breakeven point (i.e. payback period) occurs in year 19 (equal to year 15 of production). A summary of the cash flows is shown in Table 9.

Table 9 - Cash Flow Summary

Alaskan Natural Gas to Liquids Using Microchannel Reactor

Year	% of Design Capacity	EIA Base Case AEO2009	Sales	Capital Costs	Working Capital	Total Variable Costs	Fixed Costs	Depreciation Allowance	Total Income Tax	Effect-ive Tax Rate	Net Earnings	Annual Cash Flow
2009	0.0%	$59	Design	$0	$0	$0	$0	$0	$0	0%	$0	$0
2010	0.0%	$78	Construction	($2,129,023,267)	$0	$0	$0	$0	$0	0%	($2,092,382,367)	($1,638,642,311)
2011	0.0%	$86	Construction	($2,092,382,367)	$0	$0	$0	$0	$0	0%	($2,092,382,367)	($3,088,768,250)
2012	0.0%	$95	Construction	($2,092,382,367)	($68,496,900)	$0	$0	$0	$0	0%	($2,160,879,267)	($4,414,075,972)
2013	45.0%	$100	$1,847,618,227	($549,613,400)	($153,906,598)	($225,579,726)	($629,052,991)	$766,448,446	$136,973,317	60.46%	$152,492,196	($4,331,309,318)
2014	67.5%	$105	$2,916,185,265	$0	($89,011,634)	($346,764,174)	($644,150,262)	$1,226,317,514	$424,982,129	60.80%	$1,411,277,064	($3,653,446,796)
2015	90.0%	$109	$4,020,164,275	$0	($91,961,452)	($470,855,990)	($659,609,869)	$735,790,509	$1,314,618,783	61.03%	$1,483,118,182	($3,023,031,627)
2016	90.0%	$110	$4,066,132,280	$0	$0	($475,553,650)	($675,440,505)	$441,474,305	$1,511,774,238	61.11%	$1,403,363,886	($2,495,142,462)
2017	90.0%	$111	$4,101,935,542	$0	$0	($479,856,996)	($691,651,078)	$441,474,305	$1,522,681,934	61.18%	$1,407,745,535	($2,026,525,324)
2018	90.0%	$112	$4,133,201,043	$0	$0	($484,020,755)	($708,250,703)	$220,737,153	$1,665,640,907	61.23%	$1,275,288,677	($1,650,840,139)
2019	90.0%	$113	$4,167,510,936	$0	$0	($488,387,675)	($725,248,720)	$0	$1,810,508,548	61.29%	$1,143,365,993	($1,352,767,308)
2020	90.0%	$112	$4,150,630,556	$0	$0	($490,518,785)	($742,654,690)	$0	$1,787,323,172	61.26%	$1,130,133,910	($1,092,038,761)
2021	90.0%	$112	$4,160,972,219	$0	$0	($493,944,264)	($760,478,402)	$0	$1,781,168,321	61.28%	$1,125,381,233	($862,275,861)
2022	90.0%	$114	$4,226,380,019	$0	$0	($499,918,761)	($778,729,884)	$0	$1,809,788,147	61.40%	$1,137,943,228	($656,676,204)
2023	90.0%	$113	$4,184,653,024	$0	$0	($501,144,940)	($797,419,401)	$0	$1,769,828,892	61.32%	$1,116,259,791	($478,196,585)
2024	90.0%	$114	$4,224,133,466	$0	$0	($506,099,947)	($816,557,467)	$0	$1,781,274,869	61.39%	$1,120,201,183	($319,692,328)
2025	90.0%	$115	$4,272,118,536	$0	$0	($511,513,944)	($836,154,846)	$0	$1,797,841,233	61.48%	$1,126,608,513	($178,620,761)
2026	90.0%	$116	$4,315,067,584	$0	$0	($516,779,432)	($856,222,562)	$0	$1,810,887,989	61.55%	$1,131,177,601	($53,272,356)
2027	90.0%	$119	$4,395,257,587	$0	$0	($523,800,750)	($876,771,904)	$0	$1,847,489,796	61.69%	$1,147,195,138	$59,226,180
2028	90.0%	$121	$4,471,375,871	$0	$0	($530,720,746)	($897,814,429)	$0	$1,881,262,317	61.83%	$1,161,578,378	$160,030,618
2029	90.0%	$122	$4,518,079,255	$0	$0	($536,400,945)	($919,361,976)	$0	$1,895,812,858	61.91%	$1,166,503,476	$249,616,324
2030	90.0%	$125	$4,615,813,515	$0	$0	($544,463,418)	($941,426,663)	$0	$1,943,034,525	62.08%	$1,186,888,909	$330,281,171
2031	90.0%	$126	$4,678,432,683	$0	$0	($551,033,658)	($964,020,903)	$0	$1,967,278,783	62.19%	$1,196,099,339	$402,219,948
2032	90.0%	$128	$4,741,901,356	$0	$0	($557,732,183)	($987,157,405)	$0	$1,991,755,704	62.30%	$1,205,256,065	$466,369,952
2033	90.0%	$130	$4,806,231,060	$0	$0	($564,561,672)	($1,010,849,182)	$0	$2,016,465,441	62.41%	$1,214,354,765	$523,568,432
2034	90.0%	$132	$4,871,433,476	$0	$0	($571,524,866)	($1,035,109,563)	$0	$2,041,408,046	62.53%	$1,223,391,002	$574,563,216
2035	90.0%	$133	$4,937,520,441	$0	$0	($578,624,562)	($1,059,952,192)	$0	$2,066,583,464	62.64%	$1,232,360,224	$620,022,197
2036	90.0%	$135	$5,004,503,958	$0	$0	($585,863,622)	($1,085,391,045)	$0	$2,091,991,529	62.76%	$1,241,257,763	$660,541,835
2037	90.0%	$137	$5,072,396,188	$0	$403,376,584	($593,244,969)	($1,111,440,430)	$0	$2,117,631,959	62.88%	$1,653,455,414	$708,307,698
									Net Present Value at 13.0%			**$708,307,698**

14.7 Sensitivity Analysis

14.7.1 Market price of oil

The project economics are most sensitive to the price of oil, which affects sales revenue, and to the initial capital expenditure. Sensitivities were completed for both low and high cases for each condition.

For the price of oil, the Energy Information Administration's (EIA) Annual Energy Outlook 2009 was again used. In addition to the base case already discussed, the EIA publishes a low and a high case for the price of crude to 2030. Projections to 2037 (Year 29) were estimated using the same method as previously described in the base case. For the low case, the EIA estimates the price of crude to decrease to between $46 and $47 per barrel by 2015 and hover at those levels for the duration of the projection. For the project, this resulted in an IRR of 0.11% and an NPV of negative $2.80B, using the discount rate of 13%. On the contrary, in the high price case, the EIA projects the price reaching $154 per barrel by 2015 (Year 6) and approaching nearly $200 by 2030 (Year 29). This results in an NPV for the project of $3.23B and an IRR of 20.69%. As can be seen, by this analysis, summarized in Table 10, the risk to the favorability of the project due to the price of oil is enormous. For this reason, long term contracts or hedging may be appropriate to mitigate some of this risk.

Table 10 - Sensitivity of project feasibility to fluctuation in oil price

	IRR	NPV
EIA Low Price Case	0.11%	-$2,847,428,292
EIA Base Case	14.96%	$708,307,698
EIA High Price Case	20.69%	$3,228,804,759

Finally, a minimum price of oil was determined that would give the project an NPV of $0 at a discount rate of 13% and an IRR of 13%. This was accomplished by assuming a baseline crude price for 2009 (Year 1) and escalating this price at 1.0%. This minimum price is $87.73 per barrel (for 2009, Year 1). It is also worth noting that the price in the first year of production is $91 (in 2013, Year 5) in the breakeven case, while in the EIA base case, it was just under $100. A comparison of the breakeven prices and the EIA base case prices is shown in Table 11.

Table 11 - Breakeven market price of oil and corresponding EIA base case price projections					
Year	EIA Base Case AEO2009	Breakeven Case	Year	EIA Base Case AEO2009	Breakeven Case
2009	$58.61	$87.73	2024	$114.03	$101.85
2010	$77.56	$88.61	2025	$115.33	$102.87
2011	$85.58	$89.49	2026	$116.49	$103.90
2012	$94.84	$90.39	2027	$118.65	$104.94
2013	$99.75	$91.29	2028	$120.71	$105.99
2014	$104.96	$92.20	2029	$121.97	$107.05
2015	$108.52	$93.13	2030	$124.60	$108.12
2016	$109.77	$94.06	2031	$126.30	$109.20
2017	$110.73	$95.00	2032	$128.01	$110.29
2018	$111.58	$95.95	2033	$129.74	$111.39
2019	$112.50	$96.91	2034	$131.51	$112.51
2020	$112.05	$97.88	2035	$133.29	$113.63
2021	$112.33	$98.86	2036	$135.10	$114.77
2022	$114.09	$99.84	2037	$136.93	$115.92
2023	$112.97	$100.84			

14.7.2 Total Depreciable Capital and Reactor Costs

Sensitivity analysis was additionally conducted on the total depreciable capital, since a significant level of estimation was employed in calculating its components. The TDC was varied over a very large range, from $4.3 billion to $10 billion. These limits were approximated as the minimum and maximum foreseeable deviation from the current estimate of $6.28 billion; a major driver of the variation was the uncertainty about the costs of the microchannel reactors and power plant. The results of the analysis are shown in Table 12.

The results show that if significant changes occur in the value of the total depreciable capital, the NPV of the project can vary dramatically swing from positive to negative. If TDC rises above $7.6 billion, the IRR drops below 13%, the break-even point. While the range of values studied is very large, it must be stressed that such large uncertainty is not unlikely,

Table 12 - Sensitivity of project feasibility to the Total Depreciable Capital

TDC	IRR
$ 10,000,000,000	9.34%
$ 9,700,000,000	9.67%
$ 9,400,000,000	10.01%
$ 9,100,000,000	10.37%
$ 8,800,000,000	10.75%
$ 8,500,000,000	11.15%
$ 8,200,000,000	11.57%
$ 7,900,000,000	12.02%
$ 7,600,000,000	12.49%
$ 7,300,000,000	12.99%
$ 7,000,000,000	13.52%
$ 6,700,000,000	14.09%
$ 6,400,000,000	14.70%
$ 6,100,000,000	15.35%
$ 5,800,000,000	16.05%
$ 5,500,000,000	16.82%
$ 5,200,000,000	17.60%
$ 4,900,000,000	18.50%
$ 4,600,000,000	19.49%
$ 4,300,000,000	20.57%

particularly because microchannel reactors are not being sold commercially, and costing information is difficult to obtain at the time of writing. To further explore the effect of reactor price uncertainty on the project's feasibility, a two-variable analysis was conducted. The prices of SMR-101 and FTR-101 were simultaneously increased up to $2 billion per reactor system; the results are shown in Table 13. The table very clearly shows that the project is feasible as long as the combination of FTR-101 and SMR-101 prices does not lie in the red region above the dark line. Therefore, once more accurate pricing information is available; all other factors remaining the same, Table 5 should be consulted for the combination of reactor costs.

14.7.1 Fixed Costs, Variable Costs and Utility Costs

Sensitivity analyses were conducted by changing fixed costs, variable costs and utility costs by -50% to +100% of their currently estimated values. As shown in Table 14, Table 15 and Table 16, large variations in these costs do not have a significant impact on the IRR of the project, since these costs are insignificant compared to the annual sales and fixed capital investment.

Table 13 - Sensitivity of project feasibility to bare module costs of SMR-101 and FTR-101

		FTR-101 Bare Module Cost								
	IRR	$2,000MM	$1,750MM	$1,500MM	$1,250MM	$1,000MM	$743MM	$500MM	$250MM	$50MM
SMR-101 Bare Module Cost	$2,000MM	10.36%	10.68%	11.01%	11.35%	11.71%	12.09%	12.48%	12.89%	13.24%
	$1,500MM	11.01%	11.35%	11.71%	12.08%	12.48%	12.90%	13.32%	13.78%	14.17%
	$1,250MM	11.35%	11.71%	12.08%	12.48%	12.89%	13.34%	13.78%	14.27%	14.68%
	$1,000MM	11.71%	12.08%	12.48%	12.89%	13.32%	13.80%	14.27%	14.78%	15.22%
	$750MM	12.08%	12.48%	12.89%	13.32%	13.78%	14.28%	14.78%	15.33%	15.79%
	$425MM	12.60%	13.02%	13.46%	13.93%	14.42%	14.96%	15.50%	16.09%	16.60%
	$250MM	12.89%	13.32%	13.78%	14.27%	14.78%	15.35%	15.91%	16.53%	17.06%
	$50MM	13.24%	13.69%	14.17%	14.68%	15.22%	15.81%	16.40%	17.06%	17.62%

Table 14 - Sensitivity of project feasibility to the fixed cost

Fixed Cost	IRR
$1,143,939,300	11.25%
$1,000,946,888	12.24%
$857,954,475	13.19%
$714,962,063	14.09%
$571,969,650	14.96%
$428,977,238	15.80%
$285,984,825	16.62%

Table 15 - Sensitivity of project to non-sales based variable cost

Non-sales based variable cost	IRR
$ 211,146,400	14.43%
$ 184,753,100	14.57%
$ 158,359,800	14.70%
$ 131,966,500	14.83%
$ 105,573,200	14.96%
$ 79,179,900	15.09%
$ 52,786,600	15.22%

Table 16 - Sensitivity of project feasibility to utilities cost

Utilities	IRR
$15,450,800	14.92%
$13,519,450	14.93%
$11,588,100	14.94%
$9,656,750	14.95%
$7,725,400	14.96%
$5,794,050	14.97%
$3,862,700	14.98%

14.7.2 Discount Rate

Sensitivity analysis was also conducted was on the discount rate. The choice of discount rate very dramatically affects the feasibility of the project, as shown in Table 17. By convention, a discount rate of 15% is used to calculate NPV, for which the project looks unfavorable with an NPV of -$12 million. Of course, at an IRR of 14.96%, the NPV would be zero. The discount rate depends on the capital structure of the firm undertaking the project as well as the securitization of capital from the state or federal government.

Table 17 - Sensitivity of the project feasibility to the discount rate

Discount rate	NPV
11%	$1,713,933,700
13%	$708,307,700
15%	($12,454,400)
17%	($532,843,500)
19%	($910,007,500)
21%	($1,183,292,200)
23%	($1,380,248,200)

14.8 Conclusion

As previously noted, the economics of this project depend heavily on the price of oil and the CAPEX. Whether the project makes economic sense depends on what one believes about the price of oil. Ultimately, the price of oil needs to be at least $91 by the first year of production (Year 5) and increase by at least an average of 1.0% per year (assuming a discount rate of 13%, 2.4% inflation, etc). Uncertainty around the CAPEX also needs to be addressed in order to obtain more rigorous economic analysis results. The greatest source of uncertainty in CAPEX is from reactor costs, and it has been shown that a large enough deviation in the reactor cost could turn the project NPV negative. Once more information is available on the cost of microchannel reactors, the project should carefully be reconsidered in terms of the sensitivity table discussed above. Other drivers of CAPEX are the NGCC power plant, MEA separation system and COPure separation system at $1.5B, $1.5B and $1.0B, respectively. If any of these costs could be reduced, the project would become more favorable. If any of the capital costs increase, the price of oil necessary to support the project would increase.

14.9 Comparison to the Alaska Natural Gas Pipeline as an alternative

The leading competitive solution to stranded natural gas in the North Slope is the construction of a natural gas pipeline from Prudhoe Bay, Alaska to Alberta, Canada. Once delivered in Alberta, the natural gas will be able to enter the existing gas transportation infrastructure for distribution in North America.

Multiple proposals for the pipeline have been presented, but TransCanada Corp.'s proposal holds the most promise; the company was awarded a license by the Alaska Legislature in August, 2008. On-site construction will commence in April, 2016 for start of service in September, 2018. The pipeline is expected to have a capital cost of $26 billion and will be built to transport up to 4.5 billion cubic feet of natural gas per day. Alternative designs by TransCanada are still under consideration for capacities of 5.1 billion and 5.9 billion cubic feet per day.

Due to the high construction cost of the pipeline and the cost of maintaining the gas at high pressure, the natural gas pipeline must charge higher tariffs than the TAPS. Therefore, in analyzing the pipeline's future cash flows, it was assumed that a tariff of 75% of the market price of natural gas would be charged to customers wishing to utilize the pipeline to transport natural gas. The tariff is expected to decrease in the future, as capital costs are recovered.

The cash flow projections for the natural gas pipeline are shown in Table 18. Assumptions used to make these projections are explained in detail in Appendix E. While cash flows from operations are substantially positive, the enormous capital investment required in the development and construction phase drives down the internal rate of return on the project. Analysis reveals that the IRR of the pipeline project is 11.16%. Based on this information, constructing a GTL plant (IRR = 14.96%) is a somewhat more attractive alternative than building a natural gas pipeline. Moreover, the proposed GTL plant can be in service as early as

2013, almost six years before the pipeline is complete, bringing the North Slope gas reserves to market sooner.

On the other hand, due consideration must be given to the risk profile of the GTL plant versus the natural gas pipeline. The GTL plant discussed in this report utilizes novel technology, which may not meet performance targets and may experience unforeseen problems in implementation. Moreover, the natural gas pipeline has received considerable support from the government, potentially making it easier to finance than the GTL plant. One potentially significant concern in the construction of a GTL plant is a carbon emissions tax; while Alaska currently enjoys free carbon emissions, this could change in coming years. The issue of carbon emissions may be less substantial for the pipeline project.

To account for the difference in risk profiles, a hurdle rate of 10% could be postulated for the gas pipeline and 13% for the GTL plant. Comparing the IRR of each project to the corresponding hurdle rate, both projects are only marginally profitable. Therefore, the ultimate decision of which method to use to bring Alaskan natural gas to the North American market depends on the investor’s appetite for risk and the cost of financing for each project.

Table 18 - Cash Flow Projections for the Alaska Natural Gas Pipeline Project

Year	Load Factor	Average Lower 48 Wellhead Price ($/Mcf)	Annual Revenue	Depreciation Allowance	Operations and Maintenance (37% of revenue)	Tax (State and Federal)	Net Earnings	Cash Flow
2009		$5.7373	Development & Construction					($42,000,000)
2010		$6.0458						($75,000,000)
2011		$6.0099						($139,000,000)
2012		$6.1343						($138,000,000)
2013		$6.1371						($139,000,000)
2014		$6.1987						($413,000,000)
2015		$6.2711						($3,502,000,000)
2016		$6.3728						($5,937,000,000)
2017		$6.5191						($10,006,000,000)
2018		$6.7001						($6,025,000,000)
2019		$6.8684						($71,000,000)
2020	85%	$6.7480	$7,065,831,716	$5,297,400,000	$2,631,832,372	-	($863,400,656)	$4,433,999,344
2021	90%	$6.5568	$7,269,464,280	$8,475,840,000	$2,707,680,029	-	($3,914,055,748)	$4,561,784,252
2022	95%	$6.6199	$7,747,108,840	$5,085,504,000	$2,885,589,787	-	($223,984,947)	$4,861,519,053
2023	95%	$6.7228	$7,867,548,671	$3,051,302,400	$2,930,450,387	$775,250,688	$1,110,545,196	$4,161,847,596
2024	95%	$7.0541	$8,255,326,767	$3,051,302,400	$3,074,887,303	$875,288,247	$1,253,848,817	$4,305,151,217
2025	95%	$7.3330	$8,581,650,857	$1,525,651,200	$3,196,434,255	$1,586,667,337	$2,272,898,066	$3,798,549,266
2026	95%	$7.6068	$8,902,050,863		$3,315,774,644	$2,296,518,154	$3,289,758,065	$3,289,758,065
2027	95%	$7.8766	$9,217,791,288		$3,433,379,465	$2,377,971,700	$3,406,440,123	$3,406,440,123
2028	95%	$8.0948	$9,473,174,800		$3,528,502,958	$2,443,854,594	$3,500,817,248	$3,500,817,248
2029	95%	$8.2527	$9,657,983,247		$3,597,339,136	$2,491,530,794	$3,569,113,317	$3,569,113,317
2030	95%	$8.4026	$9,833,355,346		$3,662,660,529	$2,536,772,639	$3,633,922,178	$3,633,922,178
2031	95%	$8.5888	$10,051,366,524		$3,743,863,832	$2,593,014,357	$3,714,488,335	$3,714,488,335
2032	95%	$8.7793	$10,274,211,136		$3,826,867,460	$2,650,502,985	$3,796,840,691	$3,796,840,691
2033	95%	$8.9739	$10,501,996,342		$3,911,711,326	$2,709,266,170	$3,881,018,846	$3,881,018,846
2034	95%	$9.1729	$10,734,831,677		$3,998,436,229	$2,769,332,169	$3,967,063,280	$3,967,063,280
2035	95%	$9.3762	$10,972,829,107		$4,087,083,874	$2,830,729,865	$4,055,015,368	$4,055,015,368
2036	95%	$9.5841	$11,216,103,078		$4,177,696,888	$2,893,488,785	$4,144,917,405	$4,144,917,405
2037	95%	$9.7966	$11,464,770,573		$4,270,318,846	$2,957,639,105	$4,236,812,622	$4,236,812,622
2038	95%	$10.013	$11,718,951,171		$4,364,994,286	$3,023,211,676	$4,330,745,210	$4,330,745,210
2039	95%	$10.236	$11,978,767,099		$4,461,768,735	$3,090,238,028	$4,426,760,337	$4,426,760,337
2040	95%	$10.463	$12,244,343,297		$4,560,688,729	$3,158,750,393	$4,524,904,175	$4,524,904,175
2041	95%	$10.695	$12,515,807,473		$4,661,801,837	$3,228,781,717	$4,625,223,919	$4,625,223,919
2042	95%	$10.932	$12,793,290,167		$4,765,156,682	$3,300,365,676	$4,727,767,810	$4,727,767,810
2043	95%	$11.174	$13,076,924,813		$4,870,802,963	$3,373,536,693	$4,832,585,158	$4,832,585,158
2044	95%	$11.422	$13,366,847,803		$4,978,791,483	$3,448,329,953	$4,939,726,367	$4,939,726,367
2045	95%	$11.675	$13,663,198,553		$5,089,174,171	$3,524,781,424	$5,049,242,959	$5,049,242,959

Section 15 - Other Important Considerations

15.1 Plant Safety

The proposed plant has several aspects that must be designed cautiously. From feed to final product, nearly every process stream has a highly combustible component such as natural gas, hydrocarbon chains and carbon monoxide. Although the feed and product streams do not contain oxygen, a leak in piping could lead to an explosion. Microchannel geometry makes it nearly impossible for explosions to occur within the reactor; therefore, the combustion of fuel in the reactor is more easily controlled. However, throughout the rest of the plant open flames and sparks should not be permitted and proper emergency shut-off valves should be installed. Reserves of nitrogen will be used when cleaning out pipelines or regenerating catalysts. The use of nitrogen enables safe removal of any potentially combustible residue in the pipes.

Many of the streams are at high temperatures contact with hot surfaces and gases should be avoided. The flue gas from the combustion products leaves at 320°F and should be released from an elevated pipe to prevent exposure to the immediate environment. The steam stream STEAM-101 enters the steam reforming reactor at 600°F and a pressure of 230 psi and must be designed to prevent a dangerous leak.

The separation unit MEA-101 makes use of the chemical compound monoethanolamine. Monoethanolamine is a weak base that is both corrosive and flammable. Proper equipment should be kept on the site of the MEA-101 unit to deal with a monoethanolamine spill, and storage tank insulation to prevent MEA degradation. Similar care must be utilized for the COPure $CuAlCl_4$ solvent.

Plant operation in Alaska presents the potential for pipes freezing. This could lead to pipe pressure build up, and subsequent rupture. To prevent freezing, appropriate insulation and heating equipment must also be installed. A possible heating solution is to wrap all plant piping with tubes containing a stream of steam. Additionally, during periods of shutdown, the plant's liquid streams will be kept from freezing.

15.2 Environmental Considerations

Carbon dioxide is a major byproduct in the plant. Carbon dioxide is a known greenhouse gas. A step taken to lower the total carbon dioxide emissions is using the MEA-101 separation unit to remove carbon dioxide from the steam reforming products. The carbon dioxide that is purged may be sold for enhanced oil recovery, increasing the amount of crude oil that can be extracted from Alaskan reserves. Sequestration may also be utilized if enhanced oil recovery does not prove attractive. The MEA separation is not 100% efficient however, so small amounts of carbon dioxide, monoxide, and light hydrocarbon vapor separated from the final mixture is subsequently flared. The waste water stream that is separated from the FT product is contaminated with trace amounts of hydrocarbons. Releasing this waste stream into natural bodies of water would be an environmental hazard to local wildlife and plants. Instead, the waste water will also be transported and sold for use in secondary oil recovery.

15.3 Plant Control

Plant control will be an important issue for a plant of this size. The feeds to the steam reforming reactor and Fischer-Tropsch reactor must be controlled to maintain ideal reactor conditions. Streams FEED FUEL must be increased or decreased if the SMR reactor is not reaching the temperature conditions for optimal output. Similarly, CW-205 will need to be increased or decreased accordingly if the FTR reactor is not reaching optimal temperature levels.

Moreover, the air temperature in the North Slope can vary between -62°F and 54°F over a year, which has profound effects on the heat flux in the air coolers. Therefore, to maintain the heat transfer coefficient within a desired range throughout the year, fans are installed in the cooler whose power can be adjusted to achieve the desired heat transfer rate. This is integral, since too large a heat transfer coefficient could freeze the cooling water loops, and too small a coefficient could result in insufficient cooling of reactor effluent streams.

Control systems should also be installed to regulate the recycle streams of carbon dioxide and carbon monoxide. The flow of S-305 must be controlled to maintain a 2.1:1 H_2/CO molar ratio in the feed to the FT reactor (Stream S-202). Moreover, a specific flow rate (4.5E6 lb/hr) of CO_2 must be recycled back to SMR-101 (Stream CO2 RECYCLE).

15.4 Plant layout

The plant is designed to be located near Prudhoe Bay, Alaska. It must be located in the vicinity of an entrance to the Trans-Alaskan Pipeline System (TAPS); otherwise, a smaller pipeline must be constructed to deliver the plant's product to the TAPS. Prudhoe Bay was chosen since there are immense reserves of associated and unassociated natural gas and because the TAPS is nearby.

Section 16 - Conclusions and Recommendations

Based on the technical and economic analysis completed, it is recommended that further design work be undertaken so that a more precise initial investment dollar figure can be obtained. The capital expenditure is the financial variable that most affects the project feasibility and is also under the control of the project team. Oil prices, though the most influential economic factor, cannot be controlled by the project team. Therefore, as technology continues to improve, the most expensive process units must be monitored for potential cost savings. Additionally, the great amount of uncertainty associated with the cost of the microchannel reactors must be addressed. As the microchannel reactor technical performance and design are proprietary information, the next step would be to obtain additional information from a microchannel vendor.

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Section 18 - Bibliography

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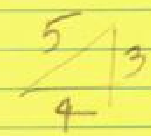
Section 19 - Appendix

Appendix - Table of Contents

Appendix A - Unit Design Calculations

Heat Exchanger Arrangement



AREA OF TRIANGLE = [1/2 BASE X HEIGHT] X 2

$= (PITCH) \times (PITCH) \cos 30°$

$= (P \times P\ 0.866)$

TUBE AREA WITHIN TRIANGLE = 60° X 3 = 1 TUBE $= \frac{\pi}{4} D^2$

$\frac{\pi}{4}$ (TUBESHEET DIAMETER (INCHES))^2 = (No Tubes) $0.866 P^2$

USE ↗

TS DIAMETER − Tube OD − 1/2 Tube OD = (No Tubes) P^2 0.866

PITCH = 1.25 Tube DIAMETER

Heat Exchanger Calculation

Heat X1 (HX-101)

$$LMTD = \frac{(401-123)-(225-4)}{\ln\left(\frac{401-123}{225-4}\right)} = 248.4$$

$Q = 5.354 \times 10^8$ Watt $= 5.07453 \times 10^5 \frac{Btu}{s} = 1.90508069 \times 10^9 \frac{Btu}{hr}$

Assume $U_i = 100 \frac{Btu}{ft^2 \cdot hr \cdot °F}$

$$R = \frac{406-225}{123-4} = 1.4706$$

$$S = \frac{123-4}{406-4} = .3005$$

$$F_t = \frac{\sqrt{1.4706^2+1}\,\ln[(1-.3005)/(1-1.4706 \times .3005)]}{(1.4706-1)\ln\left[\frac{2-.3005(1.4706+1-\sqrt{1.4706^2+1})}{2-.3005(1.4706+1+\sqrt{1.4706^2+1})}\right]} = \frac{.401655}{.427033} = .9406$$

$$A_i = \frac{1.90508 \times 10^9\ Btu/hr}{\left(100 \frac{Btu}{ft^2 \cdot hr \cdot °F}\right)(.9406)(420.83°F)} = 45602 ft^2$$

$$\frac{Q}{U F_t \Delta T_{LM}}$$

Largest Possible Exchanger:

Shell diameter: 118 in

Pitch = 1.25 tube diameter = (1.25)(.75) = .9375

$\frac{\pi}{4}(\text{shell diameter})^2 = (\#\text{Tubes})(\cos 30 \times \text{Pitch})$

#Tubes = 13469 tubes = 13,500 tubes

Area/Tube = $\pi D L = \frac{\pi(.75)}{12} = .1963\ ft^2/ft$

24 ft tubes ⇒ 4.712 ft²/tube

Area = 63607 ft²

$$\frac{45602 ft^2}{(20 ft\ tubes)(.1963\ ft^2/ft)} = 11615\ tubes$$

Shell Diameter =

$$\sqrt{(11615\ tubes)(\cos 30)(.9375\ pitch)\frac{4}{\pi}}$$

= 109.57 = 110 inside

112 outside

Min. Baffle Spacing

$$b_{min} = \frac{D_s}{5} = \frac{110}{5} = 22 in$$

$b_{max} = 110 in$

Heat Exchanger Calculation

Cost HX2 (HX-102)

Floating Head →

$C_B = \exp\{11.667 - .8709[\ln(A)] + 0.09005[\ln(A)]^2\}$

$A = 40980$

$= \$303{,}413$

20ft tubes

$F_p = .9803 + .018\left(\frac{14.5}{100}\right) + .0017\left(\frac{14.5}{100}\right)^2$

$= .9929$ for 15barg $= 1.03$

negligible

COPure and MEA Calculations

COPure Utility Requirements:

Electrical Power:

CO Produced: $\frac{4.4353\times10^{5}\ \text{kmol/day}}{0.6420\ \text{kmol/m}^3}\left(\frac{365\ \text{day}}{\text{yr}}\right) = 2.52\times10^{8}\ \frac{\text{Nm}^3}{\text{yr}} \cdot \frac{0.55\ \text{kw-hr}}{\text{Nm}^3\ \text{of CO recovered}}\left(\frac{3412.14\ \text{Btu}}{\text{kWh}}\right)$

density at STP: 0.6420 kmol/m³

$= \boxed{4.73\times10^{11}\ \text{Btu/yr}}$

Reboiler:

$2.52\times10^{8}\ \frac{\text{Nm}^3}{\text{yr}} \cdot \left(\frac{1\ \text{MJ}}{\text{Nm}^3\ \text{CO recovered}}\right)\left(\frac{947.8\ \text{Btu}}{\text{MJ}}\right) = \boxed{2.39\times10^{11}\ \text{Btu/yr}}$

Cooling Water:

$2.52\times10^{8}\ \text{Nm}^3/\text{yr} \cdot \left(\frac{5.5\ \text{MJ}}{\text{Nm}^3\ \text{CO recov}}\right)\left(\frac{947.8\ \text{Btu}}{\text{MJ}}\right) = \boxed{1.314\times10^{12}\ \text{Btu/yr}}$

Toluene / $CuAlCl_4$ solvent:

$\$30.00/\text{gal}\left(\frac{220\ \text{kg}}{\text{h}}\right)\left(\frac{\text{m}^3}{1016\ \text{kg}}\right)\left(\frac{264.17\ \text{gal}}{\text{m}^3}\right)\left(\frac{24\ \text{h}}{\text{day}}\right)\left(\frac{365\ \text{day}}{\text{yr}}\right) = \$15{,}032{,}729 \cdot \left(\frac{7}{10}\right)$ capacity of MEA system)

$= \$10{,}522{,}910/\text{yr} \div 42{,}923{,}635\ \text{bbl/yr} = \$0.245/\text{bbl}$

remote location, specialized solvent increases price by 1.8.

× 1.8 site Factor

$= \boxed{\$0.44/\text{bbl}}$

Plant cost

- interpolated from R.C. Costello installed cost chart for 4.53 MTPA CO produced:

$\boxed{\$1{,}496{,}470{,}800}$

MEA Requirements: (Based on Thomas expert Report):

Thomas production capacity: 2850 ton/day / GTL capacity: 22423 ton/day = 0.127 — GTL capacity is 1/0.127 = 7.87 × Thomas.

Solvent MEA cost:

$\$1.5/\text{kg-MEA}\left(\frac{220\ \text{kg}}{\text{h}}\right)\left(\frac{24\ \text{h}}{\text{day}}\right)\left(365\ \text{day/yr}\right)\times7.87 / 42{,}923{,}635\ \text{bbl/yr} = \boxed{\$0.53/\text{bbl}}$

active Carbon: $\$0.50/\text{lb} = \$1.102/\text{kg} \cdot (114\ \text{kg/day})(365\ \text{day/yr}) = \$45{,}854.22$

$NaCO_3$: $\$17.78/\text{lb} = \$1.96/\text{kg}\left(168\ \text{kg/h}\right)\left(24\ \text{h/day}\right)\left(365\ \text{day/yr}\right) = \$2{,}884{,}492$

Sum of other MEA expenses: $\$2{,}930{,}346$ / 42,923,635 bbl = $\boxed{\$0.068/\text{bbl}}$

– For utilities See Thomas p. 110

Turbine Calculations

Calculations for pricing of Turb-201

Using the Icarus charts from 1999				
Pc		**20066**	hp	14.96341 MW
Q=		1527806	gpm	
From Icarus Chart@ 20,000hp:				
	Cb	1600000	USD/unit	
	Ce(1999)	389.5		
	Ce(2007)	530.7		
	Cp	Cb*Ce(2007)/Ce(1999)		
	Cp	1600000*530.7/389.5		
Current Price:		**2,180,026**	USD for compressor Turb-201	

Compressor Calculations

Calculations for pricing of COMP-101

Using the Icarus Charts from 1999				
Flowrate=		**362747**	cubic ft/minute	
		200000	cubic ft/minute maximum capacity/compressor	
Compressors Required				
	362747/200000	=	1.813733	
			2	Compressors used
	362747/2	=	181373.3	hp per Compressor
From Icarus Chart:		10500000	USD/unit	
	Total of	21,000,000	USD in 1999	
	Ce(1999)	389.5		
	Ce(2007)	530.7		
Current Price:		**28,612,837**	USD for compressor COMP-101	

Calculations for pricing of COMP-102

Using the Icarus Charts from 1999		
Flowrate=	**389190**	cubic ft/minute
	200000	cubic ft/minute maximum capacity/compressor
Compressors Required		
389190/200000	=	1.94595
	2	Compressors used
389190/2	=	194595 hp per Compressor
From Icarus Chart:	9780000	USD/unit
Total of	19,560,000	USD in 1999
Ce(1999)	389.5	
Ce(2007)	530.7	
Current Price:	**26,650,814**	USD for compressor COMP-102

Calculations for pricing of COMP-201

Using the Icarus Charts from 1999		
Flowrate=	**478236**	cubic ft/minute
	200000	cubic ft/minute maximum capacity/compressor
Compressors Required		
478236/200000	=	2.391181
	3	Compressors used
478236/3	=	159412.1 hp per Compressor
From Icarus Chart:	12000000	USD/unit
Total of	36,000,000	USD in 1999
Ce(1999)	389.5	
Ce(2007)	530.7	
Current Price:	**49,050,578**	USD for compressor COMP-201

Pump Calculations

Calculations for pricing of PUMP101

Power Consumption(Pb)=	25.12167	hp
Flow rate (Q)=	5.04E+03	gpm
Head (H)=	17.22035	ft
Efficiency (η)=	86	%
Ft Steam Turbine Driver	2	
Fm stainless steel	2	
Ft electric motor	1.8	

Pump Pricing

Pc= Pb/n
25.1217/.86 = 29.21124419 hp

S= Q*(H^.5)
5.04E3*17.22035^.5 2.09E+04 gpm

Maximum S for single pump is 85,000gpm
S/85,000= 2.46E-01 →1 pumps required+1 Extra

Cb= exp(9.2951-0.6019*ln(S)+0.0519*(ln(S)^2))
exp(9.2951-0.6019*ln(20901.08)+0.0519*(ln(20901.08)^2))
4644.188648

Cbm Cb*Ft steam*Fm
4644.188648*2*2 18576.75459 Per Unit Pump

Electric Motor Pricing

Cb= exp(5.4866+0.13141*ln(Pc)+0.053255*(ln(Pc)^2)
+0.028628*(ln(Pc)^3)-0.0035549*(ln(Pc)^4))
1307.178185

Cbm= Cb*Ft
1307.178185*1.8 2352.920733

Price for combined pump and motor unit
18576.75+54945.065 20929.67533 USD

For two units at 2007 dollars:
20929.67533*2*530.7/394
56382.63297 USD for pump requirements of PUMP-101

<u>Calculations for pricing of PUMP201</u>

Power Consumption(Pb)=	1184.026	hp
Flow rate (Q)=	1.50E+04	gpm
Head (H)=	263.948818	ft
Efficiency (η)=	86	%
Ft Steam Turbine Driver	2	
Fm stainless steel	2	
Ft electric motor	1.8	

Pump Pricing

Pc= Pb/n

1184.026/.86 = 1376.774419 hp

S= Q*(H^.5)

15033.3891*263.948818^.5 2.44E+05 gpm

Maximum S for single pump is 85,000gpm

S/85,000= →4 pumps required+1 Extra

S per pump= S/4

2.44E5/4 6.11E+04 gpm

Cb= exp(9.2951-0.6019*ln(S)+0.0519*(ln(S)^2))

exp(9.2951-0.6019*ln(61059.995)+0.0519*(ln(61059.995)^2))

7822.101888

Cbm Cb*Ft steam*Fm

7879.52*2*2 31288.4076 Per Unit Pump

Electric Motor Pricing

Cb= exp(5.4866+0.13141*ln(Pc)+0.053255*(ln(Pc)^2)

+0.028628*(ln(Pc)^3)-0.0035549*(ln(Pc)^4))

30525.03632

Cbm= Cb*Ft

30525.03632*1.8 54945.0654

Price for combined pump and motor unit

31288.408+54945.065 86233.473 USD

For three units at 2007 dollars:

86233.473*5*530.7/394

580762.7427 USD for pump requirements of PUMP-201

<u>Calculations for pricing of PUMP202</u>

Power Consumption(Pb)=	451.35	hp
Flow rate (Q)=	2.29E+04	gpm
Head (H)=	65.98772	ft
Efficiency (η)=	86	%
Ft Steam Turbine Driver	2	
Fm stainless steel	2	
Ft electric motor	1.8	

Pump Pricing

Pc= Pb/n

451.35/.86 = 525.2042 hp

S= Q*(H^2)

2.29E4*65.99^.5 185665.8 gpm

Maximum S for single pump is 85,000gpm

S/85,000= 2.1843 →3 pumps required

S per pump= S/3

185665.8/3 61888.6 gpm

Cb= exp(9.2951-0.6019*ln(S)+0.0519*(ln(S)^2))

exp(9.2951-0.6019*ln(61888.59)+0.0519*(ln(61888.59)^2))

7879.523591

Cbm Cb*Ft steam*Fm

7879.52*2*2 31518.1 Per Unit Pump

Electric Motor Pricing

Cb= exp(5.4866+0.13141*ln(Pc)+0.053255*(ln(Pc)^2)

+0.028628*(ln(Pc)^3)-0.0035549*(ln(Pc)^4))

21214.29777

Cbm= Cb*Ft

21214.30*1.8 38185.7

Price for combined pump and motor unit

31518.09+38185.74 69703.83 USD

For three units at 2007 dollars:

69703.83*3*530.7/394

281663.6237 USD for pump requirements of PUMP-202

Calculations for pricing of PUMP301

Power Consumption(Pb)=	182.5039 hp
Flow rate (Q)=	3.65E+03 gpm
Head (H)=	235.1435 ft
Efficiency (η)=	86 %
Ft Steam Turbine Driver	2
Fm stainless steel	2
Ft electric motor	1.8

Pump Pricing

Pc= Pb/n

182.5/.86 = 212.2138372 hp

S= Q*(H^.5)

3.65E3*235.1435^.5 5.60E+04 gpm

Maximum S for single pump is 85,000gpm

S/85,000= 6.59E-01 →1 pumps required+1 Extra

Cb= exp(9.2951-0.6019*ln(S)+0.0519*(ln(S)^2))

exp(9.2951-0.6019*ln(56030.18)+0.0519*(ln(56030.18)^2))

7468.906276

Cbm Cb*Ft steam*Fm

7468.90*2*2 29875.6251 Per Unit Pump

Electric Motor Pricing

Cb= exp(5.4866+0.13141*ln(Pc)+0.053255*(ln(Pc)^2)

+0.028628*(ln(Pc)^3)-0.0035549*(ln(Pc)^4))

9826.717628

Cbm= Cb*Ft

9826.717628*1.8 17688.09173

Price for combined pump and motor unit

29875.6251+9826.717628 47563.71684 USD

For two units at 2007 dollars:

47563.717*2*530.7/394

128132.3072 USD for pump requirements of PUMP-301

Flash, Decanter, MEA and COPure Separations

Flash-301

Number = 22
$V = 1895.55\ ft^3/min$
$\tau = 5$ min
$D = (4V\tau/\prod)^{1/3} = 22.94$ ft (Seider 2005)
L = 2D = 45.88 ft
$t_s = 2.55$ in
W (lb) = $\prod (D + t_s)(L + 0.8D)t_s\rho$ = 526,751
$C_v = \exp\{7.0374 + 0.18255[\ln(W)] + 0.02297[\ln(W)]^2\}$ = \$679,585
$C_{pl} = 237.1(D)^{0.63316}(L)^{0.80161}$ = \$37,015
$F_m = 1$
$Cp = C_{pl}+C_v x F_m$ = \$716,600
$F_{BM} = 4.16$
C_{BM} = \$2,981,056 (2000 CE = 394)
$C_{IND} = C_{BM}x(525.4/394)$ = \$88,337,615 (2008)

DEC-301

Number = 30
Capacity = $349.2\ ft^3$
Cp = \$32,500 (Icarus Cost Charts
- Vertical Pressure Vessel)

$F_{BM} = 4.16$
$C_{BM} = C_P F_{BM}$ (1998 CE = 389.5)
C_{BM} = \$4,056,000
$C_{IND} = C_{BM}x(530.7/394)$ = \$5,526,365 (2008)

MEA-101

Number = 1
Efficiency = 80%
Amount of CO2 produced = $10,955.87\ ft^3/min$
$C_{installed}$ = \$967,315,790 (Thomas p.110)

COPure-301

Number = 1
Efficiency = 99%
Amount of CO produced = 4,534,760 ton/yr
$C_{installed}$ = \$1,496,470,800 (R.C. Costello)

Air Cooled Heat Exchanger Explanations/Calculations

The air-cooled heat exchanger calculations were carried out using an excel spreadsheet and the formulas specified in *Industrial Chemical Process Design* by Erwin. An overview of the inputs is next discussed.

The air temperature rise was determined by a trial-and error approach, with the results shown in the upper right box. The required tube outside surface area was calculated using A = Q/(U*DTM), where DTM is the log-mean temperature difference and U was guessed and then adjusted based on the final value to give negligible error. Table 5.4 provided initial guesses. Air-cooler face area was calculated using a 4-row, 2½-inch pitch, 10 fins/in, 5/8 in-high fins heat exchanger. This design usually gives good results. 16BWG tubes with an inner diameter (Di) of 0.87in and an outer diameter (Do) of 1in is also standard technology. A tube length of 40ft yields efficient heat transfer while minimizing cost. With this, an integer number of tubes and tubes per pass are obtained. A modified Reynolds number takes into account oil viscosity, and a shell side heat transfer coefficient (Ht) is derived from correlations. Airflow (Wa) is calculated as Wa = Q/0.24*DTA, where 0.24 Btu/lb ^{o}F is the specific heat of air, and the airside heat transfer coefficient (Ha) is calculated from correlations. The calculated U value is:

$$U = \frac{1}{(1/HT)*(AR*Do/Di) + RDt*(AR*Do/Di) + (1/Ha)}$$

where AR = ratio of outside tube extended surface to bare outside tube surface, and

RDt = tube inside fouling factor (here 0.002). This calculated U was then used instead of the initial guessed U until there was no error.

The pressure drop across the tubes was well below the 10psi limit. The fan design and power requirements were also calculated according Erwin's formulas and correlations, which include air density and flow rate.

Air Cooled Heat Exchanger Explanations/Calculations(Continued)

AIRCOOL1

Q [Btu/h]	-3.34E+09	T1 [F]	463.55
U(guess) [Btu/h F ft^2]	5.7	T2 [F]	39.2
Flow [lb/h]	2482306	TA1 [F]	14

TA2 [F]	173.0413
GTD	290.5088
LTD	25.2
DTA [F]	159.0413
DTM	249.8767

Required Tube Outside extended surface area, A				
A [ft^2]	2343612			
No. of HX	40			
Area per HX	58590.3		Np	4
Air Cooler Face Area:	5/8 in high fins, 10 fins/in, 2.5 in pitch, 4 rows:A10			
FA [[ft^2]	495.7717		Pick L[ft]	40
Tube Bundle Width [ft]	12.39429		Nt	412
No. of Tubes	262.5013		~ 228 tubes, increase A a little	
Tubes per Pass	57			
At [in^2]	0.594167		~16 BWG tubes, Di = 0.87in, Do = 1in	
Tube-Side Flow Quantity:				
Wt [lb/h]	62057.65			
Tube-Side Flow Quantity:				
Gt [lb/s ft^2]	40.56112			
Modified Re:				
Nr	97.88675	158		
J	13.236			
Inside Wall Heat Transfer Coefficient				
HT[Btu/h ft^2 F]	1500			
Air Quantity Flow:				
Wa [lb/h]	2186278		Q per HX [Btu/h]	83450000
Air-Cooler Face Area Interflow				
Ga [lb/h ft2]	4409.848			
Ha [Btu/h ft2 F]	9.1			
Calculated U	5.698526			
Fan Area Per Fan:				
FAPF [ft]	99.15434			
D fan [ft]	11.23883			
DPA [in water/row]	0.0838			
DPAT	0.8518			
DR (density ratio of air)	1.1176			
Wa [m^3/h]	840876			
Volumetric Flow of air per fan:				
ACFM	167198.8			
P_{force} [in of water]	1.028717			
B (hp)	38.47106		For safety:	80 hp motor
				203520 BTU/h
Heat Transfer Area:			~Seider Table 16.32	
A [ft^2]	4312.267			
C_p	56020.69			
F BM	2.17			
C BM	121564.9			
C INDEXED	163742.4			

Air Cooled Heat Exchanger Explanations/Calculations(Continued)

AIRCOOL2

Q [Btu/h]	-5172355800	T1 [F]	369.6
U(guess) [Btu/h F ft^2]	7.32	T2 [F]	39.2
Flow [lb/h]	4005578.89	TA1 [F]	14

TA2 [F]	172.4128
GTD	197.1872
LTD	25.2
DTA [F]	158.4128
DTM	192.4918

Required Tube Outside extended surface area, A			
A [ft^2]	3670837.29		
No. of HX	40		
Area per HX	91770.9323	Np	4
Air Cooler Face Area:	5/8 in high fins, 10 fins/in, 2.5 in pitch, 4 rows:A10		
FA [[ft^2]	776.53522	Pick L[ft]	40
Tube Bundle Width [ft]	19.4133805	Nt	412
No. of Tubes	411.160091	~ 412 tubes, increase A a little	
Tubes per Pass	103		
At [in^2]	0.5941665	~16 BWG tubes, Di = 0.87in, Do = 1in	
Tube-Side Flow Quantity:			
Wt [lb/h]	100139.472		
Tube-Side Flow Quantity:			
Gt [lb/s ft^2]	65.451545		
Modified Re:			
Nr	157.955185	158	
J	13.236		
Inside Wall Heat Transfer Coefficient			
HT[Btu/h ft^2 F]	1500		
Air Quantity Flow:			
Wa [lb/h]	3401158.63	Q per HX [Btu/h]	129308895
Air-Cooler Face Area Interflow			
Ga [lb/h ft2]	4379.92		
Ha [Btu/h ft2 F]	14.10		
Calculated U	7.33		
Fan Area Per Fan:			
FAPF [ft]	155.31		
D fan [ft]	14.07		
DPA [in water/row]	0.08		
DPAT	0.85		
DR (density ratio of air)	1.12		
Wa [m^3/h]	1308137.94		
Volumetric Flow of air per fan:			
ACFM	260108.55		
P_{force} [in of water]	1.03		
B (hp)	59.71	For safety:	100 hp motor
			253350 **BTU**/h
Heat Transfer Area:		~Seider Table 16.32	
A [ft^2]	4312.27		
C_p	56020.69		
F BM	2.17		
C BM	121564.90		
C INDEXED	163742.37		

Steam Methane Reformer SMR-101 Calculations

Steam Methane Reformer SMR-101

This microchannel reactor is based on U.S. Patent 7,250,151 B2. However, the patent does not give a detailed description of an industrial-sized reactor; instead, data is given for tests conducted using small reactors consisting of only one set of microchannels. In reality, industrial applications of this technology will be in the form of modular reactors, consisting of hundreds or thousands of channels per reactor.

A microchannel is defined in the patent as a channel having at least one internal dimension less than 2 mm. Several embodiments of integrated combustion reactors are described in the patent, using a variety of fuels and channels dimensions. Since natural gas and recycled hydrocarbons are the fuel of choice for this project (owing to the abundance of hydrocarbon reserves in the North Slope region of Alaska), the “N-type Welded Integrated Combustion Reactor” is chosen (performance results are shown in Table 5, page 59 of U.S. Patent 7,250,151 B2; channel dimensions are described on pages 35 to 38 of U.S. Patent 7,250,151 B2).

Optimum conversion of methane to syngas can be achieved by controlling the extent to which the reactants interact, which is a function of the contact time of the reactants with the catalyst. For the test run of N3 Welded ICR (Table 5, U.S. Patent 7,250,151 B2), the steam-methane reforming reaction has a contact time of 6.0ms. The contact time is the parameter which determines the number of channels required to handle the amount of material being dealt with in the process.

Reactor Sizing

Before the number of channels can be determined, the required reaction chamber volume must be determined (the reaction chamber volume is defined as the internal volume of an endothermic or exothermic reaction chamber, which must contain catalyst somewhere within its cross-section; therefore, it does not include the portion of the channels which is not coated with catalyst). In order to determine this volume, the structure of a microchannel reactor described in the patent is studied.

According to the patent, a microchannel reactor is made from a stack of shims, substantially planar sheets with a thickness of 2 mm or less, with channels etched into them. The shims are diffusion bonded together to form the reactor. According to pages 32 and 33 of the patent, an endothermic reaction channel is 0.25 mm thick, 9.7 mm wide and 53 cm in length. Page 37 explains that the reaction zone length is 18 cm; that is, only the last 18 cm of the reaction channel is in contact with catalyst.

The contact time is defined in the patent as the reaction chamber volume divided by inlet volumetric flow rate at the standard condition of 0°C and 1.013 bar. Consequently, the specified 6.0 ms contact time is different from the actual time the reactants spend in contact with catalyst at reaction conditions of 900°C and 35 barg. The temperature and pressure change must be dealt with before calculating the required reactor size. According to ASPEN, the volumetric flow rate of streams S-101 and CO2 RECYCLE is 58.14×10^6 ft^3/hr at standard conditions, as opposed to 5.35×10^6 ft^3/hr at reaction conditions. Therefore, to convert the feed flow rate from STP to reaction conditions, a factor of 58.14/5.35 = 10.9 ft^3 at STP/ft^3 at reaction conditions was used.

Given the required contact time, reaction chamber volume, and reactant volume, the number of channels required to meet the plant capacity can be calculated; the calculations are shown in Table A1.

Table A1 – Sizing Calculation for Steam Methane Reformer (SMR-101)

Volumetric flow rate of feed (volumes at reaction conditions)					
Stream STEAM-101	89,065,700	bbl/day	20,836,116	ft^3/hr	(1)
Stream S-101	26,046,400	bbl/day	6,093,320	ft^3/hr	(2)
Stream CO2 RECYCLE	262,264	bbl/day	61,354	ft^3/hr	(3)
Total Volume Flow	115,374,364	bbl/day	26,990,791	ft^3/hr	(4) = (1)+(2)+(3)
Endothermic reaction channel dimensions					
Thickness	0.25	mm			(5)
Width	9.70	mm			(6)
Reaction zone length	18.8	cm	188	mm	(7)
Reaction zone volume	455.9	mm^3	1.61×10^{-5}	ft^3	(8) = (5)×(6)×(7)
Contact time[1]	6.0	ms	1.67×10^{-6}	hr	(9)
Volume Flow per channel[2]	75.98	mm^3/ms	9.66	ft^3/hr	(10) = (8) ÷ (9)
Volume Flow per channel[3]	6.99	mm^3/ms	0.89	ft^3/hr	(11) = (10)÷10.9
Channels required	29,473,133	Channels			(12) = (4) ÷ (11)

[1] Contact time is defined in the patent as the reaction channel volume divided by the volumetric flow rate of reactants, based on volumes at standard temperature.
[2] Required volume flow per channel derived from the contact time and is therefore at STP
[3] The STP volume flow is adjusted by a factor to determine the required volume flow per channel at reaction conditions

According to Table A1, 29,473,133 endothermic reaction channels are required to process the plant's capacity. Referring to Figure 1 in Section 5, one set of channels consists of two endothermic reaction channels, one endothermic product channel, four combustion channels, two exhaust channels and four air channels. Therefore, the number of such sets required is:

$$\text{Number of channel sets required} = \frac{29{,}473{,}133 \text{ channels}}{2 \text{ channels per set}} = 14{,}736{,}566 \text{ sets}$$

Table A2 – Shim Stack in a typical set

Shim #[1]	Description	Thickness (mm)
19	Solid wall	0.51
20	Catalyst Stop	0.25
21	Endothermic Reaction	0.25
22	Welded Wall/Product	0.50
23	Endothermic Product	0.41
24	Welded Product/Wall	0.50
25	Endothermic Reaction	0.25
26	Catalyst Stop	0.25
27	Solid Wall	0.51
28	Solid Wall	0.51
29	Fuel	0.64
30	Welded Jet/Air/Wall	1.14
31	Exhaust	0.36
32	Exhaust	0.25
33	Exhaust	0.36
34	Welded Wall/Air/Jet	1.14
35	Fuel	0.64
36	Solid wall	0.51
	Total thickness	8.98 mm

[1] Corresponds to the "Shim #" column in Figure 7 of the patent

One set of channels consists of at least 18 shims of varying design and thickness. The shim stack of a small microchannel reactor is described in Figure 7 of the Velocys patent. Using the information from that figure, the thickness of one set of channels is calculated in Table A2.

Table A3 – Capacity of one module

End Plate thickness[1]	12.7	mm	(1)
Effective module height	987.3	mm	(2) = 1 m – (1)
Thickness of channel set	8.98	mm	(3)
No. of sets along module height[2]	109	pairs	(4) = (2) ÷ (3)
--> Reaction channels	220	channels	(5) = 2 × (4)
--> Combustion channels	220	channels	(6) = 2 × (4)
Shim width[3]	36	mm	(7)
No. of sets along module width[2]	41	sets	(8) = 1.5 m ÷ (7)
Total sets	4469	sets/module	(9) = (4) × (8)
--> Reaction channels	8938	channels	(10) = (9) × 2
--> Combustion channels	17,876	channels	(11) = (9) × 2

[1] Figure 7 of the patent shows that each end plate is 6.35 mm thick. End plates are placed at the top and base of the reactor, totaling to 6.35 + 6.35 = 12.70 mm

[2] A whole number is not obtained by conducting the division calculation described in the table. Instead, the result is rounded down, and the remaining width/height of the reactor is sacrificed to structural features of the module.

[3] A shim may be of any width desired; in fact, during the manufacture of this reactor, each shim will not be 36 mm wide, but will be 41 × 36 = 1,476 mm wide. The patent describes a reactor with only one channel per shim, whereas a larger, industrial scale reactor will be etched with multiple adjacent channels per shim.

The modular design of these reactors allows small modules approximately 1 m high and 1.5 m wide to be assembled into a large unit. The length of the reaction channels is already known to be 53 cm; therefore, to account for manifolding and the frame of the module, a length of 60 cm was assumed. Given these module dimensions, the capacity of one reactor module is calculated as in Table A3. Finally, knowing the number of reaction channels required, and the number of reaction channels per module, the number of modules required for this process can be found easily:

$$\frac{29{,}473{,}133 \text{ channels required}}{8{,}938\,\frac{\text{channels}}{\text{module}}} = \mathbf{3,298 \text{ modules required}}$$

Therefore, a total of 3,298 modules are required to meet the capacity of the plant and satisfy the 6.0 ms contact time requirement.

Based on this sizing, much information can be obtained about the flow within the reactor; this information, along with the calculations behind these numbers, is shown in Table A4.

Table A4 – Miscellaneous Data for SMR-101

Core Temperature	900	°C	1,533	°F	
Reaction Pressure	15	Barg			
Combustion Channel					
Width	4.10	Mm			(1)
Length	443	Mm			(2)
Thickness	0.64	Mm			(3)
Area	1,816	mm^2/combustion channel			(4) = (1) × (2)
Volume	1,162	mm^3/combustion channel			(5) = (4) ×(3)
Total no. of channels[1a]	58,955,048	Channels			(6)
Total volume	68,531,234,357	mm^3	2,420	ft^3	(7) = (6) × (5)
Fuel Flow rate	26,113,053	ft^3/hr			(8)
Air Flow Rate	199,693,651	ft^3/hr			(9)
Total Flow Rate	225,806,704	ft^3/hr			(10) = (8)+(9)
Flow per channel	3.83	ft^3/hr			(11) = (10)÷(6)
Residence Time	38.6	ms			(12) = (5) ÷ (11)
Endothermic Reaction Channel					
Area[2]	3,633	mm^2/reaction channel			(13)=(4) × 2
Total no. of channels[1b]	29,477,524	Channels			(14)
Heat Transfer					
Total heat transfer area	107,080,053,682	mm^2	1,070,800,537	cm^2	(15)=(13) × (14)
Heat duty	3.92×10^9	W	1.34×10^{10}	Btu/hr	(16)
Average area heat flux[3]	3.66	W/cm^2	12.48	Btu/hr-cm^2	(17)=(16)÷(15)

[1a] In the patent, each combustion channel shim contains two adjacent combustion channels with a rib support separating the two channels. This shim is bonded to an endothermic reaction shim containing only one, wide channel. In one *set* of channels, there would therefore be two such combustion shims (i.e. four combustion channels) and two such endothermic reaction shims. Therefore, the number of combustion channels is 3,298 modules × (8,938 × 2) combustion channels/module = 58,955,048 combustion channels.

[1b] The total number of channels is computed using the *whole* number of modules and the number of channels per module. Therefore, even though 2,794,085 endothermic reaction channels are required, 3,298 modules contain 2,797,594 channels = 8,938 channels/module × 313 modules.

[2] Heat exchange occurs between one endothermic reaction channel on one shim and two combustion channels on an adjacent shim. Therefore, the heat transfer area is 2 times the area of a combustion channel surface.

3 The average area heat flux is defined in the patent as the endothermic reaction heat duty divided by the area of endothermic reaction chamber heat transfer surface.

The average area heat flux calculated as 3.66 W/cm^2 is well within the average area heat flux range expressed in the table on page 30 of the patent.

Reactor Costing

Since microchannel reactors are still in the R&D phase for GTL applications, cost information cannot be obtained directly from manufacturers. In this infant stage, such reactors will be custom-fabricated to suit the needs of particular plants. In order to estimate the cost of the SMR-101 reactor, an estimate of metal mass is obtained. The reactor is constructed using 304-grade stainless steel.

The metal mass is estimated by taking the volume of the entire reactor, assuming it is a solid block of stainless steel. Then, the volume of empty spaces, namely the channels and catalyst inserts, is subtracted from this total volume. These calculations are presented in Table A5.

Table A5 – Calculation of reactor metal mass by subtracting void space volume from total reactor volume

Reaction channel volume		
--> Height	0.25	mm
--> Width	9.70	mm
--> Length	443	mm
--> Volume	1074.28	mm^3/channel
# per pair	2	per pair
# per module	8938	per module
Volume per module	9,601,870	mm^3 per module
Combustion channel volume		
--> Height	0.64	mm
--> Width	4.10	mm
--> Length	443	mm
--> Volume	2590.68	mm^3/channel
> # per pair	4	per pair
> # per module	17876	per module
Volume per module	46,310,910	mm^3 per module
Exhaust channel volume[1]		
--> Height (1,3)	0.36	mm
--> Width (1,3)	4.10	mm
--> Length (1,3)	443	mm
--> Volume (1+3)	1307.74	mm3/two channels
--> Height (2)	0.25	mm
--> Width (2)	4.10	mm
--> Length (2)	438	mm
--> Volume (2)	448.95	mm^3/channel
> # per pair	2	per pair
> # per module	8938	per module
Volume per module	4,012,715	mm^3 per module
Air channel volume		
--> Height	0.64	mm
--> Width	4.10	mm
--> Length	443	mm
--> Volume	1162.43	mm^3/channel
> # per pair	4	per pair
> # per module	17876	per module
Volume per module	20,779,634	mm^3 per module
Product channel volume[2]		
--> Height (1,3)	0.25	mm
--> Width (1,3)	4.10	mm
--> Length (1,3)	110	mm
--> Volume (1+3)	225.50	mm^3/two channels

--> Height (2)	0.41	mm		
--> Width (2)	4.10	mm		
--> Length (2)	443	mm		
--> Volume (2)	744.68	mm^3/channel		
> # per pair	2	per pair		
> # per module	8938	per module		
Volume per module	6,655,977	mm^3 per module		
Catalyst Volume				
--> Length	188.00	mm		
--> Width	9.40	mm		
--> Height	0.25	mm		
--> Volume	441.8	mm^3/channel		
> # per pair	2	per pair		
> # per module	8938	per module		
Volume per module	3,948,808	mm^3 per module		
Totals				
Total non-Metal Volume	91,309,914	mm^3	9.13E-02	m^3/module
Total module volume	795,000,000	mm^3	0.795	m^3/module
Metal volume	703,690,086	mm^3	7.04E-01	m^3/module
Material	SS-304			
Material Density	8,010	kg/m^3		
Material Mass	5,637	kg/module		

[1] According to the patent, exhaust channels each consist of one shim running the length of reactor (443 mm) sandwiched between two shims ended 5 mm short of the u-turn bend. They are 0.36 mm, 0.25 mm and 0.36 mm thick.
[2] According to the patent, product channels each consist of one shim running the length of the reactor (443 mm) sandwiched between two shims which add to the cross-section of the channels in the first 110 mm of the channel after a u-turn bend. The shims are 0.25 mm, 0.25 mm and 0.41 mm thick.

The price of 304-grade stainless steel can be obtained from MEPS International Ltd., an independent supplier of steel market information. The average price of stainless steel Hot Rolled Plate in 2008 was $4,573.42 per ton. This results in a material cost of

$$\$4,573.42/\text{ton} \times 5.637 \text{ tons/module} = \$25,778.35/\text{module}$$

In addition, it is anticipated that manufacturing of these modules by detailed methods such as wire EDM and laser cutting will add on very substantial costs to the reactors. There is much in the way of detailed manufacturing work to be done on plates with such small thickness and channels of such miniscule dimensions. To account for these steep manufacturing costs, a factor of 5× is used to escalate the material cost to arrive at a bare module cost for the reactors:

Bare module cost per module = 5 × $25,778.35/module = $128,892/module

and

Bare module cost of 3,298 modules = 3,298 modules × $128,892/module = **$425,084,912.**

More (or less) conservative estimates can be made by increasing (or decreasing) the 5× factor; such an analysis is done in section 14, the Economic Analysis section, to explore the effect of this approximation on the feasibility of the project.

Material Balance and Feed Composition

The enhanced heat and mass transfer properties of the microchannel reactor result in higher CO and H_2 yields, as discussed in an independent study conducted by Nexant, Inc. to evaluate Velocys' Microchannel Process Technology SMR Reactor systems. The only information available to us for closing a material balance across the reactor is that published by Nexant; therefore, that data is used to derive the composition of the SMR product stream. Nexant's data is tabulated in Table A6.

Table A6 – Nexant, Inc.'s data for Velocys' SMR microchannel reactor, based on "Tokyo" Pilot operation

Methane conversion	88.60%	
Steam to reformer, mol/mol CH4	2.64	
Effluent composition, dry basis, vol %	*Original*	*Normalized*
Carbon monoxide	20.0%	21.44%
Hydrogen	59.8%	64.09%
Carbon dioxide	10.9%	11.68%
Methane	2.60%	2.79%
Total	93.3%	100%

Assuming ideal gas behavior for the effluent, the volume fractions of the effluent stream (S-102) can be thought as analogous to the mole fraction of the stream. One problem encountered when using the given dry basis volume fractions is that the percentages add up to 93.3% rather than 100%. To rectify this, they are normalized. For example, the mol% of CO is normalized as $\frac{20}{20+59.8+10.9+2.60} = 21.44\%$. In order for the material balance to work, a feed of CO_2 must be assumed. It is assumed that this CO_2 is obtained by recycling it (Stream labeled CO2 RECYCLE) from the effluent stream. With a basis of 100 mol of product, the material balance across the reactor closes, and is shown in Table A7. Therefore, the composition of the feed stream is 24% CH_4, 12% CO_2 and 64% H_2O.

Table A7 – Material Balance across SMR-101 assuming 100-mol basis of product

	In			Out		
	Moles	*Mass (g)*			*Moles*	*Mass (g)*
CH_4	24.17	387.74			2.79	44.76
CO_2	11.74	516.68	*Total mass in*	*Total mass out*	11.68	514.04
CO	0	0			21.44	600.53
H_2	0	0	2054.19 g	2054.19 g	64.08	129.19
H_2O	63.82	1149.78			42.50	765.68
C	35.9	431.3			35.9	431.3
H	224.3	226.1			224.3	226.1
O	87.3	1396.8			87.3	1396.8

Catalyst Structure

The 18 cm long reaction zone in the endothermic reaction channels is adjacent to a catalyst insert 9.4 mm wide and 0.25 mm thick. The catalyst is 10 wt% Rh/4.5 wt% MgO/85.5 wt% Al_2O_3 on spinel support with FeCrAlY felt coating (method of preparation is described in the patent). The volume of this catalyst insert is therefore $9.4 \times 0.25 \times 180 = 441.8$ mm^3 per reactant channel. The entire system contains 29,477,524 reaction channels and hence as many catalyst inserts. The total amount of catalyst required is 13,023,170,103 mm^3 or 459.9 ft^3 (0.14 ft^3 per module).

Fischer-Tropsch Reactor FTR-201

This microchannel reactor is based on U.S. Patent 7,084,180. Several embodiments of a Fischer-Tropsch reactor are described in the patent; however, a detailed design of an industrial-sized reactor is not discussed. Test results for small reactors with only one channel are given. In reality, industrial applications of this technology will be in the form of modular reactors, consisting of hundreds or thousands of channels per reactor.

The reactor can achieve CO conversion of up to 70% and chain growth probability of up to 0.93. The superior performance of the reactor is due to the rapid heat removal from the reaction channels. The results obtained in the test runs of the patent can be reproduced by carefully controlling the reaction conditions and reactants' contact time with catalyst.

Reactor Sizing

The size of the reactor is governed by the required contact time of the reactants with catalyst in the reactor. According to the patent and Nexant's technical report on Velocys' technology, 0.26 seconds of contact time is sufficient to achieve the claimed results at 225°C and 35 barg.

Table A8 – Reaction Zone Volume Requirement for FTR-201

Volumetric flow rate of feed (volumes at reaction conditions)					
Stream S-202	13,251,363	ft^3/hr			(1)
Contact time[1]	0.26	s	7.22×10^{-5}	hr	(2)
Volume Flow S-202 at STP	178,495,856	ft^3/hr			(3) = (2) × 13.47
Reaction zone volume[2]	12,891	ft^3	3.65×10^{11}	mm^3	(4) = (2)×(3)

[1] Contact time is defined in the patent as the reaction channel volume divided by the volumetric flow rate of reactants, based on volumes at standard temperature.

[2] The reaction zone volume is given by: contact time = reaction zone volume / volumetric feed flow at STP à reaction zone volume = contact time × volumetric feed flow at STP

A complication in using contact time as a parameter to size the reactor is that contact time is defined in the patent as the volume of the reaction zone divided by the volumetric feed flow rate at 0°C and 1 atm. Therefore, the contact time referred to in the patent is different from the actual time spent by the reactants at reaction conditions in contact with the catalyst. To account for this, the volumetric flow rate of the feed (S-202) at standard conditions was found in ASPEN PLUS to be 1.79×10^{8} ft^3/hr, as opposed to 1.33×10^{7} ft^3/hr. The data suggests that a factor of 17.9/1.33 = 13.47 ft^3 at STP/ft^3 at reaction conditions should be used to convert the feed flow rate from STP to reaction conditions.

Given the contact time, the reaction zone volume required to process the syngas in stream S-202 can be calculated. The calculations are shown in Table A8.

The dimensions of the channels in an industrially-sized FTR reactor are not given in the patent; however, Mr. John Wismer provided detailed measurements for a similar reactor being studied by Arkema, Inc. The provided data is shown in Table A9.

The key piece of information derived from Table A9 is the reaction zone volume per channel:

$$\frac{1{,}017{,}450\text{mm}^3}{\text{plate}} \div \frac{70\text{ reaction channels}}{\text{plate}} = 14{,}535\text{mm}^3\text{ per channel}$$

The reactor is packed with catalyst; it is assumed that the void fraction of the packed bed is 40%.

Table A9 – Microchannel Dimensions provided by Arkema, Inc.

Plate Geometry					
Plate width	1	m	1000	mm =	(1)
Plate height	1.5	m	1500	mm =	(2)
Margins for manifolds, etc.	5	cm	50	mm =	(3)
Channel length (width-wise)			900	mm	(4) = (1)-(3)×2
Active length for channels			1400	mm	(5) = (2)-(3)×2
Reaction Plates					
Reactive channel thickness	0.95	mm	0.0374	inches	(6)
Cover plate thickness	1	mm	0.0394	inches	(7)
Reaction channel width	17	mm	0.669	inches	(8)
Spacer width	3	mm			(9)
Reaction channel pitch	20				(10) = (8)+(9)
# channels per plate	70				(11)
Cover plate metal volume	1,500,000	mm^3/plate	5.30E-02	ft^3/plate	(12) = (1)×(2)×(7)
Spacer plate metal volume	407,550	mm^3/plate	1.44E-02	ft^3/plate	(13)
Cooling Plates					
Coolant channel thickness	1.5	mm	0.0591	inches	(14)
Cover plate thickness	1	mm	0.0394	inches	(15)
Cooling channel width	3	mm	0.118	inches	(16)
Spacer width	2	mm			(17)
Cooling channel pitch	5				(18) = (16)+(17)
# channels per plate	280				(19)
Cover plate metal volume	1,500,000	mm^3/plate	5.30E-02	ft^3/plate	(20) = (1)×(2)×(15)
Spacer plate metal volume	1,116,000	mm^3/plate	3.94E-02	ft^3/plate	(21)
Combustion Volume[1]	1,134,000	mm^3/plate	4.00E-02	ft^3/plate	(22) = see footnote[1]
Plate Pairs					
Pair thickness	4.45	mm			(23)=(6)+(7)+(14)+(15)
Total reaction volume[2]	1,017,450	mm^3/plate	3.59E-02	ft^3/plate	(24) = see footnote[2]
Cooling area (rx. channel faces)	2,142,000	mm^2 /plate	23.056	ft^2/plate	(25) = (4)×(8)×(11)×2
Metal density (304 SS)	8.01	g/cm^3			(26)
Metal mass[3]	36.23	kg			(27) = see footnote[3]
Modules					
Module thickness	1	m	3.28084	ft	(28)
Plate pairs	225	per module			(29)
Total reaction volume	228,926,250	mm^3/module	8.084	ft^3/module	(30) = (24)×(29)
Cooling area	481,950,000	mm^2/module	5187.66	ft^2/module	(31) = (25)×(29)
Metal mass	8,153	kg/module			(32)=(27)×(29)

[1] The combustion volume (per plate pair) is given by the total volume of the channels (including plates), minus the cover plate metal volume and the spacer plate metal volume. That is, (22) = [(14)+(15)]×(1)×(2) – (20) – (21)

[2] The total reaction volume (per plate pair) is given by the total volume of the channels (including plates), minus the cover plate metal volume and the spacer plate metal volume. That is, (24) = [(6)+(7)]×(1)×(2) – (12) – (13)

[3] The metal volume is the spacer plate volume plus the cover plant volume; ehnce, (27)=[(12)+(13)+(20)+(21)] ×(26)

The volume for flow per channel (εv_r) and the total required reaction zone volume (V_{req}) are used to finally size the reactor:

$$\text{No. plate pairs required } (N_p) = \frac{V_{req}}{v_r} = \frac{3.65 \times 10^{11}\ \text{mm}^3}{40\% \times \frac{14{,}535\text{mm}^3}{\text{channel}} \times \frac{70\ \text{channels}}{\text{plate pair}}} = 896{,}956$$

$$\text{No. plate pairs per module} = 225$$

$$\Rightarrow \text{No. modules required } (N_m) = \frac{896{,}956}{225} = 3{,}987$$

The average area heat flux in this reactor is calculated as:

$$\Delta H_{\text{rxn}} = 2.14 \times 10^9\text{W}$$

$$A_{\text{cooling}} = \frac{481{,}950{,}000\text{mm}^2}{\text{module}} \times 3{,}987\ \text{modules} = 1.92 \times 10^{12}\text{mm}^2$$

$$Q = \frac{2.14 \times 10^9\text{W}}{1.92 \times 10^{12}\text{mm}^2 \times \frac{\text{cm}^2}{100\ \text{mm}^2}} = 0.11\text{W/cm}^2$$

Reactor Costing

Since microchannel reactors are still in the R&D phase for GTL applications, cost information cannot be obtained directly from manufacturers. In this infant stage, such reactors will be custom-fabricated to suit the needs of particular plants. In order to estimate the cost of the FR-201 reactor, the metal mass is used as the key cost-driver. The reactor is constructed using 304-grade stainless steel.

The price of 304-grade stainless steel can be obtained from MEPS International Ltd., an independent supplier of steel market information. The average price of stainless steel Hot Rolled Plate in 2008 was $4,573.42 per ton. This results in a material cost of

$4,573.42/ton × 8.153 tons/module = $37,281.69/module

In addition, it is anticipated that manufacturing of these modules by detailed methods such as wire EDM and laser cutting will add on very substantial costs to the reactors. There is much in the way of detailed manufacturing work to be done on plates with such small thickness and channels of such miniscule dimensions. To account for these steep manufacturing costs, a factor of 5× is used to escalate the material cost to arrive at a bare module cost for the reactors:

Bare module cost per module = 5 × $37,281.69/module = $186,408/module

and

Bare module cost of 3,987 modules = 3,987 modules × $186,408/module = **$743,210,558.**

More (or less) conservative estimates can be made by increasing (or decreasing) the 5× factor; such an analysis is done in section 14, the Economic Analysis section, to explore the effect of this approximation on the feasibility of the project.

Product Distribution

The product distribution is determined using the Anderson-Schulz-Flory Distribution, which is:

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

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

Table A10 – Fischer-Tropsch Product Distribution in terms of Fractional CO Conversion

Product (n)	Fractional Conversion of CO
1	0.560%
2	1.081%
3	1.501%
4	1.832%
5	2.087%
6	2.277%
7	2.412%
8	2.501%
9	2.552%
10	2.570%
11	2.562%
12	2.532%
13	2.484%
14	2.423%
15	2.351%
16	2.271%
17	2.185%
18	2.095%
19	2.002%
20	1.908%
32	27.814%

Where W_n is the product weight fraction of a hydrocarbon chain containing ***n*** Carbon atoms and α is the chain growth probability. According to the Nexant technical report on Velocys' microchannel technology, the chain growth probability lies in the range 0.89 to 0.92 (average of 0.905), while the patent claimed a value as high as 0.93. To be conservative in evaluating this new technology, only α = 0.905 was assumed, rather than the optimistic 0.93. A CO conversion of 70% per pass was assumed. Using this information, the product distribution was converted to fractional conversion of feed CO so it could be input into RYIELD in ASPEN.

The procedure used to do the calculation was iteratively performed in Microsoft Excel. Iteration was necessary since the reaction stoichiometry was specific for each hydrocarbon product. The steps of the procedure are:

1. Guess a total weight of the reaction product
2. Use α in the Anderson-Schulz-Flory distribution to calculate the weight fraction of each hydrocarbon product
3. Use the resulting product weight to calculate the number of moles of carbon atoms in each product. This is how many moles of CO react to form that component of the product. With each hydrocarbon product, there is associated a contribution to the total fractional conversion of CO which brought about that hydrocarbon product

4. Sum the moles of CO reacted in (3) above to calculate the percentage conversion of CO (using the molar flow rate of CO in the feed)
5. Repeat steps 1-4 until the percentage conversion of CO from step (4) is equal to 70%

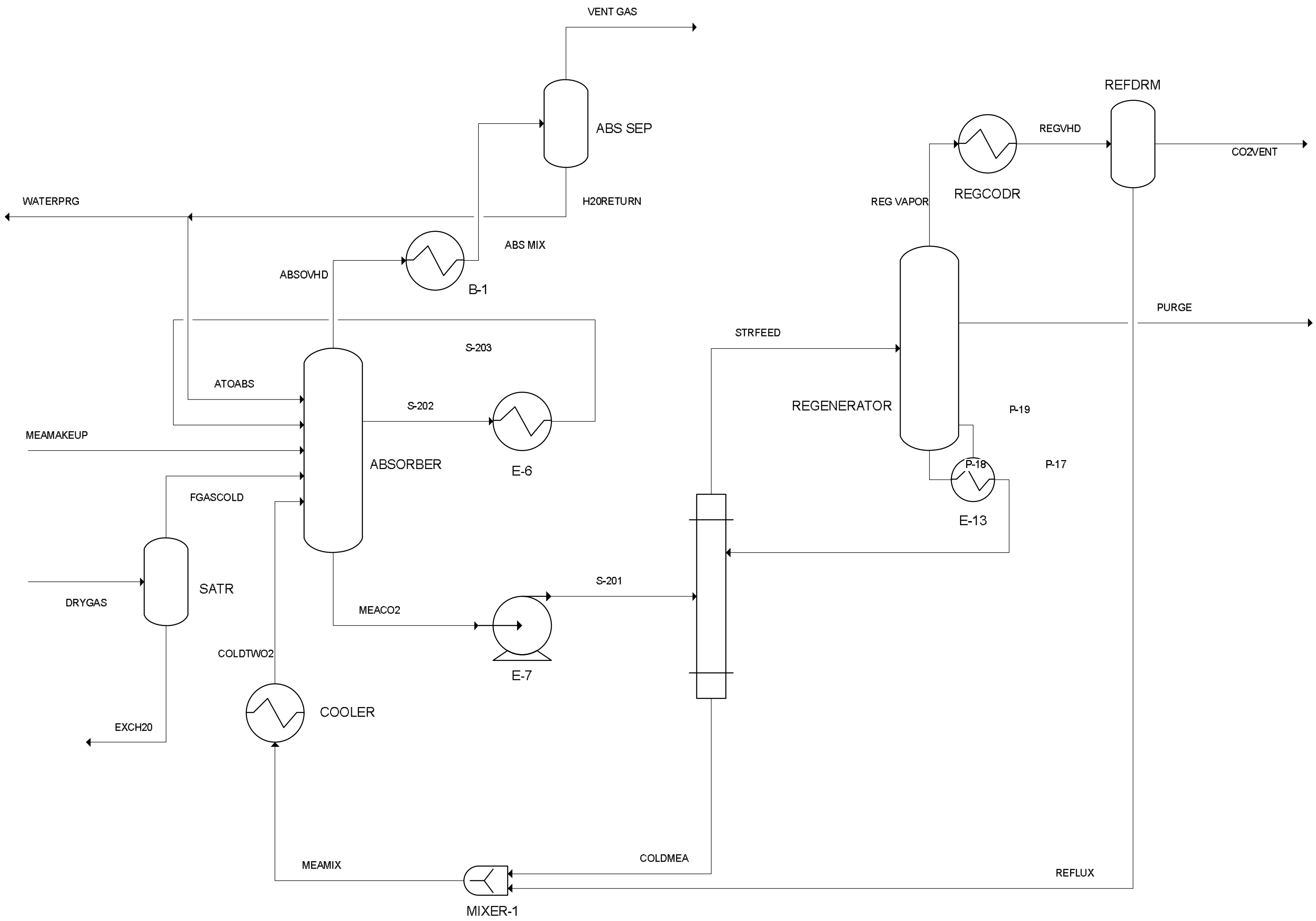
The results are shown in Table A10. Note that all products above C_{20} are grouped into a single category whose molecular formula is $C_{32}H_{66}$. C_{32} is the median hydrocarbon product for all products more than 20 carbon atoms large.

Catalyst Structure

The catalyst used to conduct Fischer-Tropsch is a fixed bed of particulate solid, containing Co/Re catalyst in a molar ratio of 21 with a metal dispersion of 5.4%. Each particle is 177-250 microns in diameter. One gram of catalyst per 800ml/hr of flow is packed into each reaction channel; at the flow rates in this particular embodiment (80,500 ml/hr), approximately 0.11g of catalyst (0.032g Co, 0.0048g Re) is loaded per channel, for a grand total of 6.7 tons of catalyst (0.11 g/channel × 896,956 plate pairs × 70 channels/plate pair).

Appendix B - Separation Specifications

MEA-CO_2 Process Flow Diagram



MEA Absorber/Stripper Block Reports:

BLOCK: ABSORBER MODEL: RADFRAC

*** SUMMARY OF KEY RESULTS ***

TOP STAGE LIQ. TEMPERATURE	F	145.685
TOP STAGE VAP. TEMPERATURE	F	145.685
BOTTOM STAGE LIQ. TEMPERATURE	F	135.643
BOTTOM STAGE VAP. TEMPERATURE	F	125.743
TOP STAGE LIQUID FLOW	LBMOL/HR	2,460,900.
BOTTOM STAGE LIQUID FLOW	LBMOL/HR	2,459,760.
TOP STAGE VAPOR FLOW	LBMOL/HR	221,397.
BOTTOM STAGE VAPOR FLOW	LBMOL/HR	276,740.
CONDENSER DUTY (W/O SUBCOOL)	BTU/HR	0.0
REBOILER DUTY	BTU/HR	0.0

***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

STAGE WITH MAXIMUM DIAMETER		2
COLUMN DIAMETER	FT	117.573
DC AREA/COLUMN AREA		0.100000
DOWNCOMER VELOCITY	FT/SEC	0.27293
WEIR LENGTH	FT	85.4301

**** SIZING PROFILES ****

STAGE	DIAMETER	TOTAL AREA	ACTIVE AREA	SIDE DC AREA
	FT	SQFT	SQFT	SQFT
1	117.17	10783.	8626.4	1078.3
2	117.57	10857.	8685.5	1085.7

****

BLOCK: REGENR MODEL: RADFRAC

INLETS - STRFEED STAGE 1
OUTLETS - REGVAPR STAGE 1
MEARECYC STAGE 8
NOPURGE STAGE 3
PROPERTY OPTION SET: ELECNRTL ELECTROLYTE NRTL / REDLICH-KWONG
HENRY-COMPS ID: GLOBAL
CHEMISTRY ID: GLOBAL - TRUE SPECIES

****

*** MASS AND ENERGY BALANCE ***

IN OUT GENERATION RELATIVE DIFF.

TOTAL BALANCE				
MOLE(LBMOL/HR)	0.247226E+07	0.252566E+07	53397.2	0.397772E-06
MASS(LB/HR)	0.621263E+08	0.621263E+08		0.319911E-10
ENTHALPY(BTU/HR)	-0.320643E+12	-0.315881E+12		-0.148525E-01

***** SIZING RESULTS *****

COLUMN DIAMETER	FT	62.5166
MAXIMUM FRACTIONAL CAPACITY		0.62000
MAXIMUM CAPACITY FACTOR	FT/SEC	0.16104
PRESSURE DROP FOR THE SECTION	PSI	0.059603
AVERAGE PRESSURE DROP/HEIGHT	IN-WATER/FT	0.078562
MAXIMUM LIQUID HOLDUP/STAGE	CUFT	1,314.09
MAX LIQ SUPERFICIAL VELOCITY	FT/SEC	0.10151

***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

STAGE WITH MAXIMUM DIAMETER		7
COLUMN DIAMETER	FT	120.563
DC AREA/COLUMN AREA		0.100000
DOWNCOMER VELOCITY	FT/SEC	0.27293
WEIR LENGTH	FT	87.6027

Stream Summary

		CO2VENT	DRYGAS	VENTGAS
From		REFDRM		ABSSEPR
To			SATR	
Substream: MIXED				
Phase:		Vapor	Mixed	Vapor
Component Mass Flow				
HYDROGEN	LB/HR	2.49	49458.23	49455.35
OXYGEN	LB/HR	0	0	0
NITROGEN	LB/HR	0	0	0
CO2	LB/HR	2885782	4291527	1388366
MEA	LB/HR	0	0	0
WATER	LB/HR	22810.87	2618922	216313.9
MEA+	LB/HR	0	0	0
H3O+	LB/HR	0	3.26	0
MEACOO-	LB/HR	0	0	0
HCO3-	LB/HR	0	10.45	0
CO3--	LB/HR	0	0	0
SULFU-01	LB/HR	0.76	24.99	24.05

METHANE	LB/HR	5323.35	136414	130017.2
CO	LB/HR	11565.99	3193532	3179308
Component Mass Fraction				
HYDROGEN		0	0	0.01
OXYGEN		0	0	0
NITROGEN		0	0	0
CO2		0.99	0.42	0.28
MEA		0	0	0
WATER		0.01	0.25	0.04
MEA+		0	0	0
H3O+		0	0	0
MEACOO-		0	0	0
HCO3-		0	0	0
CO3--		0	0	0
SULFU-01		0	0	0
METHANE		0	0.01	0.03
CO		0	0.31	0.64
Mole Flow	LBMOL/HR	67583.53	389935.8	189696.2
Mass Flow	LB/HR	2925485	10289890	4963484
Volume Flow	CUFT/HR	9631282	93116040	77302650
Temperature	F	92	100	99
Pressure	PSIA	41	16.7	14.7
Vapor Fraction		1	0.66	1
Liquid Fraction		0	0.34	0
Solid Fraction		0	0	0
Molar Enthalpy	BTU/LBMOL	-166556	-101807	-64411.4
Molar Density	LBMOL/CUFT	0.01	0	0
Mass Density	LB/CUFT	0.3	0.11	0.06
Average Molecular Weight		43.29	26.39	26.17

COPure-CO Separations and Specifications:

The COPure^{SM} Process for Carbon Monoxide Purification

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Abstract

Introduction

The ability of copper salts to dissolve carbon monoxide was first discovered by Leblanc in 1850,[1] and the use of cuprous-ammonium carbonate and formate solutions was first described in a German patent in 1914.[2] Since that time the use of copper salts to dissolve carbon monoxide has been applied in many plants, most commonly with an aqueous solution of a copper-ammonium salt. The process using an aqueous solution is complicated by side reactions. Examples are the reduction of cupric to cuprous ions by carbon monoxide, and the auto oxidation of cuprous to cupric ions with precipitation of elemental copper. As a result of the latter side reaction, it is necessary to provide oxygen to the system to maintain a sufficiently high concentration of cupric ions. Vaporization of ammonia during regeneration is also a concern.

Principal operating problems of the aqueous copper-ammonium salt CO-removal process may be listed as follows:[3]

1. Loss of active solution components
2. Control of cuprous/cupric ion-ratio
3. Recovery of pure carbon monoxide or a carbon monoxide-hydrogen mixture
4. Formation of precipitates
5. Corrosion

In 1973 Tenneco Chemicals, Inc. introduced a non-aqueous system for the absorption and recovery of carbon monoxide.[4] This process was designed to address problems associated with the aqueous copper-ammonium salt process, and in particular the corrosive nature of the aqueous system. The process was first introduced as the COSORB® process, and was based on research carried out from 1960 – 1975, by both Tenneco Chemicals, Inc. and Humble Oil and Refining Company. The organic solvent used had an aromatic base with the active component, $CuAlCl_4$. The first commercial plant using the non-aqueous system was started up in 1976. Since that time there have been 15 commercial facilities built, and many are still operating today. Nonetheless, these plants have not been without their share of problems. In many cases, problems associated with the process were solved by the individual operators.

The COPure℠ process is an evolutionary process based on many years of experience employing copper salts in an organic solvent for the recovery of carbon monoxide, and the experience of operating plants in addressing problems related to the use of this process.

Discussion

Carbon monoxide and nitrogen are very similar in nature making their separation by physical means difficult. Cryogenic distillation is expensive, and the resulting carbon monoxide product invariably contains significant quantities of nitrogen. Pressure Swing

Adsorption (PSA) is effective in separating a pure hydrogen stream from many components, but is not effective in separating CO from nitrogen.

When carbon monoxide is to be recovered from streams also bearing nitrogen, chemical complexation is the logical choice. The economics in terms of capital costs and operating costs strongly favor COPure^{SM} over non-copper complexing processes.

Other advantages to the COPure^{SM} process are:

- Recovery of CO in almost quantitative yields.
- No removal of H_2, N_2, CH_4, or CO_2 from feed required.
- High pressure or extreme temperatures not required.
- Solvent is non-corrosive. Carbon steel fabrication throughout.

The successful operation of the COPure^{SM} process relies on pretreatment of the feed stream and specifics of the COPure^{SM} design, which addresses known problems related to operation of this type of process. Water reacts quantitatively with the active $CuAlCl_4$ complex forming HCl. Any strong Lewis Base will also react with the solvent and cause it to degrade. These include ammonia, alcohols, ethers, amines, sulfides, and nitrides. The degradation products include HCl, insoluble or partially soluble inorganic compounds, and partially soluble heavy organic compounds (tars). The COPure^{SM} design includes pretreatment as required, and complete characterization of the feed is required to ensure reliable operation.

Both organic and inorganic partially soluble compounds will tend to come out at the coldest part of the plant, which is the lean solvent coolers. Therefore, special attention has been applied to this part of the plant design to ensure successful operation.

Some tar formation is normal and may be associated with the Friedel-Craft reaction of toluene (component of the solvent) catalyzed by Aluminum Chloride. In fact, fresh solvent will have some tar dissolved in it as a result of the solvent manufacturing process.

Tar is also produced by undesirable components in the feed. For, example, olefins will form alkylates that degrade at higher temperatures found in the stripper column to form high molecular weight organics (tar). The tar normally produced is accommodated by proper design. Provided contaminants in the feed are kept within specifications, the amount of tar formed is well within design parameters, and will not impact operation. These tars are properly addressed in the COPure^{SM} design.

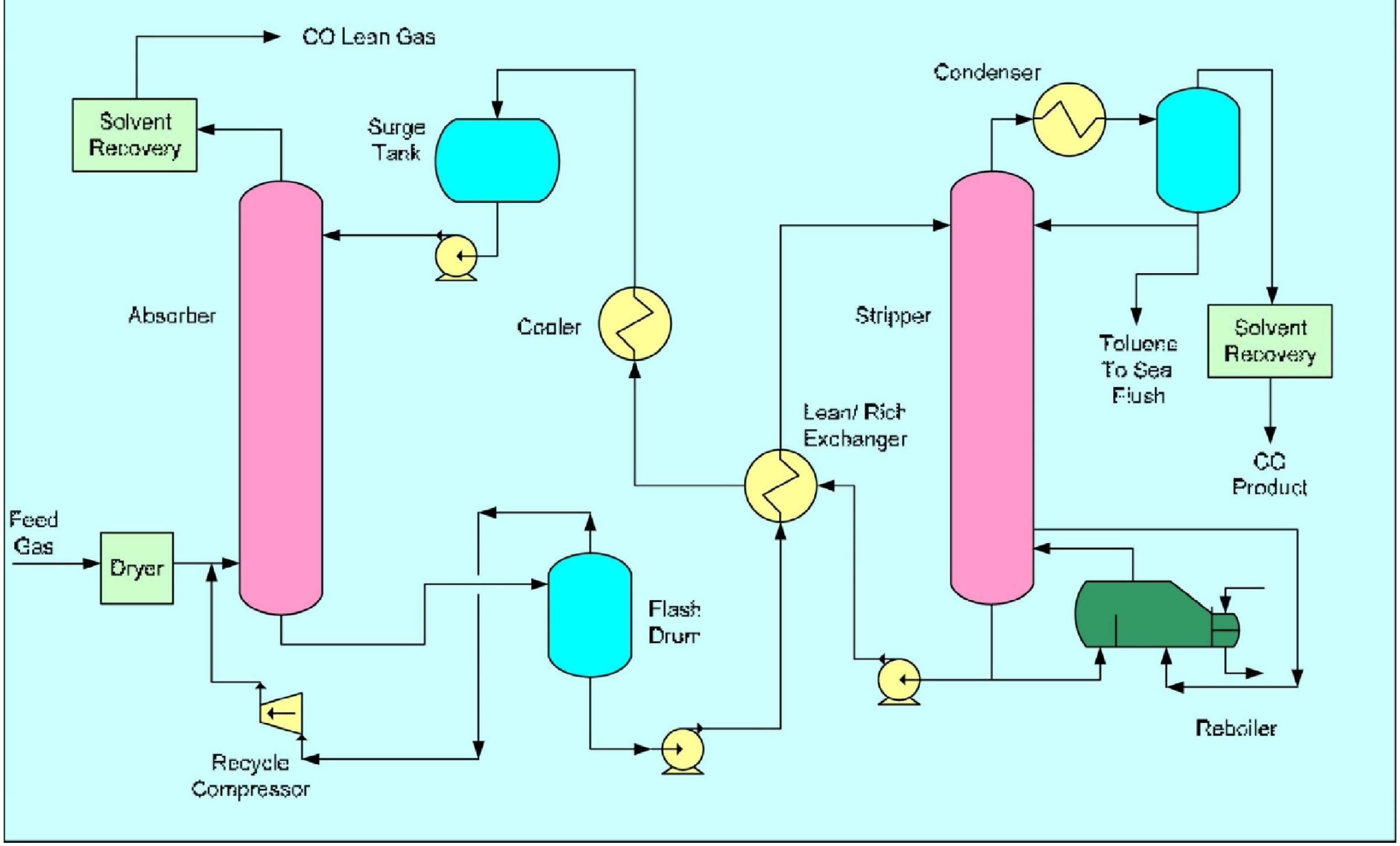
A typical flow diagram is attached as well as typical installed costs for a COPure^{SM} unit with out pretreatment or post treatment steps.

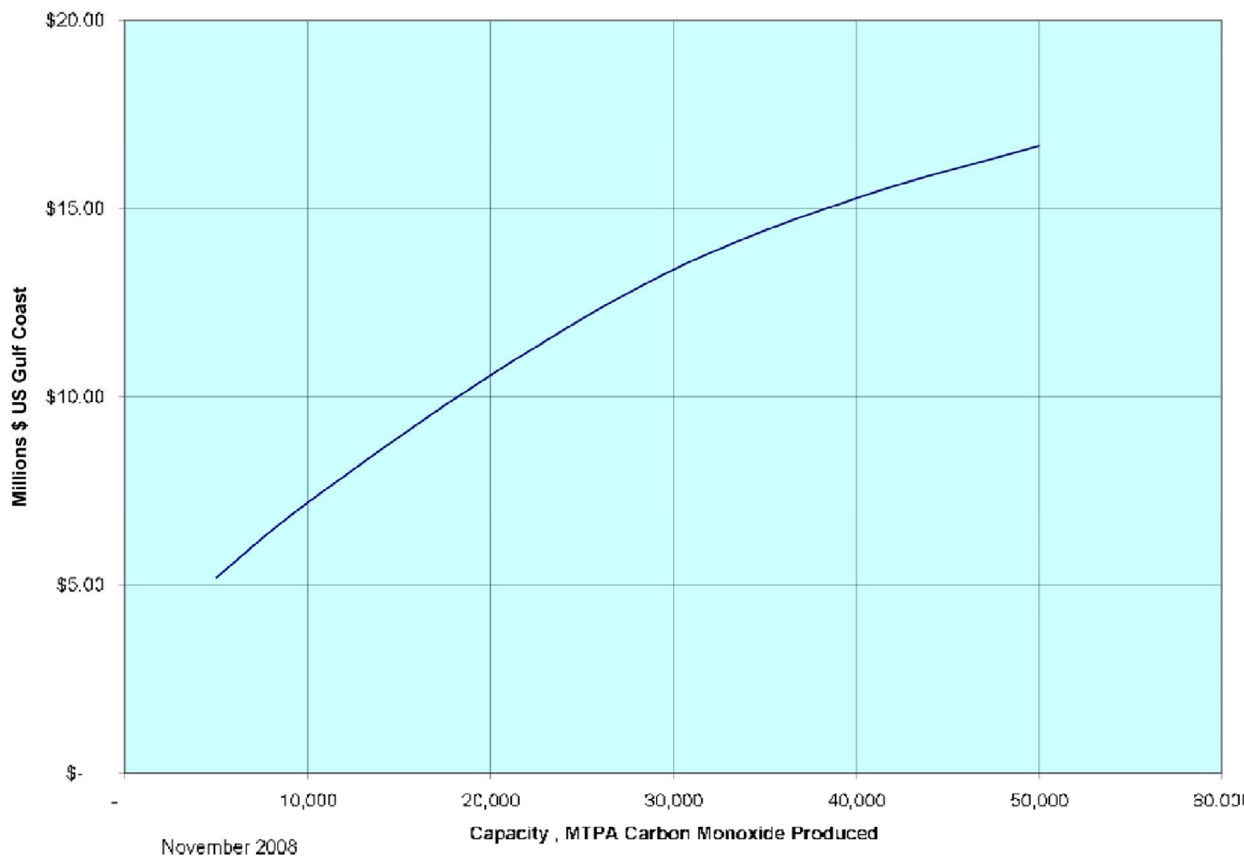
Conclusion

---

[1] Leblanc, F.: *Compt. Rend*., **30**:483 (1850)
[2] Badische Anilin und Soda Fabrik (BASF): German Patent 289,694 (April 3, 1914).
[3] Kohl, Arthur L., and Riesenfeld, Fred C., "Gas Purification," McGraw-Hill (1960), pg 502
[4] Haase, D. J., and D. G. Walker, "A Process for the Recovery of Carbon Monoxide," paper presented at Fourth Joint Meeting, AIChE-CSChE, Vancouver, B.C. (September, 9 – 12, 1973).

The COPURE^{SM} Process




$20.00
$15.00
$10.00
$5.00
$-
Millions $ US Gulf Coast
-
10,000
20,000
30,000
40,000
50,000
60,000
Capacity , MTPA Carbon Monoxide Produced
November 2008

COPure[SM] Utility Requirements

Electrical Power*

$$\frac{0.55\ \text{Kw-hr}}{\text{Nm}^3\ \text{of CO Recovered}} \times \frac{\text{Nm3}}{38.04\ \text{scf}} = \frac{0.01\ \text{kw}}{\text{scf}} \times \frac{\text{scf}}{0.0725\ \text{lbs}} = \frac{0.20\ \text{kw}}{\text{lbs}}$$

Reboiler

$$\frac{1\ \text{Megajoule}}{\text{Nm}^3\ \text{of CO Recovered}} \times \frac{947.8\ \text{BTU}}{\text{Megajoule}} \times \frac{\text{Nm3}}{38.04\ \text{scf}} = \frac{24.92\ \text{BTU}}{\text{scf}} \times \frac{\text{scf}}{0.0725\ \text{lbs}} = \frac{343.67\ \text{BTU}}{\text{lbs}}$$

Cooling Water

$$\frac{5.5\ \text{Megajoule}}{\text{Nm}^3\ \text{of CO Recovered}} \times \frac{947.8\ \text{BTU}}{\text{Megajoule}} \times \frac{\text{Nm3}}{38.04\ \text{scf}} = \frac{137.04\ \text{BTU}}{\text{scf}} \times \frac{\text{scf}}{0.0725\ \text{lbs}} = \frac{1890.17\ \text{BTU}}{\text{lbs}}$$

* Based on a summer high when refrigeration load is a maximum.
Average annual rate would typically be between 40 to 70% of this load depending on climatic variations.

List of Plants Utilizing Cuprous Aluminum Chloride Toluene Complex as an Absorption Solvent for Carbon Monoxide Purification

	Year of Operation	Client	CO Capacity NM^3/Hr	Feed	Final Application	Contract Year
1	1976	DOW, U.S.A	3,400	Acetylene Offgas	Phosgene	1975
2	1978	Makhteshim, Israel	270	Naphtha Reforming	Phosgene	1976
3	1980	Korea Fertilizer Co., Korea	690	Ammonia Reformer	Formic Acid	1978
4	1981	Korea Fine Chemical Co.	800	Naphtha Reforming	Phosgene	1978, 1988 *
5	1981	Mobay, U.S.A.	4,000	Nat. Gas Reforming	Phosgene	1979
6	1982	VEB Schwarzheide, East Germany	3,400	Cokeoven Offgas	Phosgene	1979
7	1982	Celanese Mexicana	270	Nat. Gas Reforming	DMF	1978
8	1983	Rochim, Romania'	5,230	Acetylene Offgas	Acetic Acid	1978
9	1985	Kobe Steel, Japan	500	B.O.F. Gas		1984
10	1987	M.S.K. , Yugoslavia	5,500	P.O.X. Nat. Gas	Acetic Acid	1978
11	1988	PT SKP, Indonesia	790	Ammonia Reformer	Formic Acid	1986
12	1989	Norinco, P.R. China	1000	Cokeoven Offgas	Phosgene	1985
13	1990	Korea Fine Chemical Co.	600	Naphtha Reforming	Phosgene	1988
14	1990	Rashtriya Chem. & Fertilizer, India	110	Ammonia Reformer	DMF	1987
15	1990	P.I.B., Yugoslavia	900	Nat. Gas Reforming	Phosgene	1977

* Expanded from 690 to 800 NM^3/Hr in 1988

Appendix C - Cash Flow Sensitivities

Cash Flow Summary- Oil Price Low Case

Cash Flow Summary- Oil Price Low Case

April, 2009

Alaskan Natural Gas to Liquids Using Microchannel Reactor

Year	Percentage of Design Capacity	Output (bbl)	EIA Base Case AEO2009	EIA Low Price Case AEO2009	Sales	Capital Costs	Working Capital	Total Variable Costs	Fixed Costs	Depreciation Allowance	Total Income Tax	Effective Tax Rate	Net Earnings	Annual Cash Flow	Cumulative Net Present Value at 13.0%
2009	0.0%	0	$ 58.61	$ 59.04	Design	$ -	$ -			$ -			$ -	$ -	$ -
2010	0.0%	0	$ 77.56	$ 55.45	Construction	$ (2,129,023,267)	$ -			$ -			$ -	$ (2,092,382,367)	$ (1,638,642,311)
2011	0.0%	0	$ 85.58	$ 53.14	Construction	$ (2,092,382,367)	$ -			$ -			$ -	$ (2,092,382,367)	$ (3,088,768,250)
2012	0.0%	0	$ 94.84	$ 50.51	Construction	$ (2,092,382,367)	$ (68,496,900)			$ -			$ -	$ (2,160,879,267)	$ (4,414,075,972)
2013	45.0%	18521843	$ 99.75	$ 49.15	$ 910,435,705	$ (549,613,400)	$ (75,839,294)	$ (183,406,512)	$ (629,052,991)	$ 766,448,446	$ (383,435,679)	57.36%	$ (285,036,565)	$ (144,040,813)	$ (4,492,255,554)
2014	67.5%	27782764	$ 104.96	$ 48.14	$ 1,337,513,526	$ -	$ (35,575,582)	$ (275,723,946)	$ (644,150,262)	$ 1,226,317,514	$ (463,857,814)	57.36%	$ (344,820,383)	$ 845,921,549	$ (4,085,943,762)
2015	90.0%	37043685	$ 108.52	$ 46.97	$ 1,740,002,834	$ -	$ (33,527,359)	$ (368,248,725)	$ (659,609,869)	$ 735,790,509	$ (13,563,499)	57.36%	$ (10,082,769)	$ 692,180,381	$ (3,791,725,124)
2016	90.0%	37043685	$ 109.77	$ 47.03	$ 1,742,311,706	$ -	$ -	$ (370,981,724)	$ (675,440,505)	$ 441,474,305	$ 145,932,542	57.36%	$ 108,482,629	$ 549,956,934	$ (3,584,853,399)
2017	90.0%	37043685	$ 110.73	$ 47.00	$ 1,741,059,413	$ -	$ -	$ (373,617,570)	$ (691,651,078)	$ 441,474,305	$ 134,403,921	57.36%	$ 99,912,539	$ 541,386,844	$ (3,404,633,930)
2018	90.0%	37043685	$ 111.58	$ 46.99	$ 1,740,531,477	$ -	$ -	$ (376,350,625)	$ (708,250,703)	$ 220,737,153	$ 249,626,702	57.36%	$ 185,566,293	$ 406,303,446	$ (3,284,941,669)
2019	90.0%	37043685	$ 112.50	$ 46.89	$ 1,736,969,323	$ -	$ -	$ (379,013,303)	$ (725,248,720)	$ -	$ 362,920,907	57.36%	$ 269,786,393	$ 269,786,393	$ (3,214,608,990)
2020	90.0%	37043685	$ 112.05	$ 46.77	$ 1,732,546,306	$ -	$ -	$ (381,704,994)	$ (742,654,690)	$ -	$ 348,855,847	57.36%	$ 259,330,776	$ 259,330,776	$ (3,154,779,853)
2021	90.0%	37043685	$ 112.33	$ 46.69	$ 1,729,684,911	$ -	$ -	$ (384,536,335)	$ (760,478,402)	$ -	$ 335,366,812	57.36%	$ 249,303,362	$ 249,303,362	$ (3,103,880,956)
2022	90.0%	37043685	$ 114.09	$ 46.65	$ 1,728,139,823	$ -	$ -	$ (387,497,952)	$ (778,729,884)	$ -	$ 322,312,716	57.36%	$ 239,599,271	$ 239,599,271	$ (3,060,590,986)
2023	90.0%	37043685	$ 112.97	$ 46.56	$ 1,724,845,735	$ -	$ -	$ (390,453,612)	$ (797,419,401)	$ -	$ 308,007,553	57.36%	$ 228,965,169	$ 228,965,169	$ (3,023,981,573)
2024	90.0%	37043685	$ 114.03	$ 46.49	$ 1,722,158,010	$ -	$ -	$ (393,511,052)	$ (816,557,467)	$ -	$ 293,734,532	57.36%	$ 218,354,959	$ 218,354,959	$ (2,993,085,167)
2025	90.0%	37043685	$ 115.33	$ 46.42	$ 1,719,517,625	$ -	$ -	$ (396,646,903)	$ (836,154,846)	$ -	$ 279,180,226	57.36%	$ 207,535,649	$ 207,535,649	$ (2,967,097,986)
2026	90.0%	37043685	$ 116.49	$ 46.42	$ 1,719,391,011	$ -	$ -	$ (399,973,986)	$ (856,222,562)	$ -	$ 265,688,343	57.36%	$ 197,506,119	$ 197,506,119	$ (2,945,211,876)
2027	90.0%	37043685	$ 118.65	$ 46.46	$ 1,721,147,641	$ -	$ -	$ (403,465,802)	$ (876,771,904)	$ -	$ 252,905,939	57.36%	$ 188,003,996	$ 188,003,996	$ (2,926,775,453)
2028	90.0%	37043685	$ 120.71	$ 46.50	$ 1,722,397,249	$ -	$ -	$ (407,016,708)	$ (897,814,429)	$ -	$ 239,515,921	57.36%	$ 178,050,190	$ 178,050,190	$ (2,911,323,849)
2029	90.0%	37043685	$ 121.97	$ 46.41	$ 1,719,213,949	$ -	$ -	$ (410,452,006)	$ (919,361,976)	$ -	$ 223,359,821	57.36%	$ 166,040,146	$ 166,040,146	$ (2,898,572,217)
2030	90.0%	37043685	$ 124.60	$ 46.44	$ 1,720,273,636	$ -	$ -	$ (414,164,123)	$ (941,426,663)	$ -	$ 209,182,082	57.36%	$ 155,500,767	$ 155,500,767	$ (2,888,003,877)
2031	90.0%	37043685	$ 126.30	$ 46.44	$ 1,720,450,215	$ -	$ -	$ (417,924,447)	$ (964,020,903)	$ -	$ 194,166,391	57.36%	$ 144,338,475	$ 144,338,475	$ (2,879,322,714)
2032	90.0%	37043685	$ 128.01	$ 46.45	$ 1,720,626,812	$ -	$ -	$ (421,774,828)	$ (987,157,405)	$ -	$ 178,788,011	57.36%	$ 132,906,569	$ 132,906,569	$ (2,872,248,734)
2033	90.0%	37043685	$ 129.74	$ 46.45	$ 1,720,803,428	$ -	$ -	$ (425,717,429)	$ (1,010,849,182)	$ -	$ 163,038,238	57.36%	$ 121,198,579	$ 121,198,579	$ (2,866,540,044)
2034	90.0%	37043685	$ 131.51	$ 46.46	$ 1,720,980,062	$ -	$ -	$ (429,754,462)	$ (1,035,109,563)	$ -	$ 146,908,159	57.36%	$ 109,207,878	$ 109,207,878	$ (2,861,987,917)
2035	90.0%	37043685	$ 133.29	$ 46.46	$ 1,721,156,714	$ -	$ -	$ (433,888,194)	$ (1,059,952,192)	$ -	$ 130,388,645	57.36%	$ 96,927,682	$ 96,927,682	$ (2,858,412,474)
2036	90.0%	37043685	$ 135.10	$ 46.47	$ 1,721,333,384	$ -	$ -	$ (438,120,946)	$ (1,085,391,045)	$ -	$ 113,470,351	57.36%	$ 84,351,042	$ 84,351,042	$ (2,855,658,917)
2037	90.0%	37043685	$ 136.93	$ 46.47	$ 1,721,510,072	$ -	$ 213,439,136	$ (442,455,094)	$ (1,111,440,430)	$ -	$ 96,143,705	57.36%	$ 71,470,843	$ 284,909,980	$ (2,847,428,292)
Totals Where Applicable:						$ (6,863,401,400)									

*The tax is imposed on the net profit earned on each barrel of oil pumped from state lands, after deducting costs for production and transportation.
The tax is set at its highest rate in Prudhoe Bay, where the state takes 25 percent of the net profit of a barrel when its price is at or below $52.
The percentage then escalates as oil prices rise over that benchmark.

IRR: 0.11%

Cash Flow Summary- Oil Price High Case

Cash Flow Summary- Oil Price High Case

April, 2009

Alaskan Natural Gas to Liquids Using Microchannel Reactor

Year	Percentage of Design Capacity	Output (bbl)	EIA Base Case AEO2009	EIA High Price Case AEO2009	EIA Low Price Case AEO2009	Sales	Capital Costs	Working Capital	Total Variable Costs	Fixed Costs	Depreciation Allowance	Total Income Tax	Effective Tax Rate	Net Earnings	Annual Cash Flow	Cumulative Net Present Value at 13.0%
2009	0.0%	0	$ 58.61	$ 58.55	$ 59.04	Design	$ -	$ -			$ -			$ -	$ -	$ -
2010	0.0%	0	$ 77.56	$ 88.31	$ 55.45	Construction	$ (2,129,023,267)	$ -			$ -			$ -	$ (2,092,382,367)	$ (1,638,642,311)
2011	0.0%	0	$ 85.58	$ 101.96	$ 53.14	Construction	$ (2,092,382,367)	$ -			$ -			$ -	$ (2,092,382,367)	$ (3,088,768,250)
2012	0.0%	0	$ 94.84	$ 115.73	$ 50.51	Construction	$ (2,092,382,367)	$ (68,496,900)			$ -			$ -	$ (2,160,879,267)	$ (4,414,075,972)
2013	45.0%	18521843	$ 99.75	$ 128.87	$ 49.15	$ 2,386,872,447	$ (549,613,400)	$ (198,826,475)	$ (249,846,166)	$ (629,052,991)	$ 766,448,446	$ 462,388,337	62.36%	$ 279,136,507	$ 297,145,078	$ (4,252,797,528)
2014	67.5%	27782764	$ 104.96	$ 143.17	$ 48.14	$ 3,977,653,572	$ -	$ (132,512,068)	$ (394,530,248)	$ (644,150,262)	$ 1,226,317,514	$ 1,083,871,857	63.29%	$ 628,783,690	$ 1,722,589,137	$ (3,425,406,051)
2015	90.0%	37043685	$ 108.52	$ 154.85	$ 46.97	$ 5,736,318,288	$ -	$ (146,496,771)	$ (548,082,920)	$ (659,609,869)	$ 735,790,509	$ 2,429,137,550	64.05%	$ 1,363,697,439	$ 1,952,991,178	$ (2,595,266,364)
2016	90.0%	37043685	$ 109.77	$ 163.99	$ 47.03	$ 6,074,872,675	$ -	$ -	$ (565,946,968)	$ (675,440,505)	$ 441,474,305	$ 2,838,973,366	64.64%	$ 1,553,037,531	$ 1,994,511,836	$ (1,845,011,067)
2017	90.0%	37043685	$ 110.73	$ 170.89	$ 47.00	$ 6,330,445,614	$ -	$ -	$ (580,139,949)	$ (691,651,078)	$ 441,474,305	$ 3,005,227,450	65.09%	$ 1,611,952,832	$ 2,053,427,137	$ (1,161,456,317)
2018	90.0%	37043685	$ 111.58	$ 175.90	$ 46.99	$ 6,515,985,096	$ -	$ -	$ (591,246,037)	$ (708,250,703)	$ 220,737,153	$ 3,267,895,792	65.41%	$ 1,727,855,410	$ 1,948,592,563	$ (587,423,653)
2019	90.0%	37043685	$ 112.50	$ 178.78	$ 46.89	$ 6,622,678,438	$ -	$ -	$ (598,870,213)	$ (725,248,720)	$ -	$ 3,475,892,909	65.60%	$ 1,822,666,596	$ 1,822,666,596	$ (112,258,749)
2020	90.0%	37043685	$ 112.05	$ 181.18	$ 46.77	$ 6,711,705,713	$ -	$ -	$ (605,767,167)	$ (742,654,690)	$ -	$ 3,526,730,791	65.76%	$ 1,836,553,065	$ 1,836,553,065	$ 311,444,857
2021	90.0%	37043685	$ 112.33	$ 182.20	$ 46.69	$ 6,749,363,251	$ -	$ -	$ (610,421,860)	$ (760,478,402)	$ -	$ 3,540,266,056	65.82%	$ 1,838,196,933	$ 1,838,196,933	$ 686,739,419
2022	90.0%	37043685	$ 114.09	$ 183.54	$ 46.65	$ 6,798,824,167	$ -	$ -	$ (615,678,748)	$ (778,729,884)	$ -	$ 3,562,039,204	65.91%	$ 1,842,376,331	$ 1,842,376,331	$ 1,019,613,620
2023	90.0%	37043685	$ 112.97	$ 185.41	$ 46.56	$ 6,868,222,856	$ -	$ -	$ (621,905,583)	$ (797,419,401)	$ -	$ 3,597,992,700	66.03%	$ 1,850,905,173	$ 1,850,905,173	$ 1,315,556,242
2024	90.0%	37043685	$ 114.03	$ 186.93	$ 46.49	$ 6,924,748,730	$ -	$ -	$ (627,627,634)	$ (816,557,467)	$ -	$ 3,624,337,998	66.13%	$ 1,856,225,631	$ 1,856,225,631	$ 1,578,205,192
2025	90.0%	37043685	$ 115.33	$ 188.89	$ 46.42	$ 6,997,228,552	$ -	$ -	$ (634,143,895)	$ (836,154,846)	$ -	$ 3,662,029,412	66.26%	$ 1,864,900,400	$ 1,864,900,400	$ 1,811,724,128
2026	90.0%	37043685	$ 116.49	$ 191.22	$ 46.42	$ 7,083,319,396	$ -	$ -	$ (641,350,764)	$ (856,222,562)	$ -	$ 3,709,437,806	66.41%	$ 1,876,308,264	$ 1,876,308,264	$ 2,019,642,185
2027	90.0%	37043685	$ 118.65	$ 192.52	$ 46.46	$ 7,131,743,094	$ -	$ -	$ (646,942,598)	$ (876,771,904)	$ -	$ 3,729,000,454	66.49%	$ 1,879,028,139	$ 1,879,028,139	$ 2,203,907,188
2028	90.0%	37043685	$ 120.71	$ 194.16	$ 46.50	$ 7,192,296,880	$ -	$ -	$ (653,162,192)	$ (897,814,429)	$ -	$ 3,757,131,464	66.60%	$ 1,884,188,795	$ 1,884,188,795	$ 2,367,421,415
2029	90.0%	37043685	$ 121.97	$ 196.04	$ 46.41	$ 7,262,201,461	$ -	$ -	$ (659,886,444)	$ (919,361,976)	$ -	$ 3,791,829,727	66.72%	$ 1,891,123,314	$ 1,891,123,314	$ 2,512,656,832
2030	90.0%	37043685	$ 124.60	$ 197.72	$ 46.44	$ 7,324,223,180	$ -	$ -	$ (666,341,853)	$ (941,426,663)	$ -	$ 3,820,404,110	66.83%	$ 1,896,050,554	$ 1,896,050,554	$ 2,641,518,621
2031	90.0%	37043685	$ 126.30	$ 199.04	$ 46.44	$ 7,373,149,489	$ -	$ -	$ (672,295,914)	$ (964,020,903)	$ -	$ 3,838,948,166	66.92%	$ 1,897,884,506	$ 1,897,884,506	$ 2,755,665,905
2032	90.0%	37043685	$ 128.01	$ 200.37	$ 46.45	$ 7,422,402,630	$ -	$ -	$ (678,354,740)	$ (987,157,405)	$ -	$ 3,857,345,685	67.00%	$ 1,899,544,801	$ 1,899,544,801	$ 2,856,769,569
2033	90.0%	37043685	$ 129.74	$ 201.71	$ 46.45	$ 7,471,984,784	$ -	$ -	$ (684,520,590)	$ (1,010,849,182)	$ -	$ 3,875,587,619	67.09%	$ 1,901,027,393	$ 1,901,027,393	$ 2,946,311,672
2034	90.0%	37043685	$ 131.51	$ 203.05	$ 46.46	$ 7,521,898,151	$ -	$ -	$ (690,795,776)	$ (1,035,109,563)	$ -	$ 3,893,664,635	67.18%	$ 1,902,328,177	$ 1,902,328,177	$ 3,025,606,691
2035	90.0%	37043685	$ 133.29	$ 204.41	$ 46.46	$ 7,572,144,943	$ -	$ -	$ (697,182,664)	$ (1,059,952,192)	$ -	$ 3,911,567,103	67.27%	$ 1,903,442,983	$ 1,903,442,983	$ 3,095,820,397
2036	90.0%	37043685	$ 135.10	$ 205.78	$ 46.47	$ 7,622,727,386	$ -	$ -	$ (703,683,676)	$ (1,085,391,045)	$ -	$ 3,929,285,088	67.36%	$ 1,904,367,577	$ 1,904,367,577	$ 3,157,986,603
2037	90.0%	37043685	$ 136.93	$ 207.15	$ 46.47	$ 7,673,647,724	$ -	$ 546,332,213	$ (710,301,288)	$ (1,111,440,430)	$ -	$ 3,946,808,343	67.44%	$ 1,905,097,663	$ 2,451,429,876	$ 3,228,804,759
Totals Where Applicable:							$ (6,863,401,400)									

*The tax is imposed on the net profit earned on each barrel of oil pumped from state lands, after deducting costs for production and transportation.
The tax is set at its highest rate in Prudhoe Bay, where the state takes 25 percent of the net profit of a barrel when its price is at or below $52.
The percentage then escalates as oil prices rise over that benchmark.

IRR: 20.69%

Cash Flow Summary- Oil Price Breakeven Cash

Cash Flow Summary- Oil Price Breakeven

April, 2009

Alaskan Natural Gas to Liquids Using Microchannel Reactor

Year	Percentage of Design Capacity	Output (bbl)	EIA Base Case AEO2009	Breakeven Case	Sales	Capital Costs	Working Capital	Total Variable Costs	Fixed Costs	Depreciation Allowance	Total Income Tax	Effective Tax Rate	Net Earnings	Annual Cash Flow	Cumulative Net Present Value at 13.0%
2009	0.0%	0	$58.61	$87.73	Design	$ -	$ -			$ -			$ -	$ -	$ -
2010	0.0%	0	$77.56	$88.61	Construction	$ (2,129,023,267)	$ -			$ -			$ -	$ (2,092,382,367)	$ (1,638,642,311)
2011	0.0%	0	$85.58	$89.49	Construction	$ (2,092,382,367)	$ -			$ -			$ -	$ (2,092,382,367)	$ (3,088,768,250)
2012	0.0%	0	$94.84	$90.39	Construction	$ (2,092,382,367)	$ (68,496,900)			$ -			$ -	$ (2,160,879,267)	$ (4,414,075,972)
2013	45.0%	18521843	$99.75	$91.29	$ 1,690,894,972	$ (549,613,400)	$ (140,851,551)	$ (218,527,179)	$ (629,052,991)	$ 766,448,446	$ 46,053,690	59.91%	$ 30,812,666	$ 106,796,161	$ (4,356,111,295)
2014	67.5%	27782764	$104.96	$92.20	$ 2,561,705,883	$ -	$ (72,538,549)	$ (330,812,602)	$ (644,150,262)	$ 1,226,317,514	$ 216,159,127	59.97%	$ 144,266,378	$ 1,298,045,343	$ (3,732,636,067)
2015	90.0%	37043685	$108.52	$93.13	$ 3,449,763,922	$ -	$ (73,975,235)	$ (445,187,974)	$ (659,609,869)	$ 735,790,509	$ 966,040,380	60.03%	$ 643,135,191	$ 1,304,950,465	$ (3,177,952,982)
2016	90.0%	37043685	$109.77	$94.06	$ 3,484,261,561	$ -	$ -	$ (449,369,468)	$ (675,440,505)	$ 441,474,305	$ 1,152,585,080	60.09%	$ 765,392,202	$ 1,206,866,507	$ (2,723,978,244)
2017	90.0%	37043685	$110.73	$95.00	$ 3,519,104,177	$ -	$ -	$ (453,629,585)	$ (691,651,078)	$ 441,474,305	$ 1,162,403,111	60.15%	$ 769,946,099	$ 1,211,420,404	$ (2,320,714,764)
2018	90.0%	37043685	$111.58	$95.95	$ 3,554,295,219	$ -	$ -	$ (457,969,993)	$ (708,250,703)	$ 220,737,153	$ 1,305,098,362	60.22%	$ 862,239,007	$ 1,082,976,160	$ (2,001,682,606)
2019	90.0%	37043685	$112.50	$96.91	$ 3,589,838,171	$ -	$ -	$ (462,392,401)	$ (725,248,720)	$ -	$ 1,448,021,209	60.28%	$ 954,175,841	$ 954,175,841	$ (1,752,931,204)
2020	90.0%	37043685	$112.05	$97.88	$ 3,625,736,552	$ -	$ -	$ (466,898,555)	$ (742,654,690)	$ -	$ 1,457,973,953	60.34%	$ 958,209,355	$ 958,209,355	$ (1,531,866,664)
2021	90.0%	37043685	$112.33	$98.86	$ 3,661,993,918	$ -	$ -	$ (471,490,240)	$ (760,478,402)	$ -	$ 1,467,872,465	60.41%	$ 962,152,811	$ 962,152,811	$ (1,335,429,214)
2022	90.0%	37043685	$114.09	$99.84	$ 3,698,613,857	$ -	$ -	$ (476,169,284)	$ (778,729,884)	$ -	$ 1,477,711,888	60.47%	$ 966,002,802	$ 966,002,802	$ (1,160,895,160)
2023	90.0%	37043685	$112.97	$100.84	$ 3,735,599,996	$ -	$ -	$ (480,937,554)	$ (797,419,401)	$ -	$ 1,487,487,196	60.53%	$ 969,755,845	$ 969,755,845	$ (1,005,840,167)
2024	90.0%	37043685	$114.03	$101.85	$ 3,772,955,996	$ -	$ -	$ (485,796,961)	$ (816,557,467)	$ -	$ 1,497,193,184	60.60%	$ 973,408,384	$ 973,408,384	$ (868,106,539)
2025	90.0%	37043685	$115.33	$102.87	$ 3,810,685,556	$ -	$ -	$ (490,749,460)	$ (836,154,846)	$ -	$ 1,506,824,467	60.67%	$ 976,956,783	$ 976,956,783	$ (745,774,050)
2026	90.0%	37043685	$116.49	$103.90	$ 3,848,792,411	$ -	$ -	$ (495,797,049)	$ (856,222,562)	$ -	$ 1,516,375,473	60.73%	$ 980,397,327	$ 980,397,327	$ (637,133,955)
2027	90.0%	37043685	$118.65	$104.94	$ 3,887,280,335	$ -	$ -	$ (500,941,773)	$ (876,771,904)	$ -	$ 1,525,840,436	60.80%	$ 983,726,222	$ 983,726,222	$ (540,665,834)
2028	90.0%	37043685	$120.71	$105.99	$ 3,926,153,139	$ -	$ -	$ (506,185,723)	$ (897,814,429)	$ -	$ 1,535,213,392	60.87%	$ 986,939,594	$ 986,939,594	$ (455,016,951)
2029	90.0%	37043685	$121.97	$107.05	$ 3,965,414,670	$ -	$ -	$ (511,531,038)	$ (919,361,976)	$ -	$ 1,544,488,171	60.94%	$ 990,033,485	$ 990,033,485	$ (378,983,873)
2030	90.0%	37043685	$124.60	$108.12	$ 4,005,068,817	$ -	$ -	$ (516,979,906)	$ (941,426,663)	$ -	$ 1,553,658,392	61.01%	$ 993,003,855	$ 993,003,855	$ (311,496,088)
2031	90.0%	37043685	$126.30	$109.20	$ 4,045,119,505	$ -	$ -	$ (522,534,565)	$ (964,020,903)	$ -	$ 1,562,717,458	61.08%	$ 995,846,580	$ 995,846,580	$ (251,601,409)
2032	90.0%	37043685	$128.01	$110.29	$ 4,085,570,700	$ -	$ -	$ (528,197,303)	$ (987,157,405)	$ -	$ 1,571,658,545	61.15%	$ 998,557,448	$ 998,557,448	$ (198,452,983)
2033	90.0%	37043685	$129.74	$111.39	$ 4,126,426,407	$ -	$ -	$ (533,970,463)	$ (1,010,849,182)	$ -	$ 1,580,474,599	61.22%	$ 1,001,132,163	$ 1,001,132,163	$ (151,297,703)
2034	90.0%	37043685	$131.51	$112.51	$ 4,167,690,671	$ -	$ -	$ (539,856,440)	$ (1,035,109,563)	$ -	$ 1,589,158,329	61.29%	$ 1,003,566,340	$ 1,003,566,340	$ (109,465,903)
2035	90.0%	37043685	$133.29	$113.63	$ 4,209,367,578	$ -	$ -	$ (545,857,683)	$ (1,059,952,192)	$ -	$ 1,597,702,196	61.37%	$ 1,005,855,506	$ 1,005,855,506	$ (72,362,168)
2036	90.0%	37043685	$135.10	$114.77	$ 4,251,461,254	$ -	$ -	$ (551,976,700)	$ (1,085,391,045)	$ -	$ 1,606,098,411	61.44%	$ 1,007,995,098	$ 1,007,995,098	$ (39,457,160)
2037	90.0%	37043685	$136.93	$115.92	$ 4,293,975,866	$ -	$ 355,862,235	$ (558,216,054)	$ (1,111,440,430)	$ -	$ 1,614,338,920	61.51%	$ 1,009,980,462	$ 1,365,842,696	$ (0)
Totals Where Applicable:						$ (6,863,401,400)									

*The tax is imposed on the net profit earned on each barrel of oil pumped from state lands, after deducting costs for production and transportation.
The tax is set at its highest rate in Prudhoe Bay, where the state takes 25 percent of the net profit of a barrel when its price is at or below $52.
The percentage then escalates as oil prices rise over that benchmark.

IRR: 13.00%

Appendix D - Problem Statement

2. Alaskan Natural Gas to Liquid (GTL) using Microchannel Reactors (recommended by John Wismer, Arkema, Inc.)

The development of technology to convert methane to useful hydrocarbons has been escalating in recent years. This family of technologies – designated as Gas to Liquids or GTL – can target a variety of end products, such as methanol, gasoline or diesel fuel. As of today, most of the natural gas produced by oil wells in remote locations – sometimes referred to as stranded gas- is wasted. As a result, a premium is put on technologies most easily adapted to hostile environments. For most technologies the first step is the steam reforming of methane into a mixture of mostly CO and H_2 – usually called syngas. The syngas is then converted to a useful liquid, such as methanol, gasoline, or diesel fuel in a catalyzed synthesis reaction.

Your client is a major oil company that is exploring technology options in this area. You have been asked to evaluate a promising technology that offers the possibility of a compact plant through the use of microchannel technology. The use of microchannels in heat exchangers has been shown to increase overall heat transfer coefficients by as much as an order of magnitude. This technology has been extended to reactor systems, in which the combined effects of high heat and mass transfer rates yield very high reaction rates – even for highly exothermic or endothermic systems. The potentially small footprints of microchannel systems makes them ideally suited to the challenge of GTL processing in remote locations.

The proposed technology first proposes using the steam reforming of methane to produce a synthesis gas:

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO \qquad (3)$$

In addition to being highly endothermic, the above reaction is both kinetically and equilibrium limited. Invariably, it is accompanied by the water-gas shift reaction.

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

The required heat is often supplied by partial combustion of the methane using an air co feed. With the microchannel technology, the heat can be supplied by fuel combustion that occurs in adjacent channels[2,5]. Part of the advantage of microchannels is the ability to run combustion reactions in a controlled manner. The very high surface area to volume ratio allows free radicals to get “quenched” as they are formed, tempering the rate of combustion. Furthermore, since the heat of combustion is transferred as quickly as it is generated, there is no need to operate with a large amount of excess air in the combustion channels. On the process side, the channels are coated with a highly effective catalyst and diffusion is eliminated as a mass-transfer resistance. The second step of the process is the Fischer-Tropsch synthesis, whereby the carbon monoxide in the syngas is hydrogenated into alipahatic hydrocarbons primarily. The target products are paraffinic oligomers in the C5 to C10 range:

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

However, the synthesis also can produce olefins, alcohols, coke, and carbon dioxide[7]. The Fischer-Tropsch synthesis is highly exothermic. One of the non-selectives of Fischer-Tropsch synthesis is methane. Together with the light gases, methane can be recycled either to the inlet of the Fischer-Tropsch reactor or to the reformer. One of the problems with the above process is that hydrogen is produced in excess. Either the excess hydrogen can be oxidized to recover energy or CO_2 from combustion can be added to the make up the carbon deficit. In most process concepts, the latter approach, called autothermal reforming[8], is used but that technique compromises some of the microchannel advantages. A major design challenge is to seek a heat and material balance that makes optimum use of the microchannel technology.

The only current commercialization venture involving this technology is offshore oil drilling platform[6]. However, it appears to be well suited to onshore areas that place a premium on small footprint, low environmental-impact processing. The site for you to explore is the North Slope of Alaska, where this technology can be used in lieu of or as a stopgap measure for a trans-continental pipeline that is in the planning stages. In this sense, the North Slope gas is not truly stranded. BP claims that the pipeline project is more economical then GTL technologies at the gas production capacities of the North Slope[9]. However, the pipeline project is long term and expensive, costing $30B to $40B by the time it is completed in 2018, the earliest possible date. The scale of the GTL project should be about 100 kbpd – the scale originally proposed by Exxon for its now abandoned Alaskan GTL project[10]. At this capacity, the liquid product can be fed directly into the TAPS (Trans Alaskan Pipeline System) where it would be blended with crude oil for shipment to U.S. Northwest refineries. The current TAPS throughput is about 700kpd with a maximum[4] capacity of about 2Mbpd. At this capacity, the TAPS will still have enough capacity to handle the ANWR oil – if it ever gets delivered.

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1. Wang, Yong et al., U.S. Patent 7,084,180 B2, "Fischer-Tropsch Synthesis Using Microchannel Technology and Novel Catalyst and Microchannel Reactor", Aug 1, 2006.

2. Tonkovich, A.Y., "Microchannel Process Technology for Compact Methane Steam Reforming" , *Chemical Engineering Science*, **59**, 4819-4824 (2004).

3. Tonkovich, A.Y., "From Seconds to Milliseconds to Microseconds though Tailored Microchannel Reactor Design of a Steam Methane Reformer," *Catalysis Today*, **120**, 21-29 (2007).

4. Cao, C. et al., "Catalyst Screening and Kinetic Studies Using Microchannel Reactors", Catalysis Today, **125**, 29-33 (2007).

5. Tonkovich et al., U.S. Patent 0033455A1, "Integrated combustion Reactors and Methods of Conducting Simultaneous Endothermic and Exothermic Reactions", Feb. 19, 2004

6. "A new Offshore GTL production System takes Advantage of Microchannel Reactors", *Chemical Engineering*, January, 2008.

7. www.pnl.gov/biobased/docs/**acs2003**presentation.pdf (Battelle presentation showing Fischer-Tropsch results).

8. Parkinson, G., "Gas to Liquids Gain Momentum," *Chemical Engineering Progress*, May 2005.

9. Alexander's Oil and Gas Connection, Voume 9, Issue #2- January 29,2004, "BP and Partner prove Alaska GTL technologies" at http://www.gasandoil.com/goc/company/cnn40481.htm

10. See www.arcticgaspipeline.com/GTL.htm.

Appendix E - Pipeline Analysis

Appendix E – Pipeline Analysis

Several postulations were made in order to prepare projected cash flows for TransCanada's natural gas pipeline project. The estimates used in the analysis are summarized in this section.

Since TransCanada, Inc. was awarded a license from the Alaska Legislature for the pipeline project in August, 2008, the company plans to begin on-site construction in April, 2016 and begin operations in September, 2018. However, the project has been delayed multiple times in the past; accounting for construction and legal delays, the project is postulated to begin operation no sooner than 2020.

TransCanada is using a 4.5 billion cubic feet per day capacity as their base case, which is the maximum capacity used in this analysis. Possibilities exist for a 5.1 bcf/day or 5.9 bcf/day pipeline; however, capital cost data in unavailable for these variations at this time. The load factors used for the first two years of operation are 85% and 90%, and 95% onwards.

TransCanada will be charging its customers a high fee for using the pipeline to transport their gas, to cover the large capital cost of the project. According to the Institute of Social and Economic Research, University of Alaska, Anchorage, the tariff charged for pipeline use will be approximately 75% of the value of the gas at the pipeline's outlet. The outlet value of the gas is taken to be the Lower 48 Wellhead price projected in the Energy Information Administration Annual Energy Outlook, 2009. This 75% tariff is the source of the revenue for TransCanada.

The annual capital expenditure in the development phase was obtained from TransCanada's 2007 Application for License to the Alaska Gasline Inducement Act. This capital was depreciated using the 5-year MACRS depreciation schedule.

The cost of operations and maintenance is estimated as a percentage of total revenue. TransCanada's financial statements suggest that the typical total cost of operating its other pipelines was about 37% of pipeline revenue in 2008. A 37.25% factor was used in the cash flow projections. State taxes were at 9.4% and federal tax at 35%. Pipelines are generally not charged oil/gas windfall tax, so none was accounted for in the analysis. One should be mindful, however, that the windfall tax burden may sometimes be shared by a pipeline company under certain circumstances, even though the company is never directly taxed by the government.

A 10% discount rate was used to discount the projected cash flows to obtain an NPV of $1.58 billion; the discount rate was so chosen to reflect that the supply of North Slope gas as well the demand for its transportation will remain strong.

Appendix F - Correspondences

MEA Correspondence

Sophie,
The gas must be free of particulate and free of water. Use a molecular sieve to remove the water vapor.
A scrubber before the dehydration unit can get rid of particulate or a bag house maybe.
The reject gas from the absorption column has all gases but CO.
The gas off of the desorption column is pure CO.
Run the reject has through a mol sieve and recover the Hydrogen.
Back blend the pure hydrogen with the pure Co for your proper ratio.

Regards,

Rocky Costello, P.E.

Sophie

That is metric tons per annum (year) of finished CO.
Use $30.00 per gallon.
Regards,

--
Rocky C. Costello
-Following are the attachments with the correspondence:

Velocys Correspondence

From: McDaniel, Jeff [mailto:mcdaniel@velocys.com]
Sent: Thursday, January 29, 2009 4:27 PM
To: Jeffrey Hammond
Subject: RE: GTL Project Inquiry

Jeff,

The attached report provides an overview of our microchannel technology.
I do not have much additional information that I can provide on a
non-confidential basis. We will have much more information as we
complete the field demonstrations that will occur later this year and in
2010.

Regards,
Jeff McDaniel

Appendix G - MSDS Reports

Material Safety Data Sheet

1. Product and Company Identification

Product name	: **Carbon Dioxide, Gas**
Chemical formula	: CO2
Synonyms	: Carbonic Acid Gas, Carbon Dioxide, Carbon Oxide, Carbonic Anhydride
Company	: Specialty Gases of America, Inc 6055 Brent Dr. Toledo, OH 43611
Telephone	: 419-729-7732
Emergency	: 800-424-9300

2. Composition/Information on Ingredients

Components	CAS Number	% Volume
Carbon Dioxide, Gas	124-38-9	100%

3. Hazards Identification

<u>Emergency Overview</u>

Containers may rupture or explode if exposed to heat.
May cause difficulty breathing.

<u>Potential Health Effects</u>

Inhalation	: Changes in blood pressure, ringing in the ears, nausea, difficulty breathing, irregular heartbeat, headache, drowsiness, dizziness, tingling sensation, tremors, weakness, visual disturbances, suffocation, convulsions, unconsciousness, coma.
Eye contact	: Blurred vision, frostbite.
Skin contact	: Blisters, frostbite.
Ingestion	: Ingestion of a gas is unlikely.
Chronic Health Hazard	: Not applicable.

4. First Aid Measures

General advice	: None.
Eye contact	: Contact with liquid: Immediately flush eyes with plenty of water for at least 15 minutes. Then get immediate medical attention.
Skin contact	: If frostbite or freezing occur, immediately flush with plenty of lukewarm water (105-115 F; 41-46 C). DO NOT USE HOT WATER. If warm water is not available, gently wrap affected parts in blanket. Get immediate medical attention.
Ingestion	: If a large amount is swallowed, get medical attention.
Inhalation	: If adverse effects occur, remove to uncontaminated area. Give artificial respiration if not breathing. If breathing is difficult, oxygen should be

		supplied-air respirator with full facepiece and operated in a pressure-demand or other positive-pressure mode in combination with a separate escape supply. Any self-contained breathing apparatus with a full facepiece.
Hand protection	:	Wear insulated gloves.
Eye protection	:	For the gas: Eye protection is not required, but recommended. For the liquid: Wear splash resistant safety goggles. Contact lenses should not be worn. Provide an emergency eye wash fountain and quick drench shower in the immediate work area.
Skin and body protection	:	For the gas, Protective clothing is not required. For the liquid: Wear appropriate protective, cold insulating clothing.
Ventilation	:	Provide local exhaust ventilation system. Ensure compliance with applicable exposure limits.

9. Physical and Chemical Properties

Form	:	Gas.
Color	:	Colorless.
Odor	:	Odorless.
Taste	:	Acid taste.
Molecular weight	:	44.01
Vapor pressure	:	43700 mmHg @ 21 C
Vapor density	:	1.5 (air = 1)
Specific gravity	:	1.527 @ 21 C (water = 1)
Boiling point	:	-109.3 to -79 F (-78.50 to -61.7 C) (liquid)
Freezing point	:	-71 F (-57 C) @ 4000 mmHg
Water solubility	:	Soluble.

10. Stability and Reactivity

Stability	:	Stable at normal temperatures and conditions.
Conditions to avoid	:	Protect from physical damage and heat. Containers may rupture or explode if exposed to heat. Avoid contact with water or moisture.
Materials to avoid	:	Combustible materials, oxidizing materials, metal salts, reducing agents, metal carbide, metals, bases, potassium, sodium, ethyleneimine.
Hazardous decomposition products	:	Thermal decomposition products: oxides of carbon.

11. Toxicological Information

<u>Acute Health Hazard</u>

Ingestion	:	Not available.
Inhalation	:	Not available.
Skin	:	Not available.
Medical conditions aggravated by exposure	:	Heart or cardiovascular disorders, respiratory disorders.

12. Ecological Information

<u>Ecotoxicity Data</u>

Fish toxicity	:	150000 ug/L 48 day(s) (Mortality) Brown trout (Salmo trutta)

13. Disposal Considerations

Waste from residues / unused products : Dispose in accordance with all applicable regulations.

Contaminated packaging : Return cylinder to supplier.

14. Transport Information

DOT (US only)

Proper shipping name : Carbon Dioxide

Class : 2.2

UN/ID No. : UN1013

Labeling : Non-Flammable Gas

Further information

Cylinders should be transported in a secure upright position in a well ventilated truck.

15. Regulatory Information

OSHA Process Safety (29 CFR 1910.119) Hazard Class(es)

Not regulated.

TCSA

Material is listed in TSCA inventory.

SARA Title III Section 302 Extremely Hazardous Substances (40 CFR 355.30)

Not regulated.

SARA Title III Section 304 Extremely Hazardous Substances (40 CFR 355.40)

Not regulated.

SARA Title III SARA Sections 311/312 Hazardous Categories (40 CFR 370.21)

Acute: Yes
Chronic: No
Fire: No
Reactive: No
Sudden Release: Yes

SARA Title III Section 313 (40 CFR 372.65)

Not regulated.

16. Other Information

Prepared by : Specialty Gases of America, Inc.

For additional information, please visit our website at www.americangasgroup.com.

administered by qualified personnel. Get immediate medical attention.

5. Fire-Fighting Measures

Suitable extinguishing media	:	Use extinguishing agents appropriate for surrounding fire.
Specific hazards	:	Negligible fire hazard. Containers may rupture or explode if exposed to heat.
Fire fighting	:	Move container from fire area if it can be done without risk. Cool containers with water spray until well after the fire is out. Stay away from the ends of tanks. For tank, rail car or tank truck: Evacuation radius: 800 meters (1/2 mile). Use extinguishing agents appropriate for surrounding fire. Cool containers with water spray until well after the fire is out. Do not get water directly on material. Avoid inhalation of material or combustion by-products. Stay upwind and keep out of low areas.

6. Accidental Release Measures

Personal precautions	:	None.
Environmental precautions	:	None.
Methods for cleaning up	:	Do not touch spilled material. Stop leak if possible without personal risk. Reduce vapors with water spray. Keep unnecessary people away. Isolate hazard area and deny entry. Ventilate closed spaces before entering.
Additional advice	:	None.

7. Handling and Storage

Handling

Secure cylinder when using to protect from falling. Use suitable hand truck to move cylinders.

Storage

Store in accordance with all current regulations and standards. Protect from physical damage. Store in a well-ventilated area. Subject to storage regulation: U.S. OSHA 29 CFR 1910.101. Keep separated from incompatible substances.

8. Exposure Controls / Personal Protection

Exposure limits

5000 ppm (9000 mg/m3) OSHA TWA
10000 ppm (18000 mg/m3) OSHA TWA (vacated by 58 FR 35338, June 30, 1993)
30000 ppm (54000 mg/m3) OSHA STEL (vacated by 58 FR 35338, June 30, 1993)
5000 ppm ACGIH TWA
30000 ppm ACGIH STEL
5000 ppm (9000 mg/m3) NIOSH recommended TWA 10 hour(s)
30000 ppm (54000 mg/m3) NIOSH recommended STEL

Engineering measures

Not available.

Personal protective equipment

Respiratory protection	:	The following respirators and maximum use concentrations are drawn from NIOSH and/or OSHA. 40000 ppm – Any supplied-air respirator. Any self-contained breathing apparatus with a full facepiece. Escape – Any appropriate escape-type, self-contained breathing apparatus. For unknown concentrations or immediately dangerous to life or death – Any

Material Safety Data Sheet

1. Product and Company Identification

Product name : **Carbon Monoxide**

Chemical formula : CO

Synonyms : Carbon Oxide; Carbon Oxide (CO);

Company : Specialty Gases of America, Inc
6055 Brent Dr.
Toledo, OH 43611

Telephone : 419-729-7732

Emergency : 800-424-9300

2. Composition/Information on Ingredients

Components	CAS Number	% Volume
Carbon Monoxide	630-08-0	100%

3. Hazards Identification

Emergency Overview
Flammable gas. May cause flash fire. Flash back hazard.
May cause blood damage, suffocation.

Potential Health Effects

Inhalation : Changes in body temperature, changes in blood pressure, nausea, vomiting, chest pain, difficulty breathing, irregular heartbeat, headache, drowsiness, dizziness, disorientation, hallucination, pain in extremities, tremors, loss of coordination, hearing loss, visual disturbances, eye damage, suffocation, blood disorders, convulsion, coma. May cause loss of appetite, heart damage, nerve damage, birth defects, brain damage in long term exposure.

Eye contact : No information on significant adverse effects.

Skin contact : No information on significant adverse effects.

Ingestion : Ingestion of a gas is unlikely.

Chronic Health Hazard : Not applicable.

4. First Aid Measures

General advice : None.

Eye contact : Immediately flush eyes with plenty of water for at least 15 minutes. Then get immediate medical attention.

Skin contact : Wash skin with soap and water for at least 15 minutes while removing contaminated clothing and shoes. Get medical attention, if needed. Thoroughly clean and dry contaminated clothing and shoes before reuse.

Ingestion : If a large amount is swallowed, get medical attention.

Inhalation	:	If adverse effects occur, remove to uncontaminated area. Give artificial respiration if not breathing. If breathing is difficult, oxygen should be administered by qualified personnel. Get immediate medical attention.

5. Fire-Fighting Measures

Suitable extinguishing media	:	Carbon dioxide, regular dry chemical. Large fires: Use regular foam or flood with fine water spray.
Specific hazards	:	Severe explosion hazard. Vapor/air mixtures are explosive. Pressurized containers may rupture or explode if exposed to sufficient heat. Vapors or gases may ignite at distant ignition sources and flash back.
Fire fighting	:	Move container from fire area if it can be done without risk. Cool containers with water spray until well after the fire is out. Stay away from the ends of tanks. For fires in cargo or storage area: If this is impossible then take the following precautions: Keep unnecessary people away, isolate hazard area and deny entry. Let the fire burn. Withdraw immediately in case of rising sound from venting safety device or any discoloration of tanks due to fire. For tank, rail car or tank truck: Let burn unless leak can be stopped immediately. For smaller tanks or cylinders, extinguish and isolate from other flammables. Evacuation radius: 800 meters (1/2 mile). Do not attempt to extinguish fire unless flow of material can be stopped first. Flood with fine water spray. Cool containers with water. Apply water from a protected location or from a safe distance. Avoid inhalation of material or combustion by-products. Stay upwind and keep out of low areas. Stop flow of gas.

6. Accidental Release Measures

Personal precautions	:	None.
Environmental precautions	:	Water release – Subject to California Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65). Keep out of water supplies and sewers.
Methods for cleaning up	:	Avoid heat, flames, sparks and other sources of ignition. Stop leak if possible without personal risk. Reduce vapors with water spray. Keep unnecessary people away. Isolate hazard area and deny entry. Remove sources of ignition. Ventilate closed spaces before entering.
Additional advice	:	None.

7. Handling and Storage

Handling

Secure cylinder when using to protect from falling. Use suitable hand truck to move cylinders.

Storage

Store in accordance with all current regulations and standards. Grounding and bonding required. Subject to storage regulation: U.S. OSHA 29 CFR 1910.101. Keep separated from incompatible substances.

8. Exposure Controls / Personal Protection

Exposure limits

50 ppm (55 mg/m3) OSHA TWA
35 ppm (40 mg/m3) OSHA TWA (vacated by 58 FR 35338, June 30, 1993)
200 ppm (229 mg/m3) OSHA ceiling (vacated by 58 FR 35338, June 30, 1993)
25 ppm ACGIH TWA
35 ppm (40 mg/m3) NIOSH recommended TWA 10 hour(s)
200 ppm (229 mg/m3) NIOSH recommended ceiling

Engineering measures

Not available.

Personal protective equipment

Respiratory protection	:	The following respirators and maximum use concentrations are drawn from NIOSH and/or OSHA. 350 ppm – Any supplied-air respirator. 875 ppm – Any supplied-air respirator operated in a continuous flow mode. 1200 ppm – Any air-purifying respirator with a full facepiece and a canister providing protection against this substance. End of service life indicator required (ESLI). Any self-contained breathing apparatus with a full facepiece. Any supplied-air respirator with a full facepiece. Escape – Any air-purifying respirator with a full facepiece and a canister providing protection against this substance. End of service life indicator required (ESLI). Any appropriate escape-type, self-contained breathing apparatus. For unknown concentrations or immediately dangerous to life or death – Any supplied-air respirator with full facepiece and operated in a pressure-demand or other positive-pressure mode in combination with a separate escape supply. Any self-contained breathing apparatus with a full facepiece.
Hand protection	:	Wear appropriate chemical resistant gloves.
Eye protection	:	Eye protection is not required, but recommended.
Skin and body protection	:	Protective clothing is not required.
Ventilation	:	Ventilation equipment should be explosion-resistant if explosive concentrations of material are present. Provide local exhaust ventilation system. Ensure compliance with applicable exposure limits.

9. Physical and Chemical Properties

Form	:	Gas.
Color	:	Colorless.
Odor	:	Odorless.
Taste	:	Tasteless.
Molecular weight	:	28.01
Vapor pressure	:	760 mmHg @ -191 C
Vapor density	:	0.968 (air = 1)
Specific gravity	:	Not applicable.
Boiling point	:	-314 F (-192 C)
Freezing point	:	-326 F (-199 C)
Water solubility	:	2.3% @ 20 C

10. Stability and Reactivity

Stability	:	Stable at normal temperatures and conditions.
Conditions to avoid	:	Avoid heat, flames, sparks and other sources of ignition. Minimize contact with material. Avoid inhalation of material or combustion by-products. Keep out of water supplies and sewers.
Materials to avoid	:	Combustible materials, oxidizing materials, halogens, metal oxides, metals, lithium.
Hazardous decomposition products	:	Thermal decomposition products: oxides of carbon.

11. Toxicological Information

Toxicity Data

1807 ppm/4 hour(s) inhalation-rat LC50.

Acute Health Hazard

Ingestion	:	Not available.
Inhalation	:	Toxic.
Skin	:	Not available.
Target organs	:	Blood.
Medical conditions aggravated by exposure	:	Blood system disorders, heart or cardiovascular disorders, hormonal disorders, respiratory disorders.

12. Ecological Information

Ecotoxicity Data

Fish toxicity	:	75000 ug/L 1 day(s) LC100 (Mortality) Orangespotted sunfish (Lepomis humilis).

Fate and Transport

KOW	:	1479.11 (log = 3.17) (estimated from water solubility).
KOC	:	2760.58 (log = 3.44) (estimated from water solubility).
Henry's Law Constant	:	1.2 E -3 atm-m3/mol.
Bioconcentration	:	2.13 (estimated from water solubility).
Aquatic Processes	:	1.3766993 hour(s) (River Model: 1 m deep, 1 m/s flow, 3 m/s wind).
Environmental summary	:	Relatively non-persistent in the environment. Not expected to leach through the soil or the sediment. Accumulates very little in the body of living organisms. Highly volatile from water.

13. Disposal Considerations

Waste from residues / unused products	:	Dispose in accordance with all applicable regulations. Subject to disposal regulations: U.S. EPA 40 CFR 262. Hazardous Waste Number(s): D001.
Contaminated packaging	:	Return cylinder to supplier.

14. Transport Information

DOT (US only)

Proper shipping name	:	Carbon Monoxide, Compressed
Class	:	2.3
UN/ID No.	:	UN1016
Labeling	:	2,3; 2.1
Additional shipping description	:	Toxic-Inhalation Hazard Zone D

Further information

Cylinders should be transported in a secure upright position in a well ventilated truck.

15. Regulatory Information

OSHA Process Safety (29 CFR 1910.119) Hazard Class(es)

Not regulated.

TCSA

Material is listed in TSCA inventory.

SARA Title III Section 302 Extremely Hazardous Substances (40 CFR 355.30)

Not regulated.

SARA Title III Section 304 Extremely Hazardous Substances (40 CFR 355.40)

Not regulated.

SARA Title III SARA Sections 311/312 Hazardous Categories (40 CFR 370.21)

Acute: Yes
Chronic: No
Fire: Yes
Reactive: No
Sudden Release: Yes

SARA Title III Section 313 (40 CFR 372.65)

Not regulated.

16. Other Information

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For additional information, please visit our website at www.americangasgroup.com.

ScienceLab.com
Chemicals & Laboratory Equipment

Health	2
Fire	1
Reactivity	0
Personal Protection	E

Material Safety Data Sheet
Cobalt MSDS

Section 1: Chemical Product and Company Identification

Product Name: Cobalt

Catalog Codes: SLC1684, SLC3475

CAS#: 7440-48-4

RTECS: GF8750000

TSCA: TSCA 8(b) inventory: Cobalt

CI#: Not available.

Synonym:

Chemical Formula: Co

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Cobalt	7440-48-4	100

Toxicological Data on Ingredients: Cobalt: ORAL (LD50): Acute: 6170 mg/kg [Rat].

Section 3: Hazards Identification

Potential Acute Health Effects: Hazardous in case of skin contact (irritant), of eye contact (irritant), of ingestion, of inhalation.

Potential Chronic Health Effects:
Hazardous in case of inhalation.
CARCINOGENIC EFFECTS: Classified A3 (Proven for animal.) by ACGIH.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.
DEVELOPMENTAL TOXICITY: Not available.
The substance is toxic to lungs.
Repeated or prolonged exposure to the substance can produce target organs damage.

Section 4: First Aid Measures

Eye Contact: Check for and remove any contact lenses. Do not use an eye ointment. Seek medical attention.

Skin Contact:
After contact with skin, wash immediately with plenty of water. Gently and thoroughly wash the contaminated skin with running water and non-abrasive soap. Be particularly careful to clean folds, crevices, creases and groin. Cover the irritated skin with an emollient. If irritation persists, seek medical attention. Wash contaminated clothing before reusing.

Serious Skin Contact:
Wash with a disinfectant soap and cover the contaminated skin with an anti-bacterial cream. Seek medical attention.

Inhalation: Allow the victim to rest in a well ventilated area. Seek immediate medical attention.

Serious Inhalation:
Evacuate the victim to a safe area as soon as possible. Loosen tight clothing such as a collar, tie, belt or waistband. If breathing is difficult, administer oxygen. If the victim is not breathing, perform mouth-to-mouth resuscitation. Seek medical attention.

Ingestion:
Do not induce vomiting. Loosen tight clothing such as a collar, tie, belt or waistband. If the victim is not breathing, perform mouth-to-mouth resuscitation. Seek immediate medical attention.

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: Flammable.

Auto-Ignition Temperature: Not available.

Flash Points: Not available.

Flammable Limits: Not available.

Products of Combustion: Some metallic oxides.

Fire Hazards in Presence of Various Substances: Not available.

Explosion Hazards in Presence of Various Substances:
Risks of explosion of the product in presence of mechanical impact: Not available.
Risks of explosion of the product in presence of static discharge: Not available.

Fire Fighting Media and Instructions:
Flammable solid.
SMALL FIRE: Use DRY chemical powder.
LARGE FIRE: Use water spray or fog. Cool containing vessels with water jet in order to prevent pressure build-up, autoignition or explosion.

Special Remarks on Fire Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill: Use appropriate tools to put the spilled solid in a convenient waste disposal container.

Large Spill:
Flammable solid.
Stop leak if without risk. Do not touch spilled material. Use water spray curtain to divert vapor drift. Prevent entry into sewers, basements or confined areas; dike if needed. Eliminate all ignition sources. Call for assistance

on disposal. Be careful that the product is not present at a concentration level above TLV. Check TLV on the MSDS and with local authorities.

Section 7: Handling and Storage

Precautions:
Keep locked up Keep away from heat. Keep away from sources of ignition. Ground all equipment containing material. Do not ingest. Do not breathe dust. Wear suitable protective clothing In case of insufficient ventilation, wear suitable respiratory equipment If ingested, seek medical advice immediately and show the container or the label. Avoid contact with skin and eyes

Storage:
Flammable materials should be stored in a separate safety storage cabinet or room. Keep away from heat. Keep away from sources of ignition. Keep container tightly closed. Keep in a cool, well-ventilated place. Ground all equipment containing material. Keep container dry. Keep in a cool place.

Section 8: Exposure Controls/Personal Protection

Engineering Controls:
Use process enclosures, local exhaust ventilation, or other engineering controls to keep airborne levels below recommended exposure limits. If user operations generate dust, fume or mist, use ventilation to keep exposure to airborne contaminants below the exposure limit.

Personal Protection:
Splash goggles. Lab coat. Dust respirator. Be sure to use an approved/certified respirator or equivalent. Gloves.

Personal Protection in Case of a Large Spill:
Splash goggles. Full suit. Dust respirator. Boots. Gloves. A self contained breathing apparatus should be used to avoid inhalation of the product. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Exposure Limits:
TWA: 0.05 (mg/m3) from OSHA
Consult local authorities for acceptable exposure limits.

Section 9: Physical and Chemical Properties

Physical state and appearance: Solid.

Odor: Not available.

Taste: Not available.

Molecular Weight: 58.93 g/mole

Color: Not available.

pH (1% soln/water): Not applicable.

Boiling Point: 3100°C (5612°F)

Melting Point: 1493°C (2719.4°F)

Critical Temperature: Not available.

Specific Gravity: 8.92 (Water = 1)

Vapor Pressure: Not applicable.

Vapor Density: Not available.

Volatility: Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: Not available.

Ionicity (in Water): Not available.

Dispersion Properties: Not available.

Solubility: Insoluble in cold water.

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Not available.

Incompatibility with various substances: Not available.

Corrosivity: Non-corrosive in presence of glass.

Special Remarks on Reactivity: Not available.

Special Remarks on Corrosivity: Not available.

Polymerization: No.

Section 11: Toxicological Information

Routes of Entry: Eye contact. Inhalation. Ingestion.

Toxicity to Animals: Acute oral toxicity (LD50): 6170 mg/kg [Rat].

Chronic Effects on Humans:
CARCINOGENIC EFFECTS: Classified A3 (Proven for animal.) by ACGIH.
The substance is toxic to lungs.

Other Toxic Effects on Humans: Hazardous in case of skin contact (irritant), of ingestion, of inhalation.

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans: Not available.

Special Remarks on other Toxic Effects on Humans: Not available.

Section 12: Ecological Information

Ecotoxicity: Not available.

BOD5 and COD: Not available.

Products of Biodegradation:
Possibly hazardous short term degradation products are not likely. However, long term degradation products may

arise.

Toxicity of the Products of Biodegradation: The products of degradation are as toxic as the original product.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:

Section 14: Transport Information

DOT Classification: CLASS 4.1: Flammable solid.

Identification: : Metal powder, Flammable, n.o.s. (Cobalt metal, powder) : UN3089 PG: III

Special Provisions for Transport: Not available.

Section 15: Other Regulatory Information

Federal and State Regulations:
California prop. 65: This product contains the following ingredients for which the State of California has found to cause cancer, birth defects or other reproductive harm, which would require a warning under the statute: Cobalt
California prop. 65: This product contains the following ingredients for which the State of California has found to cause cancer which would require a warning under the statute: Cobalt
Pennsylvania RTK: Cobalt
Massachusetts RTK: Cobalt
TSCA 8(b) inventory: Cobalt

Other Regulations: OSHA: Hazardous by definition of Hazard Communication Standard (29 CFR 1910.1200).

Other Classifications:

WHMIS (Canada): CLASS D-2A: Material causing other toxic effects (VERY TOXIC).

DSCL (EEC):
R36/38- Irritating to eyes and skin.
R40- Possible risks of irreversible effects.

HMIS (U.S.A.):

Health Hazard: 2

Fire Hazard: 1

Reactivity: 0

Personal Protection: E

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

Health: 2

Flammability: 1

Reactivity: 0

Specific hazard:

Protective Equipment:
Gloves.
Lab coat.
Dust respirator. Be sure to use an approved/certified respirator or equivalent. Wear appropriate respirator when ventilation is inadequate.
Splash goggles.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

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Last Updated: 11/06/2008 12:00 PM

ScienceLab.com
Chemicals & Laboratory Equipment

Health	2
Fire	2
Reactivity	0
Personal Protection	G

Material Safety Data Sheet
n-Decane MSDS

Section 1: Chemical Product and Company Identification

Product Name: n-Decane

Catalog Codes: SLD1165

CAS#: 124-18-5

RTECS: JR2125000

TSCA: TSCA 8(b) inventory: n-Decane

CI#: Not available.

Synonym:

Chemical Name: Decane

Chemical Formula: C10H22

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
{n-}Decane	124-18-5	100

Toxicological Data on Ingredients: n-Decane: VAPOR (LC50): Acute: 1369 ppm 8 hours [Rat]. 72300 mg/m 2 hours [Mouse].

Section 3: Hazards Identification

Potential Acute Health Effects:
Hazardous in case of ingestion, of inhalation. Slightly hazardous in case of skin contact (irritant, permeator), of eye contact (irritant).

Potential Chronic Health Effects:
Slightly hazardous in case of skin contact (sensitizer).
CARCINOGENIC EFFECTS: Not available.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.
DEVELOPMENTAL TOXICITY: Not available.
The substance may be toxic to central nervous system (CNS).
Repeated or prolonged exposure to the substance can produce target organs damage.

Section 4: First Aid Measures

Eye Contact:
Check for and remove any contact lenses. In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Get medical attention if irritation occurs.

Skin Contact: Wash with soap and water. Cover the irritated skin with an emollient. Get medical attention if irritation develops.

Serious Skin Contact: Not available.

Inhalation:
If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention.

Serious Inhalation:
Evacuate the victim to a safe area as soon as possible. Loosen tight clothing such as a collar, tie, belt or waistband. If breathing is difficult, administer oxygen. If the victim is not breathing, perform mouth-to-mouth resuscitation. WARNING: It may be hazardous to the person providing aid to give mouth-to-mouth resuscitation when the inhaled material is toxic, infectious or corrosive. Seek medical attention.

Ingestion:
Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. If large quantities of this material are swallowed, call a physician immediately. Loosen tight clothing such as a collar, tie, belt or waistband.

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: Flammable.

Auto-Ignition Temperature: 210°C (410°F)

Flash Points: CLOSED CUP: 46°C (114.8°F).

Flammable Limits: LOWER: 0.8% UPPER: 5.4%

Products of Combustion: These products are carbon oxides (CO, CO_2).

Fire Hazards in Presence of Various Substances:
Flammable in presence of open flames and sparks, of heat.
Non-flammable in presence of shocks.

Explosion Hazards in Presence of Various Substances:
Risks of explosion of the product in presence of mechanical impact: Not available.
Risks of explosion of the product in presence of static discharge: Not available.

Fire Fighting Media and Instructions:
Flammable liquid, insoluble in water.
SMALL FIRE: Use DRY chemical powder.
LARGE FIRE: Use water spray or fog. Cool containing vessels with water jet in order to prevent pressure build-up, autoignition or explosion.

Special Remarks on Fire Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill: Absorb with an inert material and put the spilled material in an appropriate waste disposal.

Large Spill:
Toxic flammable liquid, insoluble or very slightly soluble in water.
Keep away from heat. Keep away from sources of ignition. Stop leak if without risk. Absorb with DRY earth, sand or other non-combustible material. Do not get water inside container. Do not touch spilled material. Prevent entry into sewers, basements or confined areas; dike if needed. Call for assistance on disposal.

Section 7: Handling and Storage

Precautions:
Keep away from heat. Keep away from sources of ignition. Ground all equipment containing material. Do not ingest. Do not breathe gas/fumes/ vapor/spray. Wear suitable protective clothing. In case of insufficient ventilation, wear suitable respiratory equipment. If ingested, seek medical advice immediately and show the container or the label. Keep away from incompatibles such as oxidizing agents.

Storage:
Store in a segregated and approved area. Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame).

Section 8: Exposure Controls/Personal Protection

Engineering Controls:
Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of vapors below their respective threshold limit value. Ensure that eyewash stations and safety showers are proximal to the work-station location.

Personal Protection:
Safety glasses. Lab coat. Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Gloves.

Personal Protection in Case of a Large Spill:
Splash goggles. Full suit. Vapor respirator. Boots. Gloves. A self contained breathing apparatus should be used to avoid inhalation of the product. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Exposure Limits: Not available.

Section 9: Physical and Chemical Properties

Physical state and appearance: Liquid.

Odor: Not available.

Taste: Not available.

Molecular Weight: 142.28 g/mole

Color: Colorless.

pH (1% soln/water): Not applicable.

Boiling Point: 174.1°C (345.4°F)

Melting Point: -27.9°C (-18.2°F)

Critical Temperature: 344.4°C (651.9°F)

Specific Gravity: 0.73 (Water = 1)

Vapor Pressure: Not available.

Vapor Density: 4.9 (Air = 1)

Volatility: Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: The product is more soluble in oil; log(oil/water) = 6

Ionicity (in Water): Not available.

Dispersion Properties: See solubility in water, methanol, diethyl ether.

Solubility:
Partially soluble in methanol, diethyl ether.
Insoluble in cold water.
Solubility in Ether: >10%
Solubility in Ethanol: >10%

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Heat, ignition sources (flames, sparks, etc.), incompatible materials

Incompatibility with various substances: Reactive with oxidizing agents.

Corrosivity: Non-corrosive in presence of glass.

Special Remarks on Reactivity: Not available.

Special Remarks on Corrosivity: Not available.

Polymerization: Will not occur.

Section 11: Toxicological Information

Routes of Entry: Absorbed through skin. Eye contact. Inhalation.

Toxicity to Animals:
WARNING: THE LC50 VALUES HEREUNDER ARE ESTIMATED ON THE BASIS OF A 4-HOUR EXPOSURE.
Acute toxicity of the vapor (LC50): 1369 8 hours [Rat].

Chronic Effects on Humans: May cause damage to the following organs: central nervous system (CNS).

Other Toxic Effects on Humans:
Hazardous in case of ingestion, of inhalation.
Slightly hazardous in case of skin contact (irritant, permeator).

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans: Animals tumorigen.

Special Remarks on other Toxic Effects on Humans:
Acute Potential Health Effects:
Skin: Causes skin irritation with inflammation and skin cracking.

Eyes: Causes eye irritation.
Inhalation: Causes respiratory tract irritation with coughing, wheezing, and mild inflammation. May cause shortness of breath or suffocation and affect behavior/central nervous system and cause dizziness, headache, lightheadness, passing out, and other narcotic or CNS depression effects.
Ingestion: Causes gastrointestinal tract irritation with abdominal spasms, nausea, vomiting, and diarrhea. It may affect behavior/central nervous system with symptoms similar to that of inhalation.
Chronic Potential Health Effects:
Skin: Prolonged or repeated skin contact may cause dermatitis.

Section 12: Ecological Information

Ecotoxicity: Not available.

BOD5 and COD: Not available.

Products of Biodegradation:
Possibly hazardous short term degradation products are not likely. However, long term degradation products may arise.

Toxicity of the Products of Biodegradation: The products of degradation are less toxic than the product itself.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:
Waste must be disposed of in accordance with federal, state and local environmental control regulations.

Section 14: Transport Information

DOT Classification: CLASS 3: Flammable liquid.

Identification: : n-Decane UNNA: 2247 PG: III

Special Provisions for Transport: Not available.

Section 15: Other Regulatory Information

Federal and State Regulations:
Rhode Island RTK hazardous substances: n-Decane
Pennsylvania RTK: n-Decane
New Jersey: n-Decane
TSCA 8(b) inventory: n-Decane

Other Regulations:
OSHA: Hazardous by definition of Hazard Communication Standard (29 CFR 1910.1200).
EINECS: This product is on the European Inventory of Existing Commercial Chemical Substances.

Other Classifications:

WHMIS (Canada):
CLASS B-4: Flammable solid.
CLASS D-2B: Material causing other toxic effects (TOXIC).

DSCL (EEC):
R10- Flammable.

S9- Keep container in a well-ventilated place.
S16- Keep away from sources of ignition - No smoking.
S23- Do not breathe gas/fumes/vapour/spray [***]
S24- Avoid contact with skin.
S28- After contact with skin, wash immediately with plenty of [***]
S33- Take precautionary measures against static discharges.
S37- Wear suitable gloves.
S45- In case of accident or if you feel unwell, seek medical advice immediately (show the label where possible).

HMIS (U.S.A.):

Health Hazard: 2

Fire Hazard: 2

Reactivity: 0

Personal Protection: g

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

Health: 0

Flammability: 2

Reactivity: 0

Specific hazard:

Protective Equipment:
Gloves.
Lab coat.
Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Wear appropriate respirator when ventilation is inadequate.
Safety glasses.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

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Material Safety Data Sheet

1. Product and Company Identification

Product name : **Hydrogen, compressed**

Chemical formula : H2

Synonyms : Dihydrogen; parahydrogen; refrigerant gas R702; water gas

Company : Specialty Gases of America, Inc
6055 Brent Dr.
Toledo, OH 43611

Telephone : 419-729-7732

Emergency : 800-424-9300

2. Composition/Information on Ingredients

Components	CAS Number	% Volume
Hydrogen	1333-74-0	99+%

3. Hazards Identification

Emergency Overview
DANGER! Flammable high-pressure gas.
Can form explosive mixtures with air.
May ignite if valve is opened to air.
Burns with invisible flame.
May cause dizziness and drowsiness.

Potential Health Effects

Inhalation : Asphixiant. 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.

Eye contact : No harm expected.

Skin contact : No harm expected.

Ingestion : An unlikely route of exposure; this product is gas at normal temperature and pressure.

Chronic Health Hazard : No harm expected.

4. First Aid Measures

Eye contact : Flush eyes thoroughly with water for at least 15 minutes. Hold the eyelids open and away from the eyeballs to ensure all surfaces are flushed thoroughly. See a physician, preferably an ophthalmologist, immediately.

Skin contact : Wash with soap and water. If irritation persists, seek medical attention.

Ingestion : An unlikely route of exposure; this product is gas at normal temperature and pressure.

Inhalation : Immediately remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, qualified personnel may give oxygen. Call a physician immediately.

5. Fire-Fighting Measures

Suitable extinguishing media	:	CO_2, dry chemical, water spray, or fog.
Specific hazards	:	Flammable gas. Flame is nearly invisible. Escaping gas may ignite spontaneously. Hydrogen has a low ignition energy. Fireball of gas cloud ignites immediately after release. Forms explosive mixtures with air and oxidizing agents. Heat of fire can build pressure in cylinder and cause it to rupture. Hydrogen cylinders are equipped with pressure relief devices. (Exceptions may exist where authorized by DOT). 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.
Fire fighting	:	Evacuate all personnel from danger area. Immediately deluge cylinders with water from maximum distant until cool, then move them away from fire area if without risk. Continue cooling water spray while moving cylinders. Do not extinguish flames emitted from cylinders; allow them to burn out. Self-contained breathing apparatus may be required by rescue workers. On site fire fighters must comply with OSHA 29 CFR 1910.156.

6. Accidental Release Measures

Personal precautions	:	Forms explosive mixtures with air. Immediately evacuate all personnel from danger area. Use self-contained breathing apparatus where needed. 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. Flammable gas may spread from leak. Before entering area, especially confined areas, check atmosphere with an appropriate device.
Environmental precautions	:	None.
Methods for cleaning up	:	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 supplier for assistance.
Additional advice	:	None.

7. Handling and Storage

<u>Handling</u>

Protect cylinders from damage. Use a suitable hand truck to move cylinders; do not drag, roll, slide, or drop. 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. Do not crack or open disconnected hydrogen cylinder valves; escaping gas may ignite spontaneously. Never attempt to lift a cylinder by its cap; the cap is intended solely to protect the valve. Never insert and 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.

Storage

Store and use with adequate ventilation. Store only where temperature will not exceed 125 F (52 C). Separate hydrogen cylinders 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. Firmly secure cylinders upright to keep them from falling or being knocked over. Screw valve protection cap firmly in place by hand. Post "No Smoking or Open Flames" signs in storage and use areas. There must be no sources of ignition. All electrical equipment in storage area must be explosion-proof. Storage areas must meet national electric codes for Class 1 hazardous areas. Store full and empty cylinders separately. Use a first-in, first-out inventory system to prevent storing full cylinders for long period of time. For full details and requirements, see NFPA 50A, published by the National Fire Protection Association.

8. Exposure Controls / Personal Protection

Engineering measures

An explosion-proof local exhaust system is acceptable. Use only in a closed system.

Personal protective equipment

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.
Hand protection	:	Wear work gloves for cylinder handling.
Eye protection	:	Safety glasses and a full-face shield are recommended.
Skin and body protection	:	Metatarsal shoes for cylinder handling. Regardless of protective equipment, never touch live electrical parts.

9. Physical and Chemical Properties

Form	:	Gas.
Color	:	Colorless.
Odor	:	Odorless.
Molecular weight	:	2.016
Vapor pressure	:	Not applicable.
Gas density	:	0.00521 lb/ft^3 (0.08342 kg/m^3) @ 70 F (21.1 C) and 1 atm
Specific gravity	:	0.06960 @ 32 F (0 C) and 1 atm (air = 1)
Boiling point	:	-422.97 F (-252.76 C)
Melting point	:	-434.56 F (-259.2 C)
Water solubility	:	0.019 vol @ 60 F (15.6 C) and 1 atm

10. Stability and Reactivity

Stability	:	Stable under normal conditions.
Conditions to avoid	:	None known.
Materials to avoid	:	Oxidizing agents, lithium, halogens.
Hazardous decomposition products	:	None.

11. Toxicological Information

Acute Health Hazard

Ingestion	:	Not available.
Inhalation	:	Not available.

Skin	:	Not available.

12. Ecological Information

No adverse ecological effects expected. This product does not contain any Class I or Class II ozone-depleting chemicals. This product is not listed as a marine pollutant by DOT.

13. Disposal Considerations

Waste from residues / unused products	:	Do not attempt to dispose of residual or unused quantities. Return cylinder to supplier.
Contaminated packaging	:	Return cylinder to supplier.

14. Transport Information

DOT (US only)

Proper shipping name	:	Hydrogen, compressed
Class	:	2.1
UN/ID No.	:	UN1049
Labeling	:	Flammable Gas

Further information

Cylinders should be transported in a secure upright position in a well ventilated truck.
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)].

15. Regulatory Information

OSHA Process Safety (29 CFR 1910.119) Hazard Class(es)

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.

TCSA

Material is listed in TSCA inventory.

SARA Sections 302/304 (40 CFR 355)

Threshold Planning Quantity (TPQ): None
Extremely Hazardous Substances (EHS) RQ: None

SARA Sections 311/312

Immediate: No
Delayed: No
Pressure: Yes
Reactivity: No
Fire: Yes

SARA Section 313 (40 CFR 372.65)

Hydrogen does not require reporting under Section 313.

CERCLA (40 CFR Parts 117 and 302)

Reportable Quantity (RQ): None

16. Other Information

Prepared by : Specialty Gases of America, Inc.

For additional information, please visit our website at www.americangasgroup.com.

Material Safety Data Sheet

1. Product and Company Identification

Product name : **Methane, Compressed Gas**

Chemical formula : C-H4

Synonyms : Fire Damp; Marsh Gas; Methyl Hydride; Natural Gas; Methane

Company : Specialty Gases of America, Inc
6055 Brent Dr.
Toledo, OH 43611

Telephone : 419-729-7732

Emergency : 800-424-9300

2. Composition/Information on Ingredients

Components	CAS Number	% Volume
Methane	74-82-8	100%

3. Hazards Identification

Emergency Overview

Flammable gas. May cause flash fire. Flash back hazard. Electrostatic charges may be generated by flow, agitation, etc.
May cause difficulty breathing.

Potential Health Effects

Inhalation : Nausea, vomiting, difficulty breathing, irregular heartbeat, headache, drowsiness, fatigue, dizziness, disorientation, mood swing, tingling sensation, loss of coordination, suffocation, convulsions, unconsciousness, coma.

Eye contact : No information on significant adverse effects.

Skin contact : No information on significant adverse effects.

Ingestion : Ingestion of a gas is unlikely.

Chronic Health Hazard : None known.

4. First Aid Measures

General advice : None.

Eye contact : Flush eyes with plenty of water.

Skin contact : Wash exposed skin with soap and water.

Ingestion : If a large amount is swallowed, get immediate medical attention.

Inhalation : If adverse effects occur, remove to uncontaminated area. Give artificial respiration if not breathing. If breathing is difficult, oxygen should be administered by qualified personnel. Get immediate medical attention.

Note to physician : For inhalation, consider oxygen.

5. Fire-Fighting Measures

Suitable extinguishing media	:	Carbon dioxide, regular dry chemical. Large fires: Use regular foam or flood with fine water spray.
Specific hazards	:	Severe fire hazard. Severe explosion hazard. Pressurized containers may rupture or explode if exposed to sufficient heat. Vapor/air mixtures are explosive above flash point. Electrostatic discharges may be generated by flow or agitation resulting in ignition or explosion.
Fire fighting	:	Move container from fire area if it can be done without risk. For fires in cargo or storage area: Cool containers with water from unmanned hose holder or monitor nozzle until well after fire is out. If this is impossible, take the following precautions: Keep unnecessary people away, isolate hazard area and deny entry. Let the fire burn. Withdraw immediately in case of rising sound from venting safety device or any discoloration of tanks due to fire. For tank, rail car or tank truck: stop leak if possible without personal risk. Let burn unless leak can be stopped immediately. For smaller tanks or cylinders, extinguish and isolate from other flammables. Evacuation radius: 800 meters (1/2 mile). Stop flow of gas.

6. Accidental Release Measures

Personal precautions	:	None.
Environmental precautions	:	None.
Methods for cleaning up	:	Avoid heat, flames, sparks and other sources of ignition. Stop leak if possible without personal risk. Reduce vapors with water spray. Keep unnecessary people away, isolate hazard area and deny entry. Remove sources of ignition. Ventilate closed spaces before entering.
Additional advice	:	None.

7. Handling and Storage

Handling

Secure cylinder when using to protect from falling. Use suitable hand truck to move cylinders.

Storage

Store in accordance with all current regulations and standards. Grounding and bonding required. Subject to storage regulations: U.S. OSHA 29 CFR 1910.101. Keep separated from incompatible substances.

8. Exposure Controls / Personal Protection

Exposure limits

1000 ppm ACGIH TWA

Engineering measures

Ventilation equipment should be explosion-resistant if explosive concentrations of material are present. Provide local exhaust or process enclosure ventilation system. Ensure compliance with applicable exposure limits.

Personal protective equipment

Respiratory protection	:	Under conditions of frequent use or heavy exposure, respiratory protection may be needed. For unknown concentrations or immediately dangerous to life or health – Any supplied-air respirator with full facepiece and operated in a pressure-demand or other positive pressure mode in combination with a separate escape supply. Any self-contained breathing apparatus with a full facepiece.

Hand protection	:	Wear appropriate chemical resistant gloves.
Eye protection	:	Eye protection not required, but recommended.
Skin and body protection	:	Protective clothing is not required.

9. Physical and Chemical Properties

Form	:	Gas.
Color	:	Colorless.
Odor	:	Odorless.
Molecular weight	:	16.04
Vapor pressure	:	760 mmHg @ -161 C
Vapor density	:	0.555 (air = 1)
Specific gravity	:	Not applicable.
Boiling point	:	-260 F (-162 C)
Freezing point	:	-297 F (-183 C)
Water solubility	:	3.5% @ 17 C
Evaporation rate	:	Not applicable.

10. Stability and Reactivity

Stability	:	Stable at normal temperatures and pressure.
Conditions to avoid	:	Avoid heat, sparks, flames or other sources of ignition. Containers may rupture or explode if exposed to heat.
Materials to avoid	:	Halogens, oxidizing materials, combustible materials.
Hazardous decomposition products	:	Thermal decomposition products: oxides of carbon.

11. Toxicological Information

<u>Toxicity Data</u>

50 pph/2 hour(s) inhalation-mouse LC50

<u>Acute Health Hazard</u>

Ingestion	:	None known.
Inhalation	:	Relatively non-toxic.
Skin	:	None known.
Medical conditions aggravated by exposure	:	None known.

12. Ecological Information

<u>Fate and Transport</u>

KOW	:	724.44 (log = 2.87) (estimated from water solubility).
KOC	:	2192.80 (log = 3.34) (estimated from water solubility).
Henry's Law constant	:	4.6 E -4 atm-m3/mol.
Bioconcentration	:	1.68 (estimated from water solubility).
Aquatic processes	:	1.0416679 hours (Rover Model: 1 m deep, 1 m/s flow, 3 m/s wind).
Environmental summary	:	Relatively non-persistent in the environment. Not expected to leach through the soil or the sediment. Accumulates very little in the bodies of living organisms. Moderately volatile from water.

13. Disposal Considerations

Waste from residues / unused products	:	Dispose in accordance with all applicable regulations. Subject to disposal regulations: U.S. EPA 40 CFR 262. Hazardous Waste Number(s): D001.
Contaminated packaging	:	Return cylinder to supplier.

14. Transport Information

DOT (US only)

Proper shipping name	:	Methane, Compressed
Class	:	2.1
UN/ID No.	:	UN1971
Labeling	:	Flammable Gas

Further information

Cylinders should be transported in a secure upright position in a well ventilated truck.

15. Regulatory Information

OSHA Process Safety (29 CFR 1910.119) Hazard Class(es)

Not regulated.

TCSA

Material is listed in TSCA inventory.

SARA Title III Section 302 Extremely Hazardous Substances (40 CFR 355.30)

Not regulated.

SARA Title III Section 304 Extremely Hazardous Substances (40 CFR 355.40)

Not regulated.

SARA Title III SARA Sections 311/312 Hazardous Categories (40 CFR 370.21)

Acute: Yes
Chronic: No
Fire: Yes
Reactive: No
Sudden Release: Yes

SARA Title III Section 313 (40 CFR 372.65)

Not regulated.

16. Other Information

Prepared by	:	Specialty Gases of America, Inc.

For additional information, please visit our website at www.americangasgroup.com.

Material Safety Data Sheet

1. Product and Company Identification

Product name	: **Pentanes**
Chemical formula	: C5H12
Synonyms	: Isopentane; Isoamylhydride; ethyldimethylmethane
Company	: Specialty Gases of America, Inc 6055 Brent Dr. Toledo, OH 43611
Telephone	: 419-729-7732
Emergency	: 800-424-9300

2. Composition/Information on Ingredients

Components	CAS Number	% Volume
Isopentane	78-78-4	99+%

3. Hazards Identification

Emergency Overview

DANGER! Flammable, volatile liquid.
Can form explosive mixtures with air.
Eye and skin irritant.
May cause dizziness and drowsiness.

Potential Health Effects

Inhalation	: Overexposure may cause incoordination, blurred vision, headache, loss of appetite, confusion and unconsciousness.
Eye contact	: May irritate the eyes, causing redness and swelling of the conjunctiva.
Skin contact	: May irritate the skin, causing redness and possible swelling.
Ingestion	: May irritate the mouth and throat; may also cause pneumonitis if aspirated.
Chronic Health Hazard	: May cause anoxemia.

4. First Aid Measures

Eye contact	: Flush eyes thoroughly with water for at least 15 minutes. Hold the eyelids open and away from the eyeballs to ensure all surfaces are flushed thoroughly. See a physician, preferably an ophthalmologist, immediately.
Skin contact	: Remove contaminated clothing and wash skin with plenty of soap and water. Wash clothes before reuse. Call a physician.
Ingestion	: Rinse mouth with water. Give two glasses of water or milk. Do not induce vomiting. Call a physician.
Inhalation	: Immediately remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, qualified personnel may give oxygen. Call a physician immediately.

5. Fire-Fighting Measures

Suitable extinguishing media	:	CO_2, dry chemical, water spray, or fog.
Specific hazards	:	Flammable gas. Forms explosive mixtures with air and oxidizing agents. Heat of fire can build pressure in cylinder and cause it to rupture. Isopentane containers are equipped with pressure relief devices. (Exceptions may exist where authorized by DOT). No part of a container should be subjected to a temperature higher than 125 F (52 C). If venting or leaking isopentane catches fire, do not extinguish flames. Flammable vapors 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.
Fire fighting	:	Evacuate all personnel from danger area. Immediately cool containers with water spray from maximum distant taking care not to extinguish flames. Remove ignition sources if without risk. If flames are accidentally extinguished, explosive re-ignition may occur. Reapproach with extreme caution using self-contained breathing apparatus. 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 fighters must comply with OSHA 29 CFR 1910.156.

6. Accidental Release Measures

Personal precautions	:	Forms explosive mixtures with air. Immediately evacuate all personnel from danger area. Use self-contained breathing apparatus where needed. Remove all sources of ignition if without risk. Reduce vapors with fog or fine water spray. Shut off flow if without risk. Ventilate area or move leaking cylinders to a well-ventilated area. Flammable gas may spread from leak. Before entering area, especially confined areas, check atmosphere with an appropriate device.
Environmental precautions	:	None.
Methods for cleaning up	:	Cover spilled liquid with an absorbent or flush with water. 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 supplier for assistance.
Additional advice	:	None.

7. Handling and Storage

Handling

Protect cylinders from damage. Use a suitable hand truck to move cylinders; do not drag, roll, slide, or drop. All piped 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. Never attempt to lift a cylinder by its cap; the cap is intended solely to protect the valve. Never insert and 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. Never strike an arc on a compressed gas cylinder or make a cylinder a part of an electrical circuit.

Storage

Store and use with adequate ventilation. Separate containers 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 hour. Firmly secure cylinders upright to keep them from falling or being knocked over. Isopentane containers designed to accept a valve protection cap must be provided with a cap. Screw valve protection cap firmly in place by hand. Post "No Smoking or Open Flames" signs in storage and use areas. There must be no sources of ignition. All electrical equipment in storage area must be explosion-proof. Storage areas must meet national electric codes for Class 1 hazardous areas. 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 period of time.

8. Exposure Controls / Personal Protection

Engineering measures

Use an explosion-proof local exhaust system.

Personal protective equipment

Respiratory protection	:	Use a respirator acceptable to NIOSH and OSHA.
Hand protection	:	Wear work gloves for cylinder handling. Wear neoprene gloves where contact with product may occur.
Eye protection	:	Safety glasses are recommended.
Skin and body protection	:	Metatarsal shoes for cylinder handling, protective clothing where needed. Regardless of protective equipment, never touch live electrical parts.

9. Physical and Chemical Properties

Form	:	Liquid.
Color	:	Colorless.
Odor	:	Pleasant odor.
Molecular weight	:	72.15
Vapor pressure	:	11.1 psia (76.5 kPa) @ 68 F (20 C)
Specific gravity	:	2.48 (air = 1)
Boiling point	:	82.1 F (27.85 C)
Freezing point	:	-225.8 F (-159.9 C) @ 1atm
Water solubility	:	Negligible.

10. Stability and Reactivity

Stability	:	Stable under normal conditions.
Conditions to avoid	:	None known.
Materials to avoid	:	Oxygen, oxidizing agents.
Hazardous decomposition products	:	Thermal decomposition or burning may produce carbon monoxide and carbon dioxide.

11. Toxicological Information

Acute Health Hazard

Ingestion	:	Not available.
Inhalation	:	Not available.
Skin	:	Not available.

12. Ecological Information

No adverse ecological effects expected.

13. Disposal Considerations

Waste from residues / unused products	:	Do not attempt to dispose of residual or unused quantities. Return cylinder to supplier.
Contaminated packaging	:	Return cylinder to supplier.

14. Transport Information

DOT (US only)

Proper shipping name	:	Pentanes
Class	:	3.1
UN/ID No.	:	UN1265
Labeling	:	Flammable Liquid

Further information

Cylinders should be transported in a secure upright position in a well ventilated truck.
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)].

15. Regulatory Information

OSHA Process Safety (29 CFR 1910.119) Hazard Class(es)

Isopentane 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.

TCSA

Material is listed in TSCA inventory.

SARA Sections 302/304 (40 CFR 355)

Threshold Planning Quantity (TPQ): None
Extremely Hazardous Substances (EHS) RQ: None

SARA Sections 311/312

Immediate: Yes
Delayed: Yes
Pressure: Yes
Reactivity: No
Fire: Yes

SARA Section 313 (40 CFR 372.65)

Isopentane does not require reporting under Section 313.

CERCLA (40 CFR Parts 117 and 302)

Reportable Quantity (RQ): None

16. Other Information

Prepared by : Specialty Gases of America, Inc.

For additional information, please visit our website at www.americangasgroup.com.

Health	3
Fire	2
Reactivity	0
Personal Protection	H

Material Safety Data Sheet
Monoethanolamine MSDS

Section 1: Chemical Product and Company Identification

Product Name: Monoethanolamine

Catalog Codes: SLA4792, SLA2452, SLA3955

CAS#: 141-43-5

RTECS: KJ5775000

TSCA: TSCA 8(b) inventory: Ethanolamine

CI#: Not applicable.

Synonym: Colamine, Glycinol, Olamine; Ethanolamine; 2-Aminoethanol; 2-Hydroxyethylamine; beta-Ethanolamine; beta-Hydroxyethylamine

Chemical Name: Ethanol 2-amino

Chemical Formula: HOCH2CH2NH2 or C2-H7-N-O

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Ethanolamine	141-43-5	100

Toxicological Data on Ingredients: Ethanolamine: ORAL (LD50): Acute: 1720 mg/kg [Rat.]. 700 mg/kg [Mouse]. DERMAL (LD50): Acute: 1000 mg/kg [Rabbit.].

Section 3: Hazards Identification

Potential Acute Health Effects:
Very hazardous in case of eye contact (irritant), of ingestion, . Hazardous in case of skin contact (irritant, permeator), of inhalation (lung irritant). Slightly hazardous in case of skin contact (corrosive), of eye contact (corrosive). Liquid or spray mist may produce tissue damage particularly on mucous membranes of eyes, mouth and respiratory tract. Skin contact may produce burns. Inhalation of the spray mist may produce severe irritation of respiratory tract, characterized by coughing, choking, or shortness of breath. Inflammation of the eye is characterized by redness, watering, and itching.

Potential Chronic Health Effects:
CARCINOGENIC EFFECTS: Not available.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.

DEVELOPMENTAL TOXICITY: Not available.
The substance may be toxic to kidneys, lungs, liver, central nervous system (CNS).
Repeated or prolonged exposure to the substance can produce target organs damage. Repeated or prolonged contact with spray mist may produce chronic eye irritation and severe skin irritation. Repeated or prolonged exposure to spray mist may produce respiratory tract irritation leading to frequent attacks of bronchial infection.

Section 4: First Aid Measures

Eye Contact:
Check for and remove any contact lenses. Immediately flush eyes with running water for at least 15 minutes, keeping eyelids open. Cold water may be used. Get medical attention immediately. Finish by rinsing thoroughly with running water to avoid a possible infection.

Skin Contact:
In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Cover the irritated skin with an emollient. Cold water may be used.Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention immediately.

Serious Skin Contact:
Wash with a disinfectant soap and cover the contaminated skin with an anti-bacterial cream. Seek immediate medical attention.

Inhalation:
If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention.

Serious Inhalation:
Evacuate the victim to a safe area as soon as possible. Loosen tight clothing such as a collar, tie, belt or waistband. If breathing is difficult, administer oxygen. If the victim is not breathing, perform mouth-to-mouth resuscitation. WARNING: It may be hazardous to the person providing aid to give mouth-to-mouth resuscitation when the inhaled material is toxic, infectious or corrosive. Seek immediate medical attention.

Ingestion:
Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. If large quantities of this material are swallowed, call a physician immediately. Loosen tight clothing such as a collar, tie, belt or waistband.

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: Combustible.

Auto-Ignition Temperature: 410°C (770°F)

Flash Points: CLOSED CUP: 86°C (186.8°F). OPEN CUP: 93.34°C (200°F) (Cleveland).

Flammable Limits: LOWER: 3% UPPER: 23.5%

Products of Combustion: These products are carbon oxides (CO, CO_2), nitrogen oxides (NO, NO_2...).

Fire Hazards in Presence of Various Substances:
Flammable in presence of open flames and sparks, of heat.
Non-flammable in presence of shocks.

Explosion Hazards in Presence of Various Substances:
Risks of explosion of the product in presence of mechanical impact: Not available.
Risks of explosion of the product in presence of static discharge: Not available.

Fire Fighting Media and Instructions:

SMALL FIRE: Use DRY chemical powder.
LARGE FIRE: Use water spray, fog or foam. Do not use water jet.

Special Remarks on Fire Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill:
Dilute with water and mop up, or absorb with an inert dry material and place in an appropriate waste disposal container. If necessary: Neutralize the residue with a dilute solution of acetic acid.

Large Spill:
Combustible material. Corrosive liquid.
Keep away from heat. Keep away from sources of ignition. Stop leak if without risk. Absorb with DRY earth, sand or other non-combustible material. Do not get water inside container. Do not touch spilled material. Use water spray curtain to divert vapor drift. Prevent entry into sewers, basements or confined areas; dike if needed. Call for assistance on disposal. Neutralize the residue with a dilute solution of acetic acid. Be careful that the product is not present at a concentration level above TLV. Check TLV on the MSDS and with local authorities.

Section 7: Handling and Storage

Precautions:
Keep container dry. Keep away from heat. Keep away from sources of ignition. Ground all equipment containing material. Do not ingest. Do not breathe gas/fumes/ vapor/spray. Never add water to this product. In case of insufficient ventilation, wear suitable respiratory equipment. If ingested, seek medical advice immediately and show the container or the label. Avoid contact with skin and eyes. Keep away from incompatibles such as oxidizing agents, acids.

Storage:
Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame). Sensitive to light. Store in light-resistant containers.
Hygroscopic

Section 8: Exposure Controls/Personal Protection

Engineering Controls:
Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of vapors below their respective threshold limit value. Ensure that eyewash stations and safety showers are proximal to the work-station location.

Personal Protection:
Face shield. Full suit. Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Gloves. Boots.

Personal Protection in Case of a Large Spill:
Splash goggles. Full suit. Vapor respirator. Boots. Gloves. A self contained breathing apparatus should be used to avoid inhalation of the product. Suggested protective clothing might not be sufficient; consult a specialist BEFORE handling this product.

Exposure Limits:
TWA: 3 STEL: 5 (ppm) [United Kingdom (UK)]
TWA: 3 STEL: 6 (ppm) from ACGIH (TLV) [United States]
STEL: 15 (mg/m3) from NIOSH [United States]
TWA: 3 STEL: 6 (ppm) from NIOSH [United States]
TWA: 3 (ppm) from OSHA (PEL) [United States]
TWA: 6 (mg/m3) from OSHA (PEL) [United States]

Consult local authorities for acceptable exposure limits.

Section 9: Physical and Chemical Properties

Physical state and appearance: Liquid. (Viscous liquid.)

Odor: Ammoniacal. Fish. Unpleasant.

Taste: Not available.

Molecular Weight: 61.08 g/mole

Color: Colorless. Clear

pH (1% soln/water): 10 [Basic.]

Boiling Point: 170.8°C (339.4°F)

Melting Point: 10.3°C (50.5°F)

Critical Temperature: 341°C (645.8°F)

Specific Gravity: 1.018 (Water = 1)

Vapor Pressure: 0.1 kPa (@ 20°C)

Vapor Density: 2.1 (Air = 1)

Volatility: Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: The product is more soluble in water; log(oil/water) = -1.3

Ionicity (in Water): Not available.

Dispersion Properties: See solubility in water, methanol, diethyl ether, acetone.

Solubility:
Soluble in cold water, hot water, methanol, acetone.
Partially soluble in diethyl ether.
Solubility in Benzene @ 25 deg. C: 1.4%
Solubility in Ether: 2.1%
Solubility in Carbon Tetrachloride: 0.2%
Solubility in Heptane: <0.1%
Miscible with Chloroform, Glycerin.
Immiscible with fixed oils, solvent Hexane.
Slightly soluble in Petroleum Ether.

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Heat, ignition sources, incompatible materials, light, moisture

Incompatibility with various substances: Reactive with oxidizing agents, acids.

Corrosivity: Highly corrosive in presence of aluminum, of copper.

Special Remarks on Reactivity:
Hygroscopic; keep container tightly closed.
Sensitive to light.
INCOMPATIBLE WITH: ACETIC ACID, ACETIC ANHYDRIDE, ACROLEIN, ACRYLIC ACID, ACRYLONITRILE, CHLOROSULFONIC ACID, EPICHLOROHYDRIN, HYDROCHLORIC ACID, HYDROFLUORIC ACID, MESITYL OXIDE, NITRIC ACID, OLEUM, PROPIOLACTONE (BETA-), SULFURIC ACID, VINYL ACETATE, HALOGENS.

Special Remarks on Corrosivity: Not available.

Polymerization: Will not occur.

Section 11: Toxicological Information

Routes of Entry: Absorbed through skin. Eye contact. Inhalation. Ingestion.

Toxicity to Animals:
Acute oral toxicity (LD50): 700 mg/kg [Mouse].
Acute dermal toxicity (LD50): 1000 mg/kg [Rabbit.].

Chronic Effects on Humans: May cause damage to the following organs: kidneys, lungs, liver, central nervous system (CNS).

Other Toxic Effects on Humans:
Very hazardous in case of ingestion, .
Hazardous in case of skin contact (irritant, permeator), of inhalation (lung irritant).
Slightly hazardous in case of skin contact (corrosive), of eye contact (corrosive).

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans:
May cause adverse reproductive effects and birth defects (teratogenic) based on animal test data.
May affect genetic material (mutagenic)

Special Remarks on other Toxic Effects on Humans:
Acute Potential Health Effects:
Skin: Causes moderate skin irritation and possible burns. It can be absorbed through the skin. It may be harmful if absorbed through the skin.
Eyes: Causes severe eye irritation and possible eye burns.
Inhalation: Causes respiratory tract irritation. May cause shortness of breath and an asthma-like condition. It may also affect behavior/central nervous system (nausea, headache, weakness, dizziness, giddiness, sleepiness, loss of coordination and jugdement)
Ingestion: May be harmful if swallowed. Causes gastrointestinal tract irritation with nausea, vomiting and

Section 12: Ecological Information

Ecotoxicity: Not available.

BOD5 and COD: Not available.

Products of Biodegradation:
Possibly hazardous short term degradation products are not likely. However, long term degradation products may arise.

Toxicity of the Products of Biodegradation: The products of degradation are less toxic than the product itself.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:
Waste must be disposed of in accordance with federal, state and local environmental control regulations.

Section 14: Transport Information

DOT Classification: Class 8: Corrosive material

Identification: : Ethanolamine UNNA: 2491 PG: III

Special Provisions for Transport: Not available.

Section 15: Other Regulatory Information

Federal and State Regulations:
Connecticut hazardous material survey.: Ethanolamine
Illinois toxic substances disclosure to employee act: Ethanolamine
Rhode Island RTK hazardous substances: Ethanolamine
Pennsylvania RTK: Ethanolamine
Minnesota: Ethanolamine
Massachusetts RTK: Ethanolamine
Massachusetts spill list: Ethanolamine
New Jersey: Ethanolamine
TSCA 8(b) inventory: Ethanolamine

Other Regulations:
OSHA: Hazardous by definition of Hazard Communication Standard (29 CFR 1910.1200).
EINECS: This product is on the European Inventory of Existing Commercial Chemical Substances.

Other Classifications:

WHMIS (Canada):
CLASS B-3: Combustible liquid with a flash point between 37.8°C (100°F) and 93.3°C (200°F).
CLASS E: Corrosive liquid.

DSCL (EEC):
R20- Harmful by inhalation.
R36/37/38- Irritating to eyes, respiratory system and skin.
S26- In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.
S28- After contact with skin, wash immediately with plenty of water.
S36/37/39- Wear suitable protective clothing, gloves and eye/face protection.
S46- If swallowed, seek medical advice immediately and show this container or label.

HMIS (U.S.A.):

Health Hazard: 3

Fire Hazard: 2

Reactivity: 0

Personal Protection: H

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

Health: 3

Flammability: 2

Reactivity: 0

Specific hazard:

Protective Equipment:
Gloves.
Synthetic apron.
Vapor respirator. Be sure to use an approved/certified respirator or equivalent. Wear appropriate respirator when ventilation is inadequate.
Splash goggles.

Section 16: Other Information

References:

-SAX, N.I. Dangerous Properties of Indutrial Materials. Toronto, Van Nostrand Reinold, 6e ed. 1984.
-Hawley, G.G.. The Condensed Chemical Dictionary, 11e ed., New York N.Y., Van Nostrand Reinold, 1987.
-The Sigma-Aldrich Library of Chemical Safety Data, Edition II.

Other Special Considerations: Not available.

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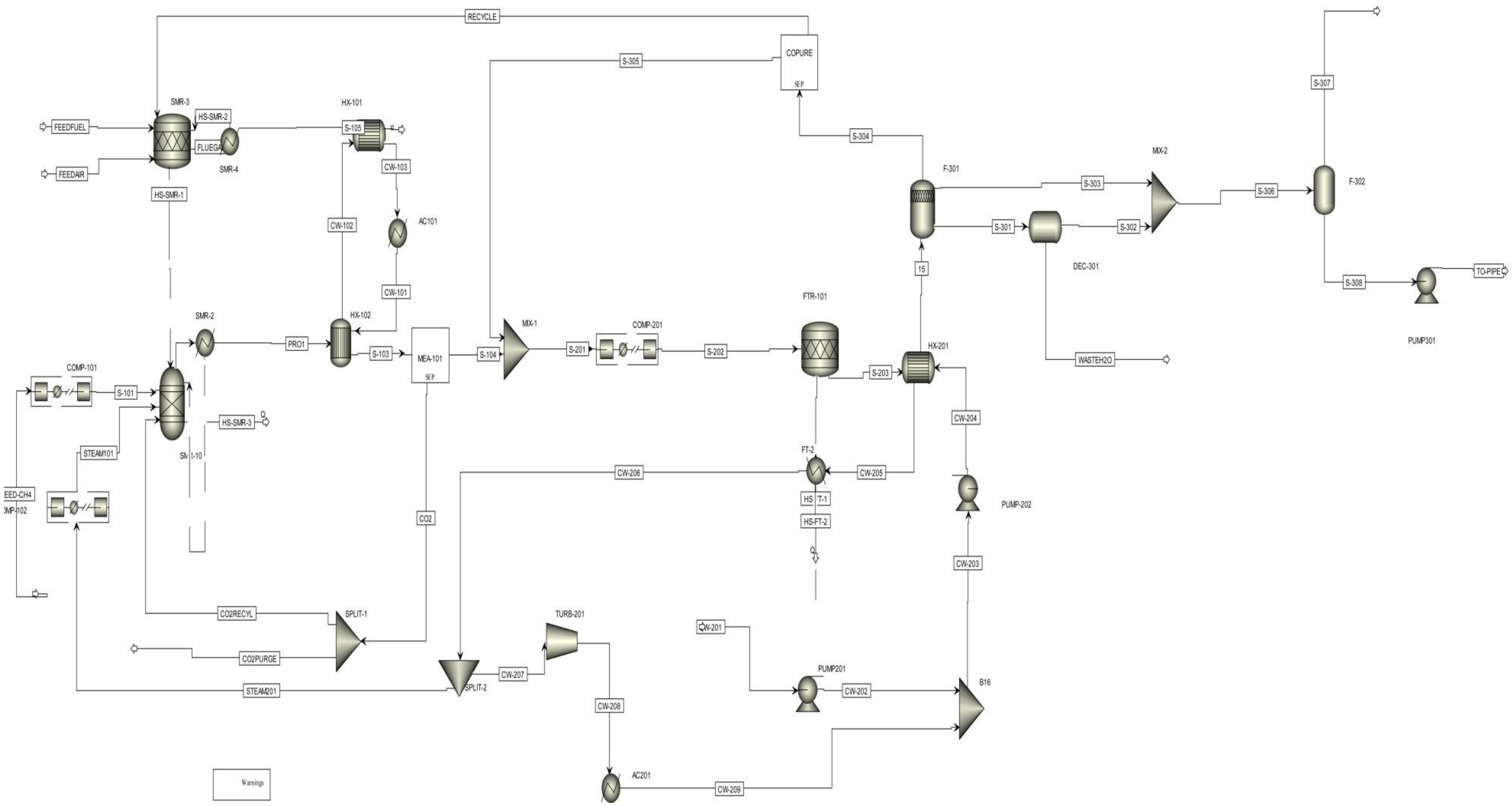
Appendix H - Aspen Results

Aspen Process Flow Diagram



Input Summary Report:

```
;
;Input Summary created by Aspen Plus Rel. 21.0 at 15:45:25 Mon Apr 13, 2009
;Directory S:\CBE 459 Senior Design\Renamed Final Aspen  Filename
c:\temp\~ap9c3e.tmp
;


DYNAMICS
    DYNAMICS RESULTS=ON

IN-UNITS SI ENTHALPY='Btu/lb' ENTROPY='Btu/lbmol-R' FLOW='lb/hr'  &
        MASS-FLOW='lb/hr' MOLE-FLOW='kmol/hr' VOLUME-FLOW='cuft/hr'  &
        ENTHALPY-FLO='Btu/hr' MOLE-HEAT-CA='Btu/lbmol-R'  &
        HEAT-TRANS-C='Btu/hr-sqft-F' PRESSURE=psi TEMPERATURE=F  &
        DELTA-T=F HEAD=ft MOLE-ENTHALP='Btu/scf'  &
        MASS-ENTHALP='Btu/lb' MOLE-ENTROPY='Btu/lbmol-R'  &
        MASS-ENTROPY='Btu/lb-R' MASS-HEAT-CA='Btu/lb-R'  &
        UA='Btu/hr-R' HEAT=Btu PDROP=psi VOL-HEAT-CAP='Btu/cuft-R'  &
        HEAT-FLUX='Btu/hr-ft' VOL-ENTHALPY='Btu/cuft'

DEF-STREAMS CONVEN ALL

DATABANKS PURE20  / AQUEOUS  / SOLIDS  / INORGANIC  /  &
        NOASPENPCD

PROP-SOURCES PURE20  / AQUEOUS  / SOLIDS  / INORGANIC

COMPONENTS
    CH4 CH4 /
    H2O H2O /
    CO CO /
    CO2 CO2 /
    H2 H2 /
    C2H6 C2H6 /
    C3H8 C3H8 /
    C4H10 C4H10-1 /
    N-HEX-01 C6H14-1 /
    N-NON-01 C9H20-1 /
    N-UND-01 C11H24 /
    N-DOD-01 C12H26 /
    N-HEX-02 C16H34 /
    N-PEN-01 C5H12-1 /
    N-HEP-01 C7H16-1 /
    N-OCT-01 C8H18-1 /
    N-TRI-01 C13H28 /
    N-TET-01 C14H30 /
    N-PEN-02 C15H32 /
    N-HEP-02 C17H36 /
    N-OCT-02 C18H38 /
    N-NON-02 C19H40 /
    N-EIC-01 C20H42 /
    N-DEC-01 C10H22-1 /
    N-DOT-01 C32H66 /
    N2 N2 /
    OXYGE-01 O2 /
    AIR AIR

FLOWSHEET
    BLOCK FTR-101 IN=S-202 OUT=S-203 HS-FT-1
    BLOCK SMR-101 IN=S-101 CO2RECYL STEAM101 HS-SMR-1 HS-SMR-4  &
        OUT=12 HS-SMR-3
    BLOCK MEA-101 IN=S-103 OUT=CO2 S-104
```

```
    BLOCK SPLIT-1 IN=CO2 OUT=CO2PURGE CO2RECYL
    BLOCK SMR-3 IN=FEEDFUEL RECYCLE FEEDAIR HS-SMR-2 OUT= &
        FLUEGAS HS-SMR-1
    BLOCK FT-2 IN=CW-205 HS-FT-1 OUT=CW-206 HS-FT-2
    BLOCK COMP-101 IN=FEED-CH4 OUT=S-101
    BLOCK HX-101IN=PRO1 CW-101 OUT=S-103 CW-102
    BLOCK HX-101 IN=S-105 CW-102 OUT=S-106 CW-103
    BLOCK COPURE IN=S-304 OUT=S-305 RECYCLE
    BLOCK MIX-1 IN=S-104 S-305 OUT=S-201
    BLOCK HX-201 IN=S-203 CW-204 OUT=15 CW-205
    BLOCK F-301 IN=15 OUT=S-304 S-303 S-301
    BLOCK DEC-301 IN=S-301 OUT=S-302 WASTEH2O
    BLOCK MIX-2 IN=S-302 S-303 OUT=S-306
    BLOCK PUMP-202 IN=CW-203 OUT=CW-204
    BLOCK COMP-201 IN=S-201 OUT=S-202
    BLOCK SMR-2 IN=12 OUT=PRO1 HS-SMR-4
    BLOCK SMR-4 IN=FLUEGAS OUT=S-105 HS-SMR-2
    BLOCK SPLIT-2 IN=CW-206 OUT=CW-207 STEAM201
    BLOCK COMP-102 IN=STEAM201 OUT=STEAM101
    BLOCK TURB-201 IN=CW-207 OUT=CW-208
    BLOCK AC101 IN=CW-103 OUT=CW-101
    BLOCK B16 IN=CW-202 CW-209 OUT=CW-203
    BLOCK PUMP201 IN=CW-201 OUT=CW-202
    BLOCK AC201 IN=CW-208 OUT=CW-209
    BLOCK F-302 IN=S-306 OUT=S-307 S-308
    BLOCK PUMP301 IN=S-308 OUT=TO-PIPE

PROPERTIES RK-SOAVE
    PROPERTIES NRTL-RK / PENG-ROB

PROP-DATA NRTL-1
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PROP-LIST NRTL
    BPVAL H2O N-HEX-01 0.0 3040.000000 .2000000000 0.0 0.0  &
        0.0 0.0 55.00000000
    BPVAL N-HEX-01 H2O 0.0 1512.000000 .2000000000 0.0 0.0  &
        0.0 0.0 55.00000000
    BPVAL H2O N-NON-01 0.0 1693.523300 .2000000000 0.0 0.0  &
        0.0 25.00000000 25.00000000
    BPVAL N-NON-01 H2O 0.0 1693.523300 .2000000000 0.0 0.0  &
        0.0 25.00000000 25.00000000
    BPVAL H2O N-UND-01 21.99718000 -2245.965000 .2000000000 0.0  &
        0.0 0.0 25.00000000 40.00000000
    BPVAL N-UND-01 H2O -5.471097000 3614.017000 .2000000000 0.0  &
        0.0 0.0 25.00000000 40.00000000
    BPVAL H2O N-DOD-01 23.42913000 -2638.143000 .2000000000 0.0  &
        0.0 0.0 25.00000000 40.00000000
    BPVAL N-DOD-01 H2O -6.088709000 3794.107000 .2000000000 0.0  &
        0.0 0.0 25.00000000 40.00000000
    BPVAL H2O N-HEX-02 28.21783000 -3920.972000 .2000000000 0.0  &
        0.0 0.0 20.00000000 50.00000000
    BPVAL N-HEX-02 H2O -5.445453000 3588.225000 .2000000000 0.0  &
        0.0 0.0 20.00000000 50.00000000
    BPVAL H2O N-PEN-01 12.38660000 -791.7913000 .2000000000 0.0  &
        0.0 0.0 0.0 30.00000000
    BPVAL N-PEN-01 H2O -10.68920000 5051.727500 .2000000000 0.0  &
        0.0 0.0 0.0 30.00000000
    BPVAL H2O N-HEP-01 10.54680000 440.7775000 .2000000000 0.0  &
        0.0 0.0 0.0 50.00000000
    BPVAL N-HEP-01 H2O -9.865200000 4795.660200 .2000000000 0.0  &
        0.0 0.0 0.0 50.00000000
```

```
BPVAL H2O N-OCT-01 1.216600000 2997.701400 .2000000000 0.0  &
    0.0 0.0 0.0 30.00000000
BPVAL N-OCT-01 H2O -12.03500000 5381.433600 .2000000000 0.0  &
    0.0 0.0 0.0 30.00000000
BPVAL H2O N-TRI-01 24.63887000 -2962.920000 .2000000000 0.0  &
    0.0 0.0 25.00000000 40.00000000
BPVAL N-TRI-01 H2O -6.914652000 4044.105000 .2000000000 0.0  &
    0.0 0.0 25.00000000 40.00000000
BPVAL H2O N-TET-01 26.14467000 -3376.979000 .2000000000 0.0  &
    0.0 0.0 40.00000000 40.00000000
BPVAL N-TET-01 H2O -5.920609000 3739.217000 .2000000000 0.0  &
    0.0 0.0 40.00000000 40.00000000
BPVAL H2O N-DEC-01 0.0 4504.280000 .2000000000 0.0 0.0  &
    0.0 25.00000000 40.00000000
BPVAL N-DEC-01 H2O 0.0 1959.410000 .2000000000 0.0 0.0  &
    0.0 25.00000000 40.00000000
BPVAL C3H8 N-PEN-01 4.112400000 -1031.210000 .3000000000  &
    0.0 0.0 0.0 63.41000000 110.0000000
BPVAL N-PEN-01 C3H8 -.7004000000 8.919100000 .3000000000  &
    0.0 0.0 0.0 63.41000000 110.0000000
BPVAL C4H10 N-HEX-01 .1644000000 -4.362500000 .3000000000  &
    0.0 0.0 0.0 -20.00000000 149.8000000
BPVAL N-HEX-01 C4H10 -.0530000000 -27.35750000 .3000000000  &
    0.0 0.0 0.0 -20.00000000 149.8000000
BPVAL C4H10 N-PEN-01 0.0 -251.0092000 .3000000000 0.0 0.0  &
    0.0 25.00000000 25.00000000
BPVAL N-PEN-01 C4H10 0.0 402.0097000 .3000000000 0.0 0.0  &
    0.0 25.00000000 25.00000000
BPVAL N-HEX-01 N-UND-01 0.0 99.41190000 .3000000000 0.0  &
    0.0 0.0 35.00000000 35.00000000
BPVAL N-UND-01 N-HEX-01 0.0 -104.5852000 .3000000000 0.0  &
    0.0 0.0 35.00000000 35.00000000
BPVAL N-HEX-01 N-DOD-01 0.0 113.4685000 .3000000000 0.0  &
    0.0 0.0 35.00000000 35.00000000
BPVAL N-DOD-01 N-HEX-01 0.0 -120.0042000 .3000000000 0.0  &
    0.0 0.0 35.00000000 35.00000000
BPVAL N-HEX-01 N-HEX-02 0.0 -6.812100000 .3000000000 0.0  &
    0.0 0.0 20.00000000 60.00000000
BPVAL N-HEX-02 N-HEX-01 0.0 -31.16210000 .3000000000 0.0  &
    0.0 0.0 20.00000000 60.00000000
BPVAL N-HEX-01 N-PEN-01 0.0 -213.8231000 .3000000000 0.0  &
    0.0 0.0 25.00000000 68.20000000
BPVAL N-PEN-01 N-HEX-01 0.0 246.7632000 .3000000000 0.0  &
    0.0 0.0 25.00000000 68.20000000
BPVAL N-HEX-01 N-HEP-01 0.0 41.09800000 .3000000000 0.0  &
    0.0 0.0 14.00000000 98.60000000
BPVAL N-HEP-01 N-HEX-01 0.0 -47.34870000 .3000000000 0.0  &
    0.0 0.0 14.00000000 98.60000000
BPVAL N-HEX-01 N-OCT-01 -.2878000000 231.9725000 .3000000000  &
    0.0 0.0 0.0 14.00000000 124.3000000
BPVAL N-OCT-01 N-HEX-01 -.8769000000 122.2197000 .3000000000  &
    0.0 0.0 0.0 14.00000000 124.3000000
BPVAL N-HEX-01 N-DEC-01 0.0 298.4441000 .3000000000 0.0  &
    0.0 0.0 35.00000000 144.8000000
BPVAL N-DEC-01 N-HEX-01 0.0 -237.0642000 .3000000000 0.0  &
    0.0 0.0 35.00000000 144.8000000
BPVAL N-HEX-02 N-OCT-01 0.0 108.8865000 .3000000000 0.0  &
    0.0 0.0 25.00000000 25.00000000
BPVAL N-OCT-01 N-HEX-02 0.0 -115.0525000 .3000000000 0.0  &
    0.0 0.0 25.00000000 25.00000000
BPVAL N-PEN-01 N-HEP-01 6.359900000 -2516.694600 .3000000000  &
    0.0 0.0 0.0 130.6000000 253.5000000
BPVAL N-HEP-01 N-PEN-01 -3.335700000 1283.840100 .3000000000  &
    0.0 0.0 0.0 130.6000000 253.5000000
```

```
    BPVAL N-HEP-01 N-OCT-01 -.2362000000 350.9965000 .3000000000  &
        0.0 0.0 0.0 39.50000000 124.3000000
    BPVAL N-OCT-01 N-HEP-01 -.5846000000 1.367600000 .3000000000  &
        0.0 0.0 0.0 39.50000000 124.3000000

PROP-DATA PRKBV-1
    IN-UNITS ENG
    PROP-LIST PRKBV
    BPVAL CH4 CO .0300000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO CH4 .0300000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CH4 CO2 .0919000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 CH4 .0919000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CH4 H2 .0156000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2 CH4 .0156000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2O CO2 .1200000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 H2O .1200000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO H2 .0919000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2 CO .0919000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 H2 -.1622000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2 CO2 -.1622000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CH4 C2H6 -2.6000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 CH4 -2.6000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CO C2H6 -.0226000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 CO -.0226000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CO2 C2H6 .1322000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 CO2 .1322000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL H2 C2H6 -.0667000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 H2 -.0667000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CH4 C3H8 .0140000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C3H8 CH4 .0140000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CO C3H8 .0259000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL C3H8 CO .0259000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 C3H8 .1241000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C3H8 CO2 .1241000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL H2 C3H8 -.0833000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C3H8 H2 -.0833000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 C3H8 1.10000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C3H8 C2H6 1.10000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CH4 C4H10 .0133000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C4H10 CH4 .0133000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CO2 C4H10 .1333000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C4H10 CO2 .1333000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL H2 C4H10 -.3970000000 0.0 0.0 -459.6699923  &
        1340.329993
```

```
BPVAL C4H10 H2 -.3970000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 C4H10 9.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 C2H6 9.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 C4H10 3.30000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 C3H8 3.30000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-HEX-01 .0422000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 CH4 .0422000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 N-HEX-01 .1100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 CO2 .1100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL H2 N-HEX-01 -.0300000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 H2 -.0300000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-HEX-01 -.0100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 C2H6 -.0100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 N-HEX-01 7.00000000E-4 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 C3H8 7.00000000E-4 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 N-HEX-01 -5.6000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 C4H10 -5.6000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-NON-01 .0474000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-NON-01 CH4 .0474000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-PEN-01 .0230000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 CH4 .0230000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 N-PEN-01 .1222000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 CO2 .1222000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-PEN-01 7.80000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 C2H6 7.80000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 N-PEN-01 .0267000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 C3H8 .0267000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 N-PEN-01 .0174000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 C4H10 .0174000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-HEP-01 .0352000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 CH4 .0352000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 N-HEP-01 .1000000000 0.0 0.0 -459.6699923  &
    1340.329993
```

```
BPVAL N-HEP-01 CO2 .1000000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL H2 N-HEP-01 -.1167000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 H2 -.1167000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-HEP-01 6.70000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 C2H6 6.70000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 N-HEP-01 5.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 C3H8 5.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 N-HEP-01 3.30000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 C4H10 3.30000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 N-HEP-01 -7.8000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 N-HEX-01 -7.8000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 N-HEP-01 7.40000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 N-PEN-01 7.40000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-OCT-01 .0496000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-OCT-01 CH4 .0496000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-OCT-01 .0185000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-OCT-01 C2H6 .0185000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 N-OCT-01 0.0 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-OCT-01 N-PEN-01 0.0 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-DEC-01 .0422000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-DEC-01 CH4 .0422000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 N-DEC-01 .1141000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-DEC-01 CO2 .1141000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-DEC-01 .0144000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-DEC-01 C2H6 .0144000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 N-DEC-01 0.0 0.0 0.0 -459.6699923 1340.329993
BPVAL N-DEC-01 C3H8 0.0 0.0 0.0 -459.6699923 1340.329993
BPVAL C4H10 N-DEC-01 7.80000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-DEC-01 C4H10 7.80000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N2 .0311000000 0.0 0.0 -459.6699923 1340.329993
BPVAL N2 CH4 .0311000000 0.0 0.0 -459.6699923 1340.329993
BPVAL CO N2 .0307000000 0.0 0.0 -459.6699923 1340.329993
BPVAL N2 CO .0307000000 0.0 0.0 -459.6699923 1340.329993
BPVAL CO2 N2 -.0170000000 0.0 0.0 -459.6699923 1340.329993
BPVAL N2 CO2 -.0170000000 0.0 0.0 -459.6699923 1340.329993
BPVAL H2 N2 .1030000000 0.0 0.0 -459.6699923 1340.329993
BPVAL N2 H2 .1030000000 0.0 0.0 -459.6699923 1340.329993
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    BPVAL C2H6 N2 .0515000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 C2H6 .0515000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL C3H8 N2 .0852000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 C3H8 .0852000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL C4H10 N2 .0800000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 C4H10 .0800000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-HEX-01 N2 .1496000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-HEX-01 .1496000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-PEN-01 N2 .1000000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-PEN-01 .1000000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-HEP-01 N2 .1441000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-HEP-01 .1441000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-OCT-01 N2 -.4100000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-OCT-01 -.4100000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-DEC-01 N2 .1122000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-DEC-01 .1122000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 OXYGE-01 -.0119000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL OXYGE-01 N2 -.0119000000 0.0 0.0 -459.6699923  &
        1340.329993

PROP-DATA RKSKBV-1
    IN-UNITS ENG
    PROP-LIST RKSKBV
    BPVAL CH4 CO .0322000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO CH4 .0322000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CH4 CO2 .0933000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 CH4 .0933000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CH4 H2 -.0222000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2 CH4 -.0222000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2O CO2 .0737000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 H2O .0737000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO H2 .0804000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2 CO .0804000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 H2 -.3426000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2 CO2 -.3426000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CH4 C2H6 -7.8000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 CH4 -7.8000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CO C2H6 -.0278000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 CO -.0278000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CO2 C2H6 .1363000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 CO2 .1363000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL H2 C2H6 -.1667000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 H2 -.1667000000 0.0 0.0 -459.6699923  &
        1340.329993
```

```
BPVAL CH4 C3H8 9.00000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 CH4 9.00000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO C3H8 .0156000000 0.0 0.0 -459.6699923 1340.329993
BPVAL C3H8 CO .0156000000 0.0 0.0 -459.6699923 1340.329993
BPVAL CO2 C3H8 .1289000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 CO2 .1289000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL H2 C3H8 -.2359000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 H2 -.2359000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 C3H8 -2.2000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 C2H6 -2.2000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 C4H10 5.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 CH4 5.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 C4H10 .1430000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 CO2 .1430000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL H2 C4H10 -.5100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 H2 -.5100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 C4H10 6.70000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 C2H6 6.70000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 C4H10 0.0 0.0 0.0 -459.6699923 1340.329993
BPVAL C4H10 C3H8 0.0 0.0 0.0 -459.6699923 1340.329993
BPVAL CH4 N-HEX-01 .0374000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 CH4 .0374000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 N-HEX-01 .1178000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 CO2 .1178000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL H2 N-HEX-01 -.0800000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 H2 -.0800000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-HEX-01 -.0156000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 C2H6 -.0156000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 N-HEX-01 -2.2000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 C3H8 -2.2000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 N-HEX-01 -.0111000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 C4H10 -.0111000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-NON-01 .0448000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-NON-01 CH4 .0448000000 0.0 0.0 -459.6699923  &
    1340.329993
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BPVAL CH4 N-PEN-01 .0190000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 CH4 .0190000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 N-PEN-01 .1311000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 CO2 .1311000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-PEN-01 5.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 C2H6 5.60000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 N-PEN-01 .0233000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 C3H8 .0233000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 N-PEN-01 .0204000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 C4H10 .0204000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-HEP-01 .0307000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 CH4 .0307000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CO2 N-HEP-01 .1100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 CO2 .1100000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL H2 N-HEP-01 -.2200000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 H2 -.2200000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-HEP-01 4.10000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 C2H6 4.10000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C3H8 N-HEP-01 4.40000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 C3H8 4.40000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C4H10 N-HEP-01 -4.0000000E-4 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 C4H10 -4.0000000E-4 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEX-01 N-HEP-01 -1.1000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 N-HEX-01 -1.1000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 N-HEP-01 1.90000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-HEP-01 N-PEN-01 1.90000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL CH4 N-OCT-01 .0448000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-OCT-01 CH4 .0448000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL C2H6 N-OCT-01 .0170000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-OCT-01 C2H6 .0170000000 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-PEN-01 N-OCT-01 -2.2000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
BPVAL N-OCT-01 N-PEN-01 -2.2000000E-3 0.0 0.0 -459.6699923  &
    1340.329993
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    BPVAL CH4 N-DEC-01 .0411000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-DEC-01 CH4 .0411000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CO2 N-DEC-01 .1304000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-DEC-01 CO2 .1304000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C2H6 N-DEC-01 .0152000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-DEC-01 C2H6 .0152000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL C3H8 N-DEC-01 0.0 0.0 0.0 -459.6699923 1340.329993
    BPVAL N-DEC-01 C3H8 0.0 0.0 0.0 -459.6699923 1340.329993
    BPVAL C4H10 N-DEC-01 6.70000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-DEC-01 C4H10 6.70000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL CH4 N2 .0278000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 CH4 .0278000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO N2 .0374000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 CO .0374000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL CO2 N2 -.0315000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 CO2 -.0315000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL H2 N2 .0978000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 H2 .0978000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL C2H6 N2 .0407000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 C2H6 .0407000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL C3H8 N2 .0763000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL N2 C3H8 .0763000000 0.0 0.0 -459.6699923 1340.329993
    BPVAL C4H10 N2 .0700000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 C4H10 .0700000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-HEX-01 N2 .1496000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-HEX-01 .1496000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-PEN-01 N2 .0878000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-PEN-01 .0878000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-HEP-01 N2 .1422000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-HEP-01 .1422000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-OCT-01 N2 -.4000000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-OCT-01 -.4000000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N-DEC-01 N2 .1033000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 N-DEC-01 .1033000000 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL N2 OXYGE-01 -7.8000000E-3 0.0 0.0 -459.6699923  &
        1340.329993
    BPVAL OXYGE-01 N2 -7.8000000E-3 0.0 0.0 -459.6699923  &
        1340.329993

STREAM CW-101
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    SUBSTREAM MIXED TEMP=35. <C> PRES=1. <atm>
    MOLE-FLOW H2O 1500000.
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STREAM CW-201
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    SUBSTREAM MIXED TEMP=4. PRES=0.
    MOLE-FLOW H2O 4612391.1

STREAM CW-203
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    SUBSTREAM MIXED TEMP=4. PRES=0.
    MOLE-FLOW H2O 7005500.14

STREAM FEED-CH4
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    SUBSTREAM MIXED TEMP=100. <F> PRES=3. <atm>
    MOLE-FLOW CH4 1746811.24

STREAM FEEDAIR
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    SUBSTREAM MIXED TEMP=25. PRES=1. <atm>
    MOLE-FLOW N2 50728. <mol/sec> / OXYGE-01 13485. <mol/sec>

STREAM FEEDFUEL
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    SUBSTREAM MIXED TEMP=25. <C> PRES=1. <atm>
    MOLE-FLOW CH4 15000. <mol/sec> / N2 162821. <mol/sec> /  &
        OXYGE-01 43500. <mol/sec>

DEF-STREAMS HEAT HS-FT-1

DEF-STREAMS HEAT HS-FT-2

DEF-STREAMS HEAT HS-SMR-1

DEF-STREAMS HEAT HS-SMR-2

DEF-STREAMS HEAT HS-SMR-3

DEF-STREAMS HEAT HS-SMR-4

BLOCK B16 MIXER
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM PRES=8.

BLOCK MIX-1 MIXER
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'

BLOCK MIX-2 MIXER
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    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM PRES=19. NPHASE=1 PHASE=L T-EST=27.
    BLOCK-OPTION FREE-WATER=NO

BLOCK SPLIT-1 FSPLIT
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    MOLE-FLOW CO2RECYL 848471. <mol/hr>

BLOCK SPLIT-2 FSPLIT
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    MOLE-FLOW STEAM201 4612391.1

BLOCK COPURE SEP
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM
    FRAC STREAM=S-305 SUBSTREAM=MIXED COMPS=CH4 H2O CO CO2  &
        H2 C2H6 C3H8 C4H10 N-HEX-01 N-NON-01 N-UND-01 N-DOD-01  &
        N-HEX-02 N-PEN-01 N-HEP-01 N-OCT-01 N-TRI-01 N-TET-01  &
        N-PEN-02 N-HEP-02 N-OCT-02 N-NON-02 N-EIC-01 N-DEC-01  &
        N-DOT-01 N2 OXYGE-01 AIR FRACS=0. 0. 1. 0. 0. 0.  &
        0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.  &
        0. 0. 0. 0. 0. 0. 0.

BLOCK MEA-101 SEP
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    PARAM
    FRAC STREAM=CO2 SUBSTREAM=MIXED COMPS=CO2 FRACS=0.8

BLOCK AC101 HEATER
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TEMP=4. PRES=1.

BLOCK AC201 HEATER
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TEMP=4. PRES=8.

BLOCK FT-2 HEATER
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    PARAM TEMP=205. <C> PRES=10. <barg>

BLOCK SMR-2 HEATER
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TEMP=401. PRES=15.
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```
BLOCK SMR-4 HEATER
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TEMP=331. PRES=0.

BLOCK F-302 FLASH2
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TEMP=27. PRES=1.

BLOCK F-301 FLASH3
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TEMP=27. PRES=15.
    PROPERTIES NRTL-RK FREE-WATER=STEAM-TA SOLU-WATER=3  &
        TRUE-COMPS=YES

BLOCK DEC-301 DECANTER
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TEMP=27. PRES=19. L2-COMPS=H2O

BLOCK HX-101HEATX
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    PARAM T-HOT=225. <C> U-OPTION=CONSTANT
    FEEDS HOT=PRO1 COLD=CW-101
    PRODUCTS HOT=S-103 COLD=CW-102
    HEAT-TR-COEF U=100. <Btu/hr-sqft-F>

BLOCK HX-101 HEATX
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM T-HOT=160. LMTD-CORRECT=0.7116 U-OPTION=CONSTANT
    FEEDS HOT=S-105 COLD=CW-102
    PRODUCTS HOT=S-106 COLD=CW-103
    HEAT-TR-COEF U=100. <Btu/hr-sqft-F>

BLOCK HX-201 HEATX
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM T-HOT=30. U-OPTION=CONSTANT
    FEEDS HOT=S-203 COLD=CW-204
    PRODUCTS HOT=15 COLD=CW-205
    HEAT-TR-COEF U=100.

BLOCK FTR-101 RSTOIC
    IN-UNITS ENG
    PARAM TEMP=225. <C> PRES=-5. <atm> HEAT-OF-REAC=YES
    STOIC 1 MIXED H2 -19. / CO -9. / N-NON-01 1. / H2O  &
        9.
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STOIC 2 MIXED H2 -3. / CO -1. / CH4 1. / H2O 1.
STOIC 3 MIXED H2 -5. / CO -2. / C2H6 1. / H2O 2.
STOIC 4 MIXED H2 -7. / CO -3. / C3H8 1. / H2O 3.
STOIC 5 MIXED H2 -9. / CO -4. / C4H10 1. / H2O 4.
STOIC 6 MIXED H2 -13. / CO -6. / N-HEX-01 1. / H2O  &
    6.
STOIC 7 MIXED H2 -11. / CO -5. / N-PEN-01 1. / H2O  &
    5.
STOIC 8 MIXED H2 -15. / CO -7. / N-HEP-01 1. / H2O  &
    7.
STOIC 9 MIXED H2 -17. / CO -8. / N-OCT-01 1. / H2O  &
    8.
STOIC 10 MIXED CO -10. / H2 -21. / N-DEC-01 1. / H2O  &
    10.
STOIC 11 MIXED H2 -23. / CO -11. / N-UND-01 1. / H2O  &
    11.
STOIC 12 MIXED H2 -25. / CO -12. / N-DOD-01 1. / H2O  &
    12.
STOIC 13 MIXED H2 -27. / CO -13. / N-TRI-01 1. / H2O  &
    13.
STOIC 14 MIXED CO -14. / H2 -29. / N-TET-01 1. / H2O  &
    14.
STOIC 15 MIXED H2 -31. / CO -15. / N-PEN-02 1. / H2O  &
    15.
STOIC 16 MIXED H2 -33. / CO -16. / N-HEX-02 1. / H2O  &
    16.
STOIC 17 MIXED CO -17. / H2 -35. / N-HEP-02 1. / H2O  &
    17.
STOIC 18 MIXED CO -18. / H2 -37. / N-OCT-02 1. / H2O  &
    18.
STOIC 19 MIXED CO -19. / H2 -39. / N-NON-02 1. / H2O  &
    19.
STOIC 20 MIXED CO -20. / H2 -41. / N-EIC-01 1. / H2O  &
    20.
STOIC 21 MIXED CO -32. / H2 -65. / H2O 32. / N-DOT-01  &
    1.
CONV 1 MIXED CO 0.0255408
CONV 2 MIXED CO 0.0056023
CONV 3 MIXED CO 0.0108199
CONV 4 MIXED CO 0.0150238
CONV 5 MIXED CO 0.0183383
CONV 6 MIXED CO 0.0227928
CONV 7 MIXED CO 0.0208901
CONV 8 MIXED CO 0.0241461
CONV 9 MIXED CO 0.0250369
CONV 10 MIXED CO 0.0257231
CONV 11 MIXED CO 0.0256404
CONV 12 MIXED CO 0.0253413
CONV 13 MIXED CO 0.0248677
CONV 14 MIXED CO 0.0242554
CONV 15 MIXED CO 0.023535
CONV 16 MIXED CO 0.0227326
CONV 17 MIXED CO 0.0218703
CONV 18 MIXED CO 0.0209666
CONV 19 MIXED CO 0.0200373
CONV 20 MIXED CO 0.0190953
CONV 21 MIXED CO 0.2784676
HEAT-RXN REACNO=1 CID=CO / REACNO=2 CID=CO / REACNO=3  &
    CID=CO / REACNO=4 CID=CO / REACNO=5 CID=CO /  &
    REACNO=6 CID=CO / REACNO=7 CID=CO / REACNO=8 CID=CO /  &
    REACNO=9 CID=CO / REACNO=10 CID=CO / REACNO=11 CID=CO / &
    REACNO=12 CID=CO / REACNO=13 CID=CO / REACNO=14  &
    CID=CO / REACNO=15 CID=CO / REACNO=16 CID=CO /  &
    REACNO=17 CID=CO / REACNO=18 CID=CO / REACNO=19  &
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        CID=CO / REACNO=20 CID=CO / REACNO=21 CID=CO

BLOCK SMR-3 RSTOIC
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    PARAM TEMP=900. <C> PRES=1. <atm>
    STOIC 2 MIXED CH4 -1. / OXYGE-01 -2. / H2O 2. / CO2  &
        1.
    STOIC 1 MIXED H2 -1. / OXYGE-01 -0.5 / H2O 1.
    STOIC 3 MIXED C2H6 -1. / OXYGE-01 -3.5 / H2O 3. / CO2  &
        2.
    STOIC 4 MIXED C3H8 -1. / OXYGE-01 -5. / H2O 4. / CO2  &
        3.
    STOIC 5 MIXED C4H10 -1. / OXYGE-01 -6.5 / H2O 5. /  &
        CO2 4.
    CONV 2 MIXED CH4 1.
    CONV 1 MIXED H2 1.
    CONV 3 MIXED C2H6 1.
    CONV 4 MIXED C3H8 1.
    CONV 5 MIXED C4H10 1.

BLOCK SMR-101 RYIELD
    IN-UNITS ENG
    PARAM TEMP=900. <C> PRES=15. <barg>
    MASS-YIELD MIXED CH4 0.0218 / H2O 0.3727 / CO 0.2923 /  &
        CO2 0.2502 / H2 0.0629

BLOCK PUMP-202 PUMP
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM PRES=10.

BLOCK PUMP201 PUMP
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM PRES=8.

BLOCK PUMP301 PUMP
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM DELP=5.

BLOCK TURB-201 COMPR
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM TYPE=ISENTROPIC PRES=8. MODEL-TYPE=TURBINE

BLOCK COMP-101 MCOMPR
    IN-UNITS SI MASS-FLOW='kg/day' MOLE-FLOW='kmol/day'  &
        VOLUME-FLOW='bbl/day'
    PARAM NSTAGE=2 TYPE=ISENTROPIC PRES=15. <barg>
    FEEDS FEED-CH4 1
    PRODUCTS S-101 2
    COOLER-SPECS 1 TEMP=100. <F> / 2 DUTY=0.

BLOCK COMP-102 MCOMPR
```

```
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM NSTAGE=1 TYPE=ISENTROPIC PRES=15.
    FEEDS STEAM201 1
    PRODUCTS STEAM101 1
    COOLER-SPECS 1 TEMP=337.

BLOCK COMP-201 MCOMPR
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    PARAM NSTAGE=1 TYPE=ISENTROPIC PRES=35. <atm>
    FEEDS S-201 1
    PRODUCTS S-202 1
    COMPR-SPECS 1 SEFF=0.6
    COOLER-SPECS 1 TEMP=225.

DESIGN-SPEC FTCW
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    DEFINE FTCW INFO-VAR INFO=HEAT VARIABLE=DUTY  &
        STREAM=HS-FT-2
    SPEC "FTCW" TO "0"
    TOL-SPEC "1000"
    VARY STREAM-VAR STREAM=CW-203 SUBSTREAM=MIXED  &
        VARIABLE=MOLE-FLOW
    LIMITS "10" "1000000000000000000000"

DESIGN-SPEC QREFOR
    IN-UNITS SI FLOW='kg/day' MASS-FLOW='kg/day'  &
        MOLE-FLOW='kmol/day' VOLUME-FLOW='bbl/day' PRESSURE=barg  &
        TEMPERATURE=C DELTA-T=C PDROP-PER-HT='mbar/m' PDROP=bar  &
        INVERSE-PRES='1/bar'
    DEFINE HEAT INFO-VAR INFO=HEAT VARIABLE=DUTY  &
        STREAM=HS-SMR-3
    SPEC "HEAT" TO "0"
    TOL-SPEC "1000"
    VARY STREAM-VAR STREAM=FEEDFUEL SUBSTREAM=MIXED  &
        VARIABLE=MOLE-FLOW
    LIMITS "0" "1000000000000000000000" STEP-SIZE=1.

EO-CONV-OPTI

STREAM-REPOR MOLEFLOW MASSFLOW STDVOLFLOW MOLEFRAC MASSFRAC  &
        STDVOLFRAC

PROPERTY-REP PCES
;
;
;
;
;
```

Block Reports:

(Units appear in alphabetical order)

```
AirCooler-101
 BLOCK:  AC101    MODEL: HEATER
 ------------------------------
   INLET STREAM:          CW-103
   OUTLET STREAM:         CW-101
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                  IN                OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           62500.0         62500.0          0.00000
       MASS(LB/HR   )          0.248231E+07    0.248231E+07     0.00000
       ENTHALPY(BTU/HR  )     -0.138929E+11   -0.172310E+11    0.193726

                        ***  INPUT DATA  ***
   TWO    PHASE  TP  FLASH
   SPECIFIED TEMPERATURE              F                        39.2000
   SPECIFIED PRESSURE                 PSI                      29.1997
   MAXIMUM NO. ITERATIONS                                      30
   CONVERGENCE TOLERANCE                                        0.000100000


                         ***  RESULTS  ***
   OUTLET TEMPERATURE    F                                  39.200
   OUTLET PRESSURE       PSI                                29.200
   HEAT DUTY             BTU/HR                           -0.33381E+10
   OUTLET VAPOR FRACTION                                    0.0000
   PRESSURE-DROP CORRELATION PARAMETER                      0.0000


   V-L PHASE EQUILIBRIUM :

      COMP                F(I)           X(I)           Y(I)           K(I)
      H2O                 1.0000         1.0000         1.0000        0.27288E-
02
```

AirCooler-201

```
BLOCK:  AC201    MODEL: HEATER
 ------------------------------
   INLET STREAM:          CW-208
   OUTLET STREAM:         CW-209
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           100853.         100853.         0.00000
       MASS(LB/HR   )          0.400558E+07    0.400558E+07     0.00000
       ENTHALPY(BTU/HR  )     -0.226311E+11   -0.278035E+11    0.186033

                         ***  INPUT DATA  ***
   TWO    PHASE  TP  FLASH
   SPECIFIED TEMPERATURE            F                           39.2000
   SPECIFIED PRESSURE               PSI                        130.726
   MAXIMUM NO. ITERATIONS                                       30
   CONVERGENCE TOLERANCE                                         0.000100000


                          ***  RESULTS  ***
   OUTLET TEMPERATURE    F                                   39.200
   OUTLET PRESSURE       PSI                                 130.73
   HEAT DUTY             BTU/HR                            -0.51724E+10
   OUTLET VAPOR FRACTION                                     0.0000
   PRESSURE-DROP CORRELATION PARAMETER                     -0.40301E-14


   V-L PHASE EQUILIBRIUM :

      COMP              F(I)           X(I)           Y(I)          K(I)
      H2O               1.0000         1.0000         1.0000      0.70881E-03
```

MIXER-B16

```
 BLOCK:  B16      MODEL: MIXER
 -----------------------------
   INLET STREAMS:         CW-202      CW-209
   OUTLET STREAM:         CW-203
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           293036.         293036.         0.00000
       MASS(LB/HR   )          0.116385E+08    0.116385E+08     0.00000
       ENTHALPY(BTU/HR  )     -0.807847E+11   -0.807847E+11     0.00000

                         ***  INPUT DATA  ***
   TWO    PHASE      FLASH
   MAXIMUM NO. ITERATIONS                                     30
   CONVERGENCE TOLERANCE                                       0.000100000
   OUTLET PRESSURE   PSI                                    130.726
```

COMP-101

BLOCK: COMP-101 MODEL: MCOMPR

INLET STREAMS: FEED-CH4 TO STAGE 1
OUTLET STREAMS: S-101 FROM STAGE 2
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	72783.8	72783.8	0.00000
MASS(LB/HR)	0.257423E+07	0.257423E+07	0.00000
ENTHALPY(BTU/HR)	-0.511237E+10	-0.489215E+10	-0.430747E-01

*** INPUT DATA ***

ISENTROPIC CENTRIFUGAL COMPRESSOR

NUMBER OF STAGES	2
FINAL PRESSURE, PSI	232.253

COMPRESSOR SPECIFICATIONS PER STAGE

STAGE NUMBER	MECHANICAL EFFICIENCY	ISENTROPIC EFFICIENCY
1	1.000	0.7200
2	1.000	0.7200

COOLER SPECIFICATIONS PER STAGE

STAGE NUMBER	PRESSURE DROP PSI	COOLER SPECIFICATION		
1	0.000	OUTLET TEMPERATURE	100.0	F
2	0.000	HEAT DUTY	0.000	BTU/HR

*** RESULTS ***

FINAL PRESSURE, PSI	232.253
TOTAL WORK REQUIRED, WATT	0.131818+09
TOTAL COOLING DUTY , BTU/HR	-0.229567+09

*** PROFILE ***

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE PSI	PRESSURE RATIO	OUTLET TEMPERATURE F
1	101.2	2.295	254.8
2	232.3	2.295	255.2

STAGE NUMBER	INDICATED HORSEPOWER WATT	BRAKE HORSEPOWER WATT
1	0.6606E+08	0.6606E+08
2	0.6576E+08	0.6576E+08

COOLER PROFILE

STAGE NUMBER	OUTLET TEMPERATURE F	OUTLET PRESSURE PSI	COOLING LOAD BTU/HR	VAPOR FRACTION
1	100.0	101.2	-.2296E+09	1.000
2	255.2	232.3	0.000	1.000

COMP-102

```
BLOCK:  COMP-102 MODEL: MCOMPR
 ------------------------------
   INLET STREAMS:    STEAM201     TO STAGE   1
   OUTLET STREAMS:   STEAM101   FROM STAGE   1
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                  IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           192183.         192183.         0.00000
       MASS(LB/HR   )         0.763291E+07    0.763291E+07     0.00000
       ENTHALPY(BTU/HR  )    -0.430279E+11   -0.421645E+11   -0.200649E-01

                        ***  INPUT DATA  ***

   ISENTROPIC CENTRIFUGAL COMPRESSOR
   NUMBER OF STAGES                                               1
   FINAL PRESSURE, PSI                                          232.253

                  COMPRESSOR SPECIFICATIONS PER STAGE

   STAGE                   MECHANICAL      ISENTROPIC
   NUMBER                  EFFICIENCY      EFFICIENCY


     1                      1.000          0.7200

                  COOLER SPECIFICATIONS PER STAGE


   STAGE      PRESSURE        COOLER
   NUMBER     DROP            SPECIFICATION
              PSI
     1         0.000          OUTLET TEMPERATURE   638.6      F

                         ***  RESULTS  ***

   FINAL PRESSURE, PSI                                          232.253
   TOTAL WORK REQUIRED, WATT                                      0.109893+09
   TOTAL COOLING DUTY , BTU/HR                                    0.488378+09

                         ***  PROFILE  ***

                         COMPRESSOR PROFILE

   STAGE      OUTLET       PRESSURE     OUTLET
   NUMBER     PRESSURE     RATIO        TEMPERATURE
              PSI                       F

     1        232.3        1.454        511.4

   STAGE      INDICATED      BRAKE
   NUMBER     HORSEPOWER     HORSEPOWER
              WATT           WATT
     1       0.1099E+09     0.1099E+09

                         COOLER PROFILE

   STAGE      OUTLET          OUTLET       COOLING      VAPOR
   NUMBER     TEMPERATURE     PRESSURE     LOAD         FRACTION
              F               PSI          BTU/HR

     1         638.6           232.3       0.4884E+09   1.000
```

COMP-201

BLOCK: COMP-201 MODEL: MCOMPR

INLET STREAMS: S-201 TO STAGE 1
OUTLET STREAMS: S-202 FROM STAGE 1
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	321093.	321093.	0.00000
MASS(LB/HR)	0.937378E+07	0.937378E+07	0.00000
ENTHALPY(BTU/HR)	-0.298349E+11	-0.297596E+11	-0.252371E-02

*** INPUT DATA ***

ISENTROPIC CENTRIFUGAL COMPRESSOR	
NUMBER OF STAGES	1
FINAL PRESSURE, PSI	514.358

COMPRESSOR SPECIFICATIONS PER STAGE

STAGE NUMBER	MECHANICAL EFFICIENCY	ISENTROPIC EFFICIENCY
1	1.000	0.6000

COOLER SPECIFICATIONS PER STAGE

STAGE NUMBER	PRESSURE DROP PSI	COOLER SPECIFICATION		
1	0.000	OUTLET TEMPERATURE	437.0	F

*** RESULTS ***

FINAL PRESSURE, PSI	514.358
TOTAL WORK REQUIRED, WATT	0.533966+09
TOTAL COOLING DUTY , BTU/HR	-0.174667+10

*** PROFILE ***

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE PSI	PRESSURE RATIO	OUTLET TEMPERATURE F
1	514.4	2.215	750.0

STAGE NUMBER	INDICATED HORSEPOWER WATT	BRAKE HORSEPOWER WATT
1	0.5340E+09	0.5340E+09

COOLER PROFILE

STAGE NUMBER	OUTLET TEMPERATURE F	OUTLET PRESSURE PSI	COOLING LOAD BTU/HR	VAPOR FRACTION
1	437.0	514.4	-.1747E+10	1.000

COPure-301

```
BLOCK:  COPURE   MODEL: SEP
 ---------------------------
   INLET STREAM:          S-304
   OUTLET STREAMS:        S-305       RECYCLE
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                   IN               OUT         RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           73730.9         73730.9          0.00000
       MASS(LB/HR   )          0.188408E+07    0.188408E+07    0.247155E-15
       ENTHALPY(BTU/HR  )     -0.346182E+10   -0.346250E+10    0.196173E-03

                          ***  INPUT DATA  ***

   FLASH SPECS FOR STREAM S-305
   TWO    PHASE  TP  FLASH
   PRESSURE DROP         PSI                                      0.0
   MAXIMUM NO. ITERATIONS                                        30
   CONVERGENCE TOLERANCE                                          0.000100000

   FLASH SPECS FOR STREAM RECYCLE
   TWO    PHASE  TP  FLASH
   PRESSURE DROP         PSI                                      0.0
   MAXIMUM NO. ITERATIONS                                        30
   CONVERGENCE TOLERANCE                                          0.000100000

   FRACTION OF FEED
     SUBSTREAM= MIXED
       STREAM= S-305     CPT= CH4       FRACTION=           0.0
                              H2O                           0.0
                              CO                            1.00000
                              CO2                           0.0
                              H2                            0.0
                              C2H6                          0.0
                              C3H8                          0.0
                              C4H10                         0.0
                              N-HEX-01                      0.0
                              N-NON-01                      0.0
                              N-UND-01                      0.0
                              N-DOD-01                      0.0
                              N-HEX-02                      0.0
                              N-PEN-01                      0.0
                              N-HEP-01                      0.0
                              N-OCT-01                      0.0
                              N-TRI-01                      0.0
                              N-TET-01                      0.0
                              N-PEN-02                      0.0
                              N-HEP-02                      0.0
                              N-OCT-02                      0.0
                              N-NON-02                      0.0
                              N-EIC-01                      0.0
                              N-DEC-01                      0.0
                              N-DOT-01                      0.0
                              N2                            0.0
                              OXYGE-01                      0.0
                              AIR                           0.0

                           ***  RESULTS  ***
```

```
 HEAT DUTY              BTU/HR                            -0.67925E+06

COMPONENT = CH4
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = H2O
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = CO
  STREAM      SUBSTREAM    SPLIT FRACTION
  S-305       MIXED                 1.00000

COMPONENT = CO2
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = H2
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = C2H6
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = C3H8
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = C4H10
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-HEX-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-NON-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-UND-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-DOD-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-HEX-02
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-PEN-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-HEP-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-OCT-01
```

```
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-TRI-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-TET-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-PEN-02
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-HEP-02
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-OCT-02
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-NON-02
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-EIC-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000

COMPONENT = N-DEC-01
  STREAM      SUBSTREAM    SPLIT FRACTION
  RECYCLE     MIXED                 1.00000
```

DEC-301

BLOCK: DEC-301 MODEL: DECANTER

INLET STREAM: S-301
FIRST LIQUID OUTLET: S-302
SECOND LIQUID OUTLET: WASTEH2O
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	151434.	151434.	0.00000
MASS(LB/HR)	0.698378E+07	0.698378E+07	-0.540611E-07
ENTHALPY(BTU/HR)	-0.408205E+11	-0.412626E+11	0.107143E-01

*** INPUT DATA ***

LIQUID-LIQUID SPLIT, TP SPECIFICATION		
SPECIFIED TEMPERATURE	F	80.6000
SPECIFIED PRESSURE	PSI	290.268
CONVERGENCE TOLERANCE ON EQUILIBRIUM		0.10000E-03
MAXIMUM NO ITERATIONS ON EQUILIBRIUM		30
EQUILIBRIUM METHOD		EQUATION-SOLVING
KLL COEFFICIENTS FROM		OPTION SET OR EOS
KLL BASIS		MOLE
KEY COMPONENT(S):	H2O	

*** RESULTS ***

OUTLET TEMPERATURE	F	80.600
OUTLET PRESSURE	PSI	290.27
CALCULATED HEAT DUTY	BTU/HR	-0.44210E+09
MOLAR RATIO 1ST LIQUID / TOTAL LIQUID		0.52509E-01

L1-L2 PHASE EQUILIBRIUM :

COMP	F	X1	X2	K
CH4	0.014867	0.28273	0.223527-04	0.790607-04
H2O	0.94765	0.0079256	0.99973	126.139
CO	0.010419	0.19836	0.292647-05	0.147532-04
CO2	0.015462	0.28996	0.00024894	0.00085852
H2	0.294506-07	0.560089-06	0.432411-10	0.772039-04
C2H6	0.0012982	0.024715	0.517535-06	0.209402-04
C3H8	0.0017229	0.032811	0.265343-07	0.808708-06
C4H10	0.0018599	0.035420	0.979164-09	0.276441-07
N-HEX-01	0.118714-04	0.00022608	0.937313-15	0.414585-11
N-NON-01	0.00014361	0.0027350	0.143254-18	0.523787-16
N-UND-01	0.126652-04	0.00024120	0.126988-20	0.526484-17
N-DOD-01	0.117930-04	0.00022459	0.357444-21	0.159153-17
N-HEX-02	0.893656-05	0.00017019	0.237264-23	0.139410-19
N-PEN-01	0.755999-05	0.00014398	0.593841-13	0.412460-09
N-HEP-01	0.104856-04	0.00019969	0.873709-17	0.437527-13
N-OCT-01	0.133700-04	0.00025462	0.462998-19	0.181836-15
N-TRI-01	0.110894-04	0.00021119	0.929196-22	0.439979-18
N-TET-01	0.103557-04	0.00019722	0.278230-22	0.141078-18
N-PEN-02	0.00068884	0.013119	0.564641-21	0.430413-19
N-HEP-02	0.00056481	0.010756	0.107565-21	1.000000-20
N-OCT-02	0.00051139	0.0097391	0.973911-22	1.000000-20
N-NON-02	0.00046300	0.0088176	0.881758-22	1.000000-20
N-EIC-01	0.00041917	0.0079829	0.798290-22	1.000000-20
N-DEC-01	0.155276-04	0.00029571	0.642578-20	0.217297-16
N-DOT-01	0.0038205	0.072759	0.727593-21	1.000000-20

FLASH-301

```
BLOCK:  F-301    MODEL: FLASH3
 ------------------------------
   INLET STREAM:           15
   OUTLET VAPOR STREAM:    S-304
   FIRST LIQUID OUTLET:    S-303
   SECOND LIQUID OUTLET:   S-301
   PROPERTY OPTION SET:    NRTL-RK   RENON (NRTL) / REDLICH-KWONG

                      ***  MASS AND ENERGY BALANCE  ***
                                IN               OUT         RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )          226866.         226866.         0.00000
       MASS(LB/HR   )         0.937378E+07    0.937378E+07    0.101984E-06
       ENTHALPY(BTU/HR  )    -0.449352E+11   -0.447530E+11   -0.405465E-02

                          ***  INPUT DATA  ***
   THREE  PHASE  TP  FLASH
   SPECIFIED TEMPERATURE F                                80.6000
   SPECIFIED PRESSURE    PSI                             232.253
   MAXIMUM NO. ITERATIONS                                 30
   CONVERGENCE TOLERANCE                                   0.000100000
   NO KEY COMPONENT IS SPECIFIED
   KEY LIQUID STREAM:      S-301

                           ***  RESULTS  ***
   OUTLET TEMPERATURE    F                                  80.600
   OUTLET PRESSURE       PSI                                232.25
   HEAT DUTY             BTU/HR                            0.18220E+09
   VAPOR FRACTION                                          0.32500
   1ST LIQUID/TOTAL LIQUID                                 0.11106E-01

   V-L1-L2 PHASE EQUILIBRIUM :
```

COMP	F(I)	X1(I)	X2(I)	Y(I)	K1(I)	K2(I)
CH4	0.296E-01	0.150E-01	0.149E-01	0.603E-01	4.03	4.05
H2O	0.633	0.220E-02	0.948	0.229E-02	1.04	0.242E-02
CO	0.887E-01	0.105E-01	0.104E-01	0.251	24.0	24.1
CO2	0.234E-01	0.156E-01	0.155E-01	0.399E-01	2.56	2.58
H2	0.207	0.296E-07	0.295E-07	0.638	0.215E+08	0.217E+08
C2H6	0.160E-02	0.131E-02	0.130E-02	0.224E-02	1.71	1.72
C3H8	0.148E-02	0.176E-02	0.172E-02	0.988E-03	0.561	0.573
C4H10	0.136E-02	0.190E-02	0.186E-02	0.317E-03	0.167	0.170
N-HEX-01	0.113E-02	0.889E-01	0.119E-04	0.139E-02	0.156E-01	117.
N-NON-01	0.841E-03	0.972E-01	0.144E-03	0.520E-04	0.535E-03	0.362
N-UND-01	0.691E-03	0.908E-01	0.127E-04	0.495E-05	0.545E-04	0.391
N-DOD-01	0.626E-03	0.824E-01	0.118E-04	0.148E-05	0.180E-04	0.126
N-HEX-02	0.421E-03	0.554E-01	0.894E-05	0.123E-07	0.222E-06	0.138E-02
N-PEN-01	0.124E-02	0.612E-01	0.756E-05	0.238E-02	0.389E-01	315.
N-HEP-01	0.102E-02	0.114	0.105E-04	0.506E-03	0.445E-02	48.2
N-OCT-01	0.928E-03	0.114	0.134E-04	0.192E-03	0.168E-02	14.3
N-TRI-01	0.567E-03	0.746E-01	0.111E-04	0.443E-06	0.594E-05	0.400E-01
N-TET-01	0.513E-03	0.676E-01	0.104E-04	0.135E-06	0.200E-05	0.131E-01
N-PEN-02	0.465E-03	0.693E-03	0.689E-03	0.481E-09	0.694E-06	0.699E-06
N-HEP-02	0.381E-03	0.568E-03	0.565E-03	0.422E-10	0.743E-07	0.748E-07

N-OCT-02	0.345E-03	0.514E-03	0.511E-03	0.138E-10	0.267E-07	0.269E-07
N-NON-02	0.313E-03	0.466E-03	0.463E-03	0.368E-11	0.791E-08	0.795E-08
N-EIC-01	0.283E-03	0.422E-03	0.419E-03	0.107E-11	0.253E-08	0.254E-08
N-DEC-01	0.762E-03	0.996E-01	0.155E-04	0.169E-04	0.170E-03	1.09
N-DOT-01	0.258E-02	0.384E-02	0.382E-02	0.880E-17	0.229E-14	0.230E-14

FLASH-302

BLOCK: F-302 MODEL: FLASH2

INLET STREAM:	S-306
OUTLET VAPOR STREAM:	S-307
OUTLET LIQUID STREAM:	S-308
PROPERTY OPTION SET:	RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	9652.33	9652.33	0.00000
MASS(LB/HR)	0.178896E+07	0.178896E+07	0.134956E-10
ENTHALPY(BTU/HR)	-0.245104E+10	-0.240497E+10	-0.187968E-01

*** INPUT DATA ***

TWO PHASE TP FLASH

SPECIFIED TEMPERATURE	F	80.6000
SPECIFIED PRESSURE	PSI	29.1997
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

*** RESULTS ***

OUTLET TEMPERATURE	F	80.600
OUTLET PRESSURE	PSI	29.200
HEAT DUTY	BTU/HR	0.46072E+08
VAPOR FRACTION		0.72087

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
CH4	0.23555	0.39898E-02	0.32521	81.509
H2O	0.69165E-02	0.71609E-02	0.68219E-02	0.95265
CO	0.16526	0.10522E-02	0.22884	217.49
CO2	0.24162	0.15226E-01	0.32927	21.626
H2	0.46663E-06	0.10163E-08	0.64691E-06	636.53
C2H6	0.20590E-01	0.18498E-02	0.27847E-01	15.054
C3H8	0.27340E-01	0.80618E-02	0.34804E-01	4.3172
C4H10	0.29513E-01	0.25120E-01	0.31215E-01	1.2426
N-HEX-01	0.15847E-01	0.43780E-01	0.50313E-02	0.11492
N-NON-01	0.19371E-01	0.68752E-01	0.25016E-03	0.36385E-02
N-UND-01	0.16199E-01	0.57969E-01	0.25559E-04	0.44092E-03
N-DOD-01	0.14699E-01	0.52641E-01	0.74837E-05	0.14216E-03
N-HEX-02	0.98968E-02	0.35456E-01	0.61373E-07	0.17309E-05
N-PEN-01	0.10908E-01	0.19939E-01	0.74111E-02	0.37169
N-HEP-01	0.20166E-01	0.66066E-01	0.23928E-02	0.36218E-01
N-OCT-01	0.20335E-01	0.70807E-01	0.79257E-03	0.11193E-01
N-TRI-01	0.13321E-01	0.47721E-01	0.19619E-05	0.41113E-04
N-TET-01	0.12067E-01	0.43231E-01	0.63805E-06	0.14759E-04
N-PEN-02	0.10929E-01	0.39155E-01	0.18948E-06	0.48393E-05
N-HEP-02	0.89614E-02	0.32105E-01	0.16522E-07	0.51463E-06

N-OCT-02	0.81138E-02	0.29069E-01	0.51913E-08	0.17859E-06
N-NON-02	0.73461E-02	0.26318E-01	0.15955E-08	0.60622E-07
N-EIC-01	0.66507E-02	0.23827E-01	0.41691E-09	0.17498E-07
N-DEC-01	0.17789E-01	0.63537E-01	0.75004E-04	0.11805E-02
N-DOT-01	0.60617E-01	0.21717	0.26701E-13	0.12295E-12

BLOCK: FT-2 MODEL: HEATER

INLET STREAM: CW-205
INLET HEAT STREAM: HS-FT-1
OUTLET STREAM: CW-206
OUTLET HEAT STREAM: HS-FT-2
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	293036.	293036.	0.00000
MASS(LB/HR)	0.116385E+08	0.116385E+08	0.00000
ENTHALPY(BTU/HR)	-0.656079E+11	-0.656079E+11	0.00000

*** INPUT DATA ***

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	401.000
SPECIFIED PRESSURE	PSI	159.734
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

*** RESULTS ***

OUTLET TEMPERATURE	F	401.00
OUTLET PRESSURE	PSI	159.73
HEAT DUTY	BTU/HR	0.73123E+10
NET DUTY	BTU/HR	-888.33
OUTLET VAPOR FRACTION		1.0000
PRESSURE-DROP CORRELATION PARAMETER		0.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
H2O	1.0000	1.0000	1.0000	1.5236

FT-2

```
BLOCK:  FT-2     MODEL: HEATER
 ------------------------------
   INLET STREAM:           CW-205
   INLET HEAT STREAM:      HS-FT-1
   OUTLET STREAM:          CW-206
   OUTLET HEAT STREAM:     HS-FT-2
   PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                    IN                OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           293036.          293036.          0.00000
       MASS(LB/HR    )        0.116385E+08    0.116385E+08     0.00000
       ENTHALPY(BTU/HR  )    -0.656079E+11   -0.656079E+11     0.00000

                          ***  INPUT DATA  ***
   TWO    PHASE  TP  FLASH
   SPECIFIED TEMPERATURE              F                         401.000
   SPECIFIED PRESSURE                 PSI                       159.734
   MAXIMUM NO. ITERATIONS                                        30
   CONVERGENCE TOLERANCE                                          0.000100000


                           ***  RESULTS  ***
   OUTLET TEMPERATURE    F                                   401.00
   OUTLET PRESSURE       PSI                                 159.73
   HEAT DUTY             BTU/HR                             0.73123E+10
   NET DUTY              BTU/HR                            -888.33
   OUTLET VAPOR FRACTION                                     1.0000
   PRESSURE-DROP CORRELATION PARAMETER                       0.0000


   V-L PHASE EQUILIBRIUM :

      COMP              F(I)           X(I)           Y(I)           K(I)
      H2O               1.0000         1.0000         1.0000         1.5236
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FTR-101

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BLOCK:  FTR-101  MODEL: RSTOIC
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   INLET STREAM:          S-202
   OUTLET STREAM:         S-203
   OUTLET HEAT STREAM:    HS-FT-1
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                             IN           OUT       GENERATION   RELATIVE
DIFF.
   TOTAL BALANCE
   MOLE(KMOL/HR )         321093.       226866.      -94227.5      0.453199E-
16
   MASS(LB/HR    )       0.937378E+07  0.937378E+07                 0.00000
   ENTHALPY(BTU/HR  )   -0.297596E+11 -0.297596E+11               -0.256368E-
15

                          ***  INPUT DATA  ***
   STOICHIOMETRY MATRIX:

    REACTION #   1:
     SUBSTREAM MIXED   :
     H2O        9.00    CO         -9.00    H2         -19.0    N-NON-01   1.00

    REACTION #   2:
     SUBSTREAM MIXED   :
     CH4        1.00    H2O         1.00    CO         -1.00    H2        -3.00

    REACTION #   3:
     SUBSTREAM MIXED   :
     H2O        2.00    CO         -2.00    H2         -5.00    C2H6       1.00

    REACTION #   4:
     SUBSTREAM MIXED   :
     H2O        3.00    CO         -3.00    H2         -7.00    C3H8       1.00

    REACTION #   5:
     SUBSTREAM MIXED   :
     H2O        4.00    CO         -4.00    H2         -9.00    C4H10      1.00

    REACTION #   6:
     SUBSTREAM MIXED   :
     H2O        6.00    CO         -6.00    H2         -13.0    N-HEX-01   1.00

    REACTION #   7:
     SUBSTREAM MIXED   :
     H2O        5.00    CO         -5.00    H2         -11.0    N-PEN-01   1.00

    REACTION #   8:
     SUBSTREAM MIXED   :
     H2O        7.00    CO         -7.00    H2         -15.0    N-HEP-01   1.00

    REACTION #   9:
     SUBSTREAM MIXED   :
     H2O        8.00    CO         -8.00    H2         -17.0    N-OCT-01   1.00

    REACTION #  10:
     SUBSTREAM MIXED   :
     H2O        10.0    CO         -10.0    H2         -21.0    N-DEC-01   1.00

    REACTION #  11:
     SUBSTREAM MIXED   :
     H2O        11.0    CO         -11.0    H2         -23.0    N-UND-01   1.00
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 REACTION #  12:
  SUBSTREAM MIXED   :
  H2O        12.0    CO         -12.0    H2         -25.0    N-DOD-01   1.00

 REACTION #  13:
  SUBSTREAM MIXED   :
  H2O        13.0    CO         -13.0    H2         -27.0    N-TRI-01   1.00

 REACTION #  14:
  SUBSTREAM MIXED   :
  H2O        14.0    CO         -14.0    H2         -29.0    N-TET-01   1.00

 REACTION #  15:
  SUBSTREAM MIXED   :
  H2O        15.0    CO         -15.0    H2         -31.0    N-PEN-02   1.00

 REACTION #  16:
  SUBSTREAM MIXED   :
  H2O        16.0    CO         -16.0    H2         -33.0    N-HEX-02   1.00

 REACTION #  17:
  SUBSTREAM MIXED   :
  H2O        17.0    CO         -17.0    H2         -35.0    N-HEP-02   1.00

 REACTION #  18:
  SUBSTREAM MIXED   :
  H2O        18.0    CO         -18.0    H2         -37.0    N-OCT-02   1.00

 REACTION #  19:
  SUBSTREAM MIXED   :
  H2O        19.0    CO         -19.0    H2         -39.0    N-NON-02   1.00

 REACTION #  20:
  SUBSTREAM MIXED   :
  H2O        20.0    CO         -20.0    H2         -41.0    N-EIC-01   1.00

 REACTION #  21:
  SUBSTREAM MIXED   :
  H2O        32.0    CO         -32.0    H2         -65.0    N-DOT-01   1.00

REACTION CONVERSION SPECS: NUMBER=   21
  REACTION #   1:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2554E-01
  REACTION #   2:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.5602E-02
  REACTION #   3:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.1082E-01
  REACTION #   4:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.1502E-01
  REACTION #   5:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.1834E-01
  REACTION #   6:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2279E-01
  REACTION #   7:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2089E-01
  REACTION #   8:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2415E-01
  REACTION #   9:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2504E-01
  REACTION #  10:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2572E-01
  REACTION #  11:
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  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2564E-01
  REACTION #  12:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2534E-01
  REACTION #  13:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2487E-01
  REACTION #  14:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2426E-01
  REACTION #  15:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2354E-01
  REACTION #  16:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2273E-01
  REACTION #  17:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2187E-01
  REACTION #  18:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2097E-01
  REACTION #  19:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2004E-01
  REACTION #  20:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.1910E-01
  REACTION #  21:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.2785


TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE F                                        437.000
PRESSURE DROP         PSI                                       73.4797
MAXIMUM NO. ITERATIONS                                          30
CONVERGENCE TOLERANCE                                            0.000100000
SIMULTANEOUS REACTIONS
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES                 NO

                        ***  RESULTS  ***
OUTLET TEMPERATURE    F                                           437.00
OUTLET PRESSURE       PSI                                         440.88
HEAT DUTY             BTU/HR                                    -0.73124E+10
VAPOR FRACTION                                                    1.0000


HEAT OF REACTIONS:

  REACTION           REFERENCE          HEAT OF
  NUMBER             COMPONENT          REACTION
                                         BTU/SCF
   1                    CO                -177.75
   2                    CO                -233.33
   3                    CO                -196.41
   4                    CO                -188.47
   5                    CO                -184.57
   6                    CO                -180.47
   7                    CO                -182.20
   8                    CO                -179.32
   9                    CO                -178.52
   10                   CO                -177.22
   11                   CO                -176.81
   12                   CO                -176.41
   13                   CO                -176.13
   14                   CO                -175.87
   15                   CO                -175.63
   16                   CO                -175.46
   17                   CO                -175.25
   18                   CO                -175.09
```

19	CO	-174.95
20	CO	-174.83
21	CO	-173.66

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT KMOL/HR
1	190.81
2	376.68
3	363.74
4	336.71
5	308.25
6	255.42
7	280.91
8	231.93
9	210.42
10	172.95
11	156.72
12	141.99
13	128.62
14	116.49
15	105.49
16	95.528
17	86.498
18	78.317
19	70.907
20	64.194
21	585.09

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
CH4	0.29619E-01	0.74891E-04	0.29619E-01	535.54
H2O	0.63332	0.99955	0.63332	0.85797
CO	0.88696E-01	0.56911E-04	0.88696E-01	2110.4
CO2	0.23394E-01	0.15978E-03	0.23394E-01	198.26
H2	0.20742	0.13788E-03	0.20742	2037.1
C2H6	0.16033E-02	0.63875E-05	0.16033E-02	339.90
C3H8	0.14842E-02	0.42895E-05	0.14842E-02	468.53
C4H10	0.13587E-02	0.27486E-05	0.13587E-02	669.38
N-HEX-01	0.11258E-02	0.53751E-06	0.11258E-02	2836.3
N-NON-01	0.84105E-03	0.22370E-07	0.84105E-03	50912.
N-UND-01	0.69082E-03	0.12509E-08	0.69082E-03	0.74783E+06
N-DOD-01	0.62586E-03	0.25919E-09	0.62586E-03	0.32698E+07
N-HEX-02	0.42108E-03	0.26870E-12	0.42108E-03	0.21220E+10
N-PEN-01	0.12382E-02	0.12911E-05	0.12382E-02	1298.7
N-HEP-01	0.10223E-02	0.21828E-06	0.10223E-02	6342.1
N-OCT-01	0.92752E-03	0.69271E-07	0.92752E-03	18131.
N-TRI-01	0.56692E-03	0.53106E-10	0.56692E-03	0.14456E+08
N-TET-01	0.51347E-03	0.83673E-11	0.51347E-03	0.83096E+08
N-PEN-02	0.46500E-03	0.15872E-11	0.46500E-03	0.39671E+09
N-HEP-02	0.38127E-03	0.73001E-13	0.38127E-03	0.70724E+10
N-OCT-02	0.34521E-03	0.10867E-13	0.34521E-03	0.43017E+11

N-NON-02	0.31255E-03	0.17543E-14	0.31255E-03
0.24124E+12			
N-EIC-01	0.28296E-03	0.38150E-15	0.28296E-03
0.10044E+13			
N-DEC-01	0.76235E-03	0.53386E-08	0.76235E-03
0.19337E+06			
N-DOT-01	0.25790E-02	0.74952E-16	0.25790E-02
0.46594E+14			

HX-102

```
 BLOCK:  HX-102     MODEL: HEATX
 -----------------------------
   HOT SIDE:
   ---------
   INLET STREAM:           PRO1
   OUTLET STREAM:          S-103
   PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE
   COLD SIDE:
   ----------
   INLET STREAM:           CW-101
   OUTLET STREAM:          CW-102
   PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE
                       ***  MASS AND ENERGY BALANCE  ***
                                     IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )            386296.         386296.         0.00000
       MASS(LB/HR   )          0.127718E+08    0.127718E+08     0.00000
       ENTHALPY(BTU/HR  )     -0.510569E+11   -0.510569E+11     0.00000
                           ***  INPUT DATA  ***

   FLASH SPECS FOR HOT SIDE:
   TWO    PHASE      FLASH
   MAXIMUM NO. ITERATIONS                                      30
   CONVERGENCE TOLERANCE                                        0.000100000

   FLASH SPECS FOR COLD SIDE:
   TWO    PHASE      FLASH
   MAXIMUM NO. ITERATIONS                                      30
   CONVERGENCE TOLERANCE                                        0.000100000

   FLOW DIRECTION AND SPECIFICATION:
     COUNTERCURRENT   HEAT EXCHANGER
     SPECIFIED HOT OUTLET TEMP
     SPECIFIED VALUE               F                         437.0000
     LMTD CORRECTION FACTOR                                     1.00000

   PRESSURE SPECIFICATION:
     HOT  SIDE PRESSURE DROP       PSI                          0.0000
     COLD SIDE PRESSURE DROP       PSI                          0.0000

   HEAT TRANSFER COEFFICIENT SPECIFICATION:
     OVERALL COEFFICIENT           BTU/HR-SQFT-F            100.0000

                         ***  OVERALL RESULTS  ***
   STREAMS:
                    --------------------------------------
                   |                                      |
   PRO1      ----->|               HOT                    |-----> S-103
   T=  7.5380D+02  |                                      |       T=
4.3700D+02
   P=  2.3225D+02  |                                      |       P=
2.3225D+02
   V=  1.0000D+00  |                                      |       V=
1.0000D+00
                   |                                      |
   CW-102    <-----|               COLD                   |<----- CW-101
   T=  2.5281D+02  |                                      |       T=
3.9200D+01
   P=  2.9200D+01  |                                      |       P=
2.9200D+01
   V=  4.8696D-01  |                                      |       V=
0.0000D+00
                    --------------------------------------
```

DUTY AND AREA:		
CALCULATED HEAT DUTY	BTU/HR	1822273928.9965
CALCULATED (REQUIRED) AREA	SQM	3783.8592
ACTUAL EXCHANGER AREA	SQM	3783.8592
PER CENT OVER-DESIGN		0.0000
HEAT TRANSFER COEFFICIENT:		
AVERAGE COEFFICIENT (DIRTY)	BTU/HR-SQFT-F	100.0000
UA (DIRTY)	BTU/HR-R	4072912.1079
LOG-MEAN TEMPERATURE DIFFERENCE:		
LMTD CORRECTION FACTOR		1.0000
LMTD (CORRECTED)	F	447.4130
NUMBER OF SHELLS IN SERIES		1
PRESSURE DROP:		
HOTSIDE, TOTAL	PSI	0.0000
COLDSIDE, TOTAL	PSI	0.0000
PRESSURE DROP PARAMETER:		
HOT SIDE:		0.0000
COLD SIDE:		0.0000

HX-101

```
 BLOCK:  HX-101   MODEL: HEATX

 -----------------------------
   HOT SIDE:
   ---------
   INLET STREAM:          S-105
   OUTLET STREAM:         S-106
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
   COLD SIDE:
   ----------
   INLET STREAM:          CW-102
   OUTLET STREAM:         CW-103
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
                      ***  MASS AND ENERGY BALANCE  ***
                                   IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           357053.         357053.         0.00000
       MASS(LB/HR   )          0.198702E+08    0.198702E+08     0.00000
       ENTHALPY(BTU/HR  )     -0.306232E+11   -0.306232E+11     0.00000
                          ***  INPUT DATA  ***
   FLASH SPECS FOR HOT SIDE:
   TWO    PHASE      FLASH
   MAXIMUM NO. ITERATIONS                                 30
   CONVERGENCE TOLERANCE                                   0.000100000
   FLASH SPECS FOR COLD SIDE:
   TWO    PHASE      FLASH
   MAXIMUM NO. ITERATIONS                                 30
   CONVERGENCE TOLERANCE                                   0.000100000
   FLOW DIRECTION AND SPECIFICATION:
     COUNTERCURRENT   HEAT EXCHANGER
     SPECIFIED HOT OUTLET TEMP
     SPECIFIED VALUE               F                     320.0000
     LMTD CORRECTION FACTOR                                0.71160
   PRESSURE SPECIFICATION:
     HOT  SIDE PRESSURE DROP       PSI                     0.0000
     COLD SIDE PRESSURE DROP       PSI                     0.0000
   HEAT TRANSFER COEFFICIENT SPECIFICATION:
     OVERALL COEFFICIENT           BTU/HR-SQFT-F         100.0000

                        ***  OVERALL RESULTS  ***

   STREAMS:
                  --------------------------------------
                 |                                      |
   S-105     ----->|               HOT                    |-----> S-106
   T=  6.2780D+02  |                                      |       T=
3.2000D+02
   P=  1.4696D+01  |                                      |       P=
1.4696D+01
   V=  1.0000D+00  |                                      |       V=
1.0000D+00
                 |                                      |
   CW-103    <-----|               COLD                   |<----- CW-102
   T=  4.6356D+02  |                                      |       T=
2.5281D+02
   P=  2.9200D+01  |                                      |       P=
2.9200D+01
   V=  1.0000D+00  |                                      |       V=  4.8696D-
01
                  --------------------------------------

   DUTY AND AREA:
     CALCULATED HEAT DUTY          BTU/HR         1515813135.5034
```

CALCULATED (REQUIRED) AREA	SQM	18226.1484
ACTUAL EXCHANGER AREA	SQM	18226.1484
PER CENT OVER-DESIGN		0.0000
HEAT TRANSFER COEFFICIENT:		
AVERAGE COEFFICIENT (DIRTY)	BTU/HR-SQFT-F	100.0000
UA (DIRTY)	BTU/HR-R	19618462.7280
LOG-MEAN TEMPERATURE DIFFERENCE:		
LMTD CORRECTION FACTOR		0.7116
LMTD (CORRECTED)	F	77.2646
NUMBER OF SHELLS IN SERIES		1
PRESSURE DROP:		
HOTSIDE, TOTAL	PSI	0.0000
COLDSIDE, TOTAL	PSI	0.0000
PRESSURE DROP PARAMETER:		
HOT SIDE:		0.0000
COLD SIDE:		0.0000

HX-201

```
 BLOCK:  HX-201   MODEL: HEATX
 -----------------------------
   HOT SIDE:
   ---------
   INLET STREAM:          S-203
   OUTLET STREAM:         15
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
   COLD SIDE:
   ----------
   INLET STREAM:          CW-204
   OUTLET STREAM:         CW-205
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                  IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           519902.         519902.         0.00000
       MASS(LB/HR   )          0.210123E+08    0.210123E+08     0.00000
       ENTHALPY(BTU/HR  )      -0.117856E+12   -0.117856E+12   -0.258941E-15

                        ***  INPUT DATA  ***

   FLASH SPECS FOR HOT SIDE:
   TWO    PHASE      FLASH
   MAXIMUM NO. ITERATIONS                                  30
   CONVERGENCE TOLERANCE                                    0.000100000
   FLASH SPECS FOR COLD SIDE:
   TWO    PHASE      FLASH
   MAXIMUM NO. ITERATIONS                                  30
   CONVERGENCE TOLERANCE                                    0.000100000
   FLOW DIRECTION AND SPECIFICATION:
     COUNTERCURRENT   HEAT EXCHANGER
     SPECIFIED HOT OUTLET TEMP
     SPECIFIED VALUE                 F                     86.0000
     LMTD CORRECTION FACTOR                                 1.00000
   PRESSURE SPECIFICATION:
     HOT  SIDE PRESSURE DROP         PSI                    0.0000
     COLD SIDE PRESSURE DROP         PSI                    0.0000
   HEAT TRANSFER COEFFICIENT SPECIFICATION:
     OVERALL COEFFICIENT             BTU/HR-SQFT-F         17.6110
                      ***  OVERALL RESULTS  ***
   STREAMS:
                   --------------------------------------
                  |                                      |
   S-203     ----->|                HOT                   |-----> 15
   T=  4.3700D+02  |                                      |       T=
8.6000D+01
   P=  4.4088D+02  |                                      |       P=
4.4088D+02
   V=  1.0000D+00  |                                      |       V=  3.6714D-
01
                  |                                      |
   CW-205    <-----|                COLD                  |<----- CW-204
   T=  3.6400D+02  |                                      |       T=
3.9221D+01
   P=  1.5973D+02  |                                      |       P=
1.5973D+02
   V=  3.2466D-01  |                                      |       V=
0.0000D+00
                   --------------------------------------

   DUTY AND AREA:
```

CALCULATED HEAT DUTY	BTU/HR	7863297672.3823
CALCULATED (REQUIRED) AREA	SQM	704002.4475
ACTUAL EXCHANGER AREA	SQM	704002.4475
PER CENT OVER-DESIGN		0.0000
HEAT TRANSFER COEFFICIENT:		
AVERAGE COEFFICIENT (DIRTY)	BTU/HR-SQFT-F	17.6110
UA (DIRTY)	BTU/HR-R	133453114.5780
LOG-MEAN TEMPERATURE DIFFERENCE:		
LMTD CORRECTION FACTOR		1.0000
LMTD (CORRECTED)	F	58.9218
NUMBER OF SHELLS IN SERIES		1
PRESSURE DROP:		
HOTSIDE, TOTAL	PSI	0.0000
COLDSIDE, TOTAL	PSI	0.0000
PRESSURE DROP PARAMETER:		
HOT SIDE:		0.0000
COLD SIDE:		0.0000

MEA-101

```
 BLOCK:  MEA-101  MODEL: SEP
 ---------------------------
   INLET STREAM:          S-103
   OUTLET STREAMS:        CO2         S-104
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                  IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )          323796.         323796.         0.00000
       MASS(LB/HR   )         0.102895E+08    0.102895E+08   -0.181024E-15
       ENTHALPY(BTU/HR  )    -0.356482E+11   -0.356493E+11    0.293829E-04

                        ***  INPUT DATA  ***

   FLASH SPECS FOR STREAM CO2
   TWO    PHASE  TP  FLASH
   PRESSURE DROP         PSI                                  0.0
   MAXIMUM NO. ITERATIONS                                    30
   CONVERGENCE TOLERANCE                                      0.000100000

   FLASH SPECS FOR STREAM S-104
   TWO    PHASE  TP  FLASH
   PRESSURE DROP         PSI                                  0.0
   MAXIMUM NO. ITERATIONS                                    30
   CONVERGENCE TOLERANCE                                      0.000100000

   FRACTION OF FEED
     SUBSTREAM= MIXED
       STREAM= CO2       CPT= CO2       FRACTION=          0.80000

                         ***  RESULTS  ***

   HEAT DUTY             BTU/HR                              -0.10475E+07

  COMPONENT = CH4
    STREAM     SUBSTREAM    SPLIT FRACTION
    S-104      MIXED                 1.00000

  COMPONENT = H2O
    STREAM     SUBSTREAM    SPLIT FRACTION
    S-104      MIXED                 1.00000

  COMPONENT = CO
    STREAM     SUBSTREAM    SPLIT FRACTION
    S-104      MIXED                 1.00000

  COMPONENT = CO2
    STREAM     SUBSTREAM    SPLIT FRACTION
    CO2        MIXED                 0.80000
    S-104      MIXED                 0.20000

  COMPONENT = H2
    STREAM     SUBSTREAM    SPLIT FRACTION
    S-104      MIXED                 1.00000
```

```
MIX-1
BLOCK:  MIX-1    MODEL: MIXER
 -----------------------------
   INLET STREAMS:          S-104       S-305
   OUTLET STREAM:          S-201
   PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           321093.         321093.         0.00000
       MASS(LB/HR   )          0.937378E+07    0.937378E+07     0.00000
       ENTHALPY(BTU/HR  )     -0.298349E+11   -0.298349E+11   -0.127860E-15

                          ***  INPUT DATA  ***
   TWO    PHASE     FLASH
   MAXIMUM NO. ITERATIONS                                   30
   CONVERGENCE TOLERANCE                                     0.000100000
   OUTLET PRESSURE:  MINIMUM OF INLET STREAM PRESSURES

MIX-2
BLOCK:  MIX-2    MODEL: MIXER
 -----------------------------
   INLET STREAMS:          S-302       S-303
   OUTLET STREAM:          S-306
   PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           9652.33         9652.33         0.00000
       MASS(LB/HR   )          0.178896E+07    0.178896E+07    0.130148E-15
       ENTHALPY(BTU/HR  )     -0.245104E+10   -0.245104E+10     0.00000

                          ***  INPUT DATA  ***
   ONE    PHASE     FLASH   SPECIFIED PHASE IS  LIQUID
   MAXIMUM NO. ITERATIONS                                   30
   CONVERGENCE TOLERANCE                                     0.000100000
   OUTLET PRESSURE   PSI                                  290.268
```

PUMP-202

```
BLOCK:  PUMP-202 MODEL: PUMP

 ----------------------------
   INLET STREAM:          CW-203
   OUTLET STREAM:         CW-204
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                    IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           293036.         293036.         0.00000
       MASS(LB/HR   )         0.116385E+08    0.116385E+08     0.00000
       ENTHALPY(BTU/HR  )      -0.807847E+11   -0.807836E+11   -0.142158E-04

                          ***  INPUT DATA  ***
    OUTLET PRESSURE  PSI                                        159.734
    DRIVER EFFICIENCY                                             1.00000

    FLASH SPECIFICATIONS:
    LIQUID PHASE CALCULATION
    NO FLASH PERFORMED
    MAXIMUM NUMBER OF ITERATIONS                                  30
    TOLERANCE                                                     0.000100000

                           ***  RESULTS  ***
    VOLUMETRIC FLOW RATE  CUFT/HR                           183,860.
    PRESSURE CHANGE  PSI                                         29.0075
    NPSH AVAILABLE   FT                                         297.208
    FLUID POWER  WATT                                       289,240.
    BRAKE POWER  WATT                                       336,570.
    ELECTRICITY  WATT                                       336,570.
    PUMP EFFICIENCY USED                                          0.85938
    NET WORK REQUIRED  WATT                                 336,570.
    HEAD DEVELOPED FT                                            65.9877
```

PUMP-202

```
BLOCK:  PUMP201  MODEL: PUMP
 ----------------------------
   INLET STREAM:          CW-201
   OUTLET STREAM:         CW-202
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                    IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           192183.         192183.         0.00000
       MASS(LB/HR   )         0.763291E+07    0.763291E+07     0.00000
       ENTHALPY(BTU/HR  )      -0.529843E+11   -0.529813E+11   -0.568598E-04

                          ***  INPUT DATA  ***
    OUTLET PRESSURE  PSI                                        130.726
    DRIVER EFFICIENCY                                             1.00000

    FLASH SPECIFICATIONS:
    LIQUID PHASE CALCULATION
    NO FLASH PERFORMED
    MAXIMUM NUMBER OF ITERATIONS                                  30
    TOLERANCE                                                     0.000100000

                           ***  RESULTS  ***
    VOLUMETRIC FLOW RATE  CUFT/HR                           120,580.
    PRESSURE CHANGE  PSI                                        116.030
```

NPSH AVAILABLE FT	33.2565
FLUID POWER WATT	758,768.
BRAKE POWER WATT	882,928.
ELECTRICITY WATT	882,928.
PUMP EFFICIENCY USED	0.85938
NET WORK REQUIRED WATT	882,928.
HEAD DEVELOPED FT	263.949

PUMP-301

BLOCK: PUMP301 MODEL: PUMP

INLET STREAM: S-308
OUTLET STREAM: TO-PIPE
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	2694.21	2694.21	0.00000
MASS(LB/HR)	0.130153E+07	0.130153E+07	0.00000
ENTHALPY(BTU/HR)	-0.113043E+10	-0.112997E+10	-0.410790E-03

*** INPUT DATA ***

PRESSURE CHANGE PSI	72.5189
DRIVER EFFICIENCY	1.00000

FLASH SPECIFICATIONS:
LIQUID PHASE CALCULATION
NO FLASH PERFORMED

MAXIMUM NUMBER OF ITERATIONS	30
TOLERANCE	0.000100000

*** RESULTS ***

VOLUMETRIC FLOW RATE CUFT/HR	29,307.2
PRESSURE CHANGE PSI	72.5189
NPSH AVAILABLE FT	0.0
FLUID POWER WATT	115,262.
BRAKE POWER WATT	136,093.
ELECTRICITY WATT	136,093.
PUMP EFFICIENCY USED	0.84694
NET WORK REQUIRED WATT	136,093.
HEAD DEVELOPED FT	235.143

```
SMR-2
BLOCK:  SMR-2    MODEL: HEATER
 ------------------------------
   INLET STREAM:          12
   OUTLET STREAM:         PRO1
   OUTLET HEAT STREAM:    HS-SMR-4
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                   IN               OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           323796.         323796.         0.00000
       MASS(LB/HR   )          0.102895E+08    0.102895E+08     0.00000
       ENTHALPY(BTU/HR  )     -0.282785E+11   -0.282785E+11    0.134898E-15

                          ***  INPUT DATA  ***
   TWO    PHASE  TP  FLASH
   SPECIFIED TEMPERATURE              F                        753.800
   SPECIFIED PRESSURE                 PSI                      232.253
   MAXIMUM NO. ITERATIONS                                       30
   CONVERGENCE TOLERANCE                                         0.000100000



                           ***  RESULTS  ***
   OUTLET TEMPERATURE    F                                   753.80
   OUTLET PRESSURE       PSI                                 232.25
   HEAT DUTY             BTU/HR                            -0.55475E+10
   OUTLET VAPOR FRACTION                                       1.0000
   PRESSURE-DROP CORRELATION PARAMETER                         0.0000


   V-L PHASE EQUILIBRIUM :

      COMP              F(I)          X(I)          Y(I)          K(I)
      CH4             0.19589E-01   0.16726E-01   0.19589E-01     46.004
      H2O             0.29823       0.49146       0.29823         23.835
      CO              0.15043       0.10652       0.15043         55.475
      CO2             0.81954E-01   0.75184E-01   0.81954E-01     42.817
      H2              0.44980       0.31011       0.44980         56.977

SMR-3
BLOCK:  SMR-3    MODEL: RSTOIC
 ------------------------------
   INLET STREAMS:         FEEDFUEL    RECYCLE     FEEDAIR
   INLET HEAT STREAM:     HS-SMR-2
   OUTLET STREAM:         FLUEGAS
   OUTLET HEAT STREAM:    HS-SMR-1
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                             IN           OUT       GENERATION   RELATIVE
DIFF.
   TOTAL BALANCE
   MOLE(KMOL/HR )         317891.       294553.      -23338.4      0.801086E-
16
   MASS(LB/HR   )       0.173879E+08  0.173879E+08                  0.00000
   ENTHALPY(BTU/HR  )    0.384507E+10  0.384507E+10                0.124013E-
15

                          ***  INPUT DATA  ***
   STOICHIOMETRY MATRIX:
```

```
 REACTION #   1:
  SUBSTREAM MIXED   :
  H2O        1.00    H2         -1.00    OXYGE-01 -0.500

 REACTION #   2:
  SUBSTREAM MIXED   :
  CH4       -1.00    H2O         2.00    CO2         1.00    OXYGE-01  -2.00

 REACTION #   3:
  SUBSTREAM MIXED   :
  H2O        3.00    CO2         2.00    C2H6       -1.00    OXYGE-01  -3.50

 REACTION #   4:
  SUBSTREAM MIXED   :
  H2O        4.00    CO2         3.00    C3H8       -1.00    OXYGE-01  -5.00

 REACTION #   5:
  SUBSTREAM MIXED   :
  H2O        5.00    CO2         4.00    C4H10      -1.00    OXYGE-01  -6.50


REACTION CONVERSION SPECS: NUMBER=    5
  REACTION #   1:
  SUBSTREAM:MIXED    KEY COMP:H2       CONV FRAC:  1.000
  REACTION #   2:
  SUBSTREAM:MIXED    KEY COMP:CH4      CONV FRAC:  1.000
  REACTION #   3:
  SUBSTREAM:MIXED    KEY COMP:C2H6     CONV FRAC:  1.000
  REACTION #   4:
  SUBSTREAM:MIXED    KEY COMP:C3H8     CONV FRAC:  1.000
  REACTION #   5:
  SUBSTREAM:MIXED    KEY COMP:C4H10    CONV FRAC:  1.000



TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE F                                    1,652.00
SPECIFIED PRESSURE    PSI                                     14.6959
MAXIMUM NO. ITERATIONS                                        30
CONVERGENCE TOLERANCE                                          0.000100000
SIMULTANEOUS REACTIONS
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES               NO

                        ***  RESULTS  ***
OUTLET TEMPERATURE    F                                         1652.0
OUTLET PRESSURE       PSI                                       14.696
HEAT DUTY             BTU/HR                                  -0.80224E+10
NET DUTY              BTU/HR                                  -0.13541E+11
VAPOR FRACTION                                                  1.0000


REACTION EXTENTS:

   REACTION           REACTION
   NUMBER             EXTENT
                      KMOL/HR
   1                   47057.
   2                   6578.9
   3                   164.92
   4                   72.816
   5                   23.374
```

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
H2O	0.20807	0.20807	0.20807	MISSING
CO2	0.34493E-01	0.34493E-01	0.34493E-01	MISSING
N-HEX-01	0.34783E-03	0.34783E-03	0.34783E-03	MISSING
N-NON-01	0.13012E-04	0.13012E-04	0.13012E-04	MISSING
N-UND-01	0.12391E-05	0.12391E-05	0.12391E-05	MISSING
N-DOD-01	0.37147E-06	0.37147E-06	0.37147E-06	MISSING
N-HEX-02	0.30828E-08	0.30828E-08	0.30828E-08	MISSING
N-PEN-01	0.59624E-03	0.59624E-03	0.59624E-03	MISSING
N-HEP-01	0.12657E-03	0.12657E-03	0.12657E-03	MISSING
N-OCT-01	0.47999E-04	0.47999E-04	0.47999E-04	MISSING
N-TRI-01	0.11095E-06	0.11095E-06	0.11095E-06	MISSING
N-TET-01	0.33865E-07	0.33865E-07	0.33865E-07	MISSING
N-PEN-02	0.12046E-09	0.12046E-09	0.12046E-09	MISSING
N-HEP-02	0.10572E-10	0.10572E-10	0.10572E-10	MISSING
N-OCT-02	0.34445E-11	0.34445E-11	0.34445E-11	MISSING
N-NON-02	0.92191E-12	0.92191E-12	0.92191E-12	MISSING
N-EIC-01	0.26690E-12	0.26690E-12	0.26690E-12	MISSING
N-DEC-01	0.42390E-05	0.42390E-05	0.42390E-05	MISSING
N2	0.69872	0.69872	0.69872	MISSING
OXYGE-01	0.57584E-01	0.57584E-01	0.57584E-01	MISSING

SMR-4

BLOCK: SMR-4 MODEL: HEATER

INLET STREAM: FLUEGAS
OUTLET STREAM: S-105
OUTLET HEAT STREAM: HS-SMR-2
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	294553.	294553.	0.00000
MASS(LB/HR)	0.173879E+08	0.173879E+08	0.00000
ENTHALPY(BTU/HR)	-0.969565E+10	-0.969613E+10	0.493018E-04

*** INPUT DATA ***

TWO PHASE TP FLASH

SPECIFIED TEMPERATURE	F	627.800
SPECIFIED PRESSURE	PSI	14.6959
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

*** RESULTS ***

OUTLET TEMPERATURE	F	627.80
OUTLET PRESSURE	PSI	14.696
HEAT DUTY	BTU/HR	-0.55188E+10
OUTLET VAPOR FRACTION		1.0000
PRESSURE-DROP CORRELATION PARAMETER		0.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
H2O	0.20807	0.35915	0.20807	273.90
CO2	0.34493E-01	0.35055E-01	0.34493E-01	465.22
N-HEX-01	0.34783E-03	0.40169E-03	0.34783E-03	409.39
N-NON-01	0.13012E-04	0.16037E-04	0.13012E-04	383.59
N-UND-01	0.12391E-05	0.14713E-05	0.12391E-05	398.16

N-DOD-01	0.37147E-06	0.42863E-06	0.37147E-06	409.71
N-HEX-02	0.30828E-08	0.30488E-08	0.30828E-08	478.02
N-PEN-01	0.59624E-03	0.69105E-03	0.59624E-03	407.92
N-HEP-01	0.12657E-03	0.14761E-03	0.12657E-03	405.39
N-OCT-01	0.47999E-04	0.69324E-04	0.47999E-04	327.35
N-TRI-01	0.11095E-06	0.12365E-06	0.11095E-06	424.22
N-TET-01	0.33865E-07	0.36248E-07	0.33865E-07	441.67
N-PEN-02	0.12046E-09	0.12417E-09	0.12046E-09	458.65
N-HEP-02	0.10572E-10	0.10252E-10	0.10572E-10	487.49
N-OCT-02	0.34445E-11	0.31545E-11	0.34445E-11	516.20
N-NON-02	0.92191E-12	0.80227E-12	0.92191E-12	543.25
N-EIC-01	0.26690E-12	0.22418E-12	0.26690E-12	562.83
N-DEC-01	0.42390E-05	0.48130E-05	0.42390E-05	416.39
N2	0.69872	0.55311	0.69872	597.26
OXYGE-01	0.57584E-01	0.51346E-01	0.57584E-01	530.23

SMR-101

```
BLOCK:  SMR-101  MODEL: RYIELD
 ------------------------------
   INLET STREAMS:          S-101       CO2RECYL    STEAM101
   INLET HEAT STREAMS:     HS-SMR-1    HS-SMR-4
   OUTLET STREAM:          12
   OUTLET HEAT STREAM:     HS-SMR-3
   PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE

     ***********************************************************************
     *                                                                     *
     *     SPECIFIED YIELDS HAVE BEEN NORMALIZED TO MAINTAIN MASS BALANCE  *
     *                                                                     *
     ***********************************************************************

                      ***  MASS AND ENERGY BALANCE  ***
                                IN           OUT       GENERATION   RELATIVE
DIFF.
   TOTAL BALANCE
   MOLE(KMOL/HR )         265815.       323796.       57980.7      0.674124E-
16
   MASS(LB/HR   )        0.102895E+08  0.102895E+08                0.362049E-
15
   ENTHALPY(BTU/HR  )   -0.282785E+11 -0.282785E+11                0.134898E-
15

                          ***  INPUT DATA  ***
   TWO    PHASE  TP  FLASH
   SPECIFIED TEMPERATURE F                                   1,652.00
   SPECIFIED PRESSURE    PSI                                   232.253
   MAXIMUM NO. ITERATIONS                                      30
   CONVERGENCE TOLERANCE                                        0.000100000

    MASS-YIELD
     SUBSTREAM MIXED   :
     CH4       0.218E-01    H2O       0.373       CO         0.292
     CO2       0.250        H2        0.629E-01

                           ***  RESULTS  ***
   OUTLET TEMPERATURE    F                                       1652.0
   OUTLET PRESSURE       PSI                                     232.25
   HEAT DUTY             BTU/HR                                 0.19088E+11
   NET DUTY              BTU/HR                                -0.39049E-04
   VAPOR FRACTION                                                1.0000


   V-L PHASE EQUILIBRIUM :

      COMP              F(I)           X(I)           Y(I)           K(I)
      CH4              0.19589E-01    0.19589E-01    0.19589E-01     MISSING
      H2O              0.29823        0.29823        0.29823         MISSING
      CO               0.15043        0.15043        0.15043         MISSING
      CO2              0.81954E-01    0.81954E-01    0.81954E-01     MISSING
      H2               0.44980        0.44980        0.44980         MISSING
```

```
SPLIT-1
 BLOCK:  SPLIT-1  MODEL: FSPLIT
 ------------------------------
   INLET STREAM:          CO2
   OUTLET STREAMS:        CO2PURGE    CO2RECYL
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           21229.0         21229.0         0.00000
       MASS(LB/HR   )         0.205975E+07    0.205975E+07     0.00000
       ENTHALPY(BTU/HR  )    -0.775619E+10   -0.775619E+10     0.00000

                          ***  INPUT DATA  ***

  MOLE-FLOW  (KMOL/HR )           STRM=CO2RECYL FLOW=       848.471
KEY= 0

                           ***  RESULTS  ***

  STREAM= CO2PURGE       SPLIT=          0.96003     KEY=  0    STREAM-ORDER=
2
          CO2RECYL                       0.039968          0
1

SPLIT-2
 BLOCK:  SPLIT-2  MODEL: FSPLIT
 ------------------------------
   INLET STREAM:          CW-206
   OUTLET STREAMS:        CW-207      STEAM201
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           293036.         293036.         0.00000
       MASS(LB/HR   )         0.116385E+08    0.116385E+08     0.00000
       ENTHALPY(BTU/HR  )    -0.656079E+11   -0.656079E+11     0.00000

                          ***  INPUT DATA  ***

  MOLE-FLOW  (KMOL/HR )           STRM=STEAM201 FLOW=   192,183.
KEY= 0

                           ***  RESULTS  ***

  STREAM= CW-207         SPLIT=          0.34417     KEY=  0    STREAM-ORDER=
2
          STEAM201                       0.65583           0
1
```

TURB-201

```
 BLOCK:  TURB-201 MODEL: COMPR
 -----------------------------
   INLET STREAM:           CW-207
   OUTLET STREAM:          CW-208
   PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                    IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )          100853.         100853.         0.00000
       MASS(LB/HR    )        0.400558E+07    0.400558E+07     0.00000
       ENTHALPY(BTU/HR  )    -0.225800E+11   -0.226311E+11    0.225607E-02

                           ***  INPUT DATA  ***

   ISENTROPIC TURBINE
    OUTLET PRESSURE  PSI                                      130.726
    ISENTROPIC EFFICIENCY                                       0.72000
    MECHANICAL EFFICIENCY                                       1.00000

                           ***  RESULTS  ***

    INDICATED  HORSEPOWER REQUIREMENT  WATT                   -0.149634+08
    BRAKE      HORSEPOWER REQUIREMENT  WATT                   -0.149634+08
    NET WORK REQUIRED                  WATT                   -0.149634+08
    POWER LOSSES                       WATT                     0.0
    ISENTROPIC HORSEPOWER REQUIREMENT  WATT                   -0.207825+08
    CALCULATED OUTLET TEMP  F                                 369.563
    ISENTROPIC TEMPERATURE  F                                 359.346
    EFFICIENCY (POLYTR/ISENTR) USED                             0.72000
    OUTLET VAPOR FRACTION                                       1.00000
    HEAD DEVELOPED,        FT                             -13,776.4
    MECHANICAL EFFICIENCY USED                                  1.00000
    INLET HEAT CAPACITY RATIO                                   1.37264
    INLET VOLUMETRIC FLOW RATE , CUFT/HR                        0.122543+08
    OUTLET VOLUMETRIC FLOW RATE, CUFT/HR                        0.144896+08
    INLET  COMPRESSIBILITY FACTOR                               0.95316
    OUTLET COMPRESSIBILITY FACTOR                               0.95733
    AV. ISENT. VOL. EXPONENT                                    1.30617
    AV. ISENT. TEMP EXPONENT                                    1.32898
    AV. ACTUAL VOL. EXPONENT                                    1.19603
    AV. ACTUAL TEMP EXPONENT                                    1.22801
```

Convergence Report:

```
CONVERGENCE BLOCK:  $OLVER10
----------------------------
    Tear Stream  :  12         S-305      HS-SMR-2   CW-203     CW-101
    Tolerance used:  0.100D-03  0.100D-03  0.100D-03  0.100D-03  0.100D-03
    Trace molefrac:  0.100D-05  0.100D-05             0.100D-05  0.100D-05

    MAXIT=   30 WAIT   1 ITERATIONS BEFORE ACCELERATING
    QMAX =   0.0      QMIN =  -5.0
    METHOD: WEGSTEIN      STATUS: CONVERGED
    TOTAL NUMBER OF ITERATIONS:    60
    NUMBER OF ITERATIONS ON LAST OUTER LOOP:     0

                         *** FINAL VALUES ***
```

VARIABLE		VALUE	PREV VALUE	ERR/TOL
TOTAL MOLEFLOW	KMOL/HR	3.2380+05	3.2380+05	0.0
TOTAL MOLEFLOW	KMOL/HR	1.8527+04	1.8527+04	0.0
TOTAL MOLEFLOW	KMOL/HR	2.9304+05	2.9304+05	0.0
TOTAL MOLEFLOW	KMOL/HR	6.2500+04	6.2500+04	0.0
CH4 MOLEFLOW	KMOL/HR	6342.7776	6342.7776	0.0
H2O MOLEFLOW	KMOL/HR	9.6565+04	9.6565+04	0.0
CO MOLEFLOW	KMOL/HR	4.8709+04	4.8709+04	0.0
CO2 MOLEFLOW	KMOL/HR	2.6536+04	2.6536+04	0.0
H2 MOLEFLOW	KMOL/HR	1.4564+05	1.4564+05	0.0
C2H6 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C3H8 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C4H10 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-NON-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-UND-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DOD-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-PEN-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEP-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-OCT-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-TRI-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-TET-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-PEN-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEP-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-OCT-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-NON-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-EIC-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DEC-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DOT-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
OXYGE-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
AIR MOLEFLOW	KMOL/HR	0.0	0.0	0.0
PRESSURE	PSI	232.2526	232.2526	0.0
MASS ENTHALPY	BTU/LB	-2748.2926	-2748.2926	0.0
CH4 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
H2O MOLEFLOW	KMOL/HR	0.0	0.0	0.0
CO MOLEFLOW	KMOL/HR	1.8527+04	1.8527+04	0.0
CO2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
H2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C2H6 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C3H8 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C4H10 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-NON-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-UND-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DOD-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-PEN-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0

N-HEP-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-OCT-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-TRI-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-TET-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-PEN-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEP-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-OCT-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-NON-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-EIC-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DEC-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DOT-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
OXYGE-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
AIR MOLEFLOW	KMOL/HR	0.0	0.0	0.0
PRESSURE	PSI	232.2526	232.2526	0.0
MASS ENTHALPY	BTU/LB	-1697.2817	-1697.2817	0.0
INFO-VAR		1.6173+09	1.6173+09	0.0
CH4 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
H2O MOLEFLOW	KMOL/HR	2.9304+05	2.9304+05	0.0
CO MOLEFLOW	KMOL/HR	0.0	0.0	0.0
CO2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
H2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C2H6 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C3H8 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C4H10 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-NON-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-UND-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DOD-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-PEN-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEP-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-OCT-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-TRI-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-TET-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-PEN-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEP-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-OCT-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-NON-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-EIC-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DEC-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DOT-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
OXYGE-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
AIR MOLEFLOW	KMOL/HR	0.0	0.0	0.0
PRESSURE	PSI	130.7261	130.7261	0.0
MASS ENTHALPY	BTU/LB	-6941.1706	-6941.1706	0.0
CH4 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
H2O MOLEFLOW	KMOL/HR	6.2500+04	6.2500+04	0.0
CO MOLEFLOW	KMOL/HR	0.0	0.0	0.0
CO2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
H2 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C2H6 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C3H8 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
C4H10 MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-NON-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-UND-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-DOD-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEX-02MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-PEN-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-HEP-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-OCT-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0
N-TRI-01MOLEFLOW	KMOL/HR	0.0	0.0	0.0

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N-TET-01MOLEFLOW KMOL/HR         0.0            0.0            0.0
N-PEN-02MOLEFLOW KMOL/HR         0.0            0.0            0.0
N-HEP-02MOLEFLOW KMOL/HR         0.0            0.0            0.0
N-OCT-02MOLEFLOW KMOL/HR         0.0            0.0            0.0
N-NON-02MOLEFLOW KMOL/HR         0.0            0.0            0.0
N-EIC-01MOLEFLOW KMOL/HR         0.0            0.0            0.0
N-DEC-01MOLEFLOW KMOL/HR         0.0            0.0            0.0
N-DOT-01MOLEFLOW KMOL/HR         0.0            0.0            0.0
N2 MOLEFLOW      KMOL/HR         0.0            0.0            0.0
OXYGE-01MOLEFLOW KMOL/HR         0.0            0.0            0.0
AIR MOLEFLOW     KMOL/HR         0.0            0.0            0.0
PRESSURE         PSI            29.1997        29.1997         0.0
MASS ENTHALPY    BTU/LB      -6941.5102     -6941.5102         0.0

                         *** ITERATION HISTORY ***
    TEAR STREAMS:

    ITERATION   MAX-ERR/TOL   STREAM ID   VARIABLE
    ---------   -----------   ---------   --------
         1       0.000        12          CH4 MOLEFLOW

CONVERGENCE BLOCK:  $OLVER17
----------------------------
    SPECS: FTCW
    MAXIT=   30 STEP-SIZE=    1.0000    % OF RANGE
                MAX-STEP=       100.    % OF RANGE
                XTOL=      1.000000E-08
    THE NEW ALGORITHM WAS USED WITH BRACKETING=NO
    METHOD: SECANT        STATUS: CONVERGED
    TOTAL NUMBER OF ITERATIONS:     1
    NUMBER OF ITERATIONS ON LAST OUTER LOOP:     0

                         *** FINAL VALUES ***
   VARIABLE                        VALUE           PREV VALUE      ERR/TOL
TOTAL MOLEFL     KMOL/HR      2.9304+05      2.9304+05         0.2603

                         *** ITERATION HISTORY ***

    DESIGN-SPEC ID: FTCW

    ITERATION  VARIABLE         ERROR          ERR/TOL
    ---------  --------         -----          -------
         1     0.2930E+06        260.3         0.2603

CONVERGENCE BLOCK:  $OLVER18
----------------------------
    SPECS: QREFOR
    MAXIT=   30 STEP-SIZE=    100.00    % OF RANGE
                MAX-STEP=       100.    % OF RANGE
                XTOL=      1.000000E-08
    THE NEW ALGORITHM WAS USED WITH BRACKETING=NO
    METHOD: SECANT        STATUS: CONVERGED
    TOTAL NUMBER OF ITERATIONS:     1
    NUMBER OF ITERATIONS ON LAST OUTER LOOP:     0

                         *** FINAL VALUES ***

   VARIABLE                        VALUE           PREV VALUE      ERR/TOL
TOTAL MOLEFL     KMOL/HR      3.1520+04      3.1520+04      1.1444-08

                         *** ITERATION HISTORY ***
    DESIGN-SPEC ID: QREFOR
    ITERATION  VARIABLE         ERROR          ERR/TOL
    ---------  --------         -----          -------
```

1	0.3152E+05 LB	0.1144E-04	0.1144E-07