Department of Chemical & Biomolecular Engineering

Senior Design Reports (CBE)

University of Pennsylvania Year 2014

OXIDATIVE COUPLING OF METHANE TO ETHYLENE

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Oxidative Coupling of Methane to Ethylene

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Presented to:

Professor Leonard Fabiano

Dr. John Vohs

April 15, 2014

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April 15, 2014

Dear Professor Fabiano and Dr. Vohs,

We would like to present our solution to the *Oxidative Coupling of Methane to Ethylene* design project recommended by Mr. Gary Sawyer. We have designed a plant to be located in Baytown, Texas that will produce 1 billion pounds of ethylene per year from natural gas. The methane will undergo oxidative coupling using parallel fixed-bed reactors filled with an LiMgO catalyst. The products of the oxidative coupling will be separated using condensation, adsorbents, and cryogenic distillation. This approach to the production of ethylene is presented as an alternative to ethane cracking that currently controls the ethylene market.

The enclosed report contains the details of the operation of the plant as well as the process equipment being used. To produce the required amount of ethylene, our plant will need 9.1 billion pounds of natural gas per year.

In addition, this report also discloses the reasoning behind every process unit chosen, as well as our decision behind the location of the plant. We provide a discussion of the economics of building and running a plant, as well as describe its profitability and market analysis. The Internal Rate of Return for this project is 25.61% and the current Net Present Value is $517,165,400. As of today, due to the current prices of natural gas and ethane, our plant will make a profit and has a ROI of 21.58%.

Sincerely,

Tyler Fini	Corey Patz	Rebecca Wentzel

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Section 1- Abstract

This report details the design of a plant using the oxidative coupling of methane (OCM) to produce one billion pounds of ethylene and 534 million pounds of ethane per year. The ethylene and ethane produced are produced for sale to an olefins plant for further refining into polymers and plastics. The OCM process consumes a total feed of 9.10 billion pounds of methane and 4.62 billion pounds of oxygen per year. The methane and oxygen will be converted in four isothermal fixed-bed catalytic reactors operating at 1292°F and 96 psi. The catalyst is LiMgO in the form of 50 mm diameter spherical pellets. The remainder of the process encompasses an intricate separations train involving condensation, pressure swing adsorption, and cryogenic distillation. The unconverted methane is combusted to produce steam that is fed to a turbine to provide power to the plant with a residual 108 MW of electricity sent into the grid. The plant will be located in Baytown, Texas where access to feedstock and the olefin plants buying the products are easily attainable. After conducting an analysis of the sensitivity of the plant's Internal Rate of Return with variable pricing and ethylene prices, it was determined that the plant is profitable exhibiting a Return on Investment of 25.61% and a Net Present Value of $517.2 million. Further research into catalysts increasing conversion of methane coupled with increased selectivity to C_2 hydrocarbons will offer more attractive returns.

Section 2- Introduction

Ethylene is the chemical industry's primary building block, with a worldwide production capacity in 2012 of 141 million tonnes per year.[1] It is used industrially for processes like polymerization to polyethylene, oxidation to ethylene oxide, oligomerization to form olefins, and halogenation to vinyl chloride. Ninety percent of ethylene is used to produce chemicals like ethylene oxide and polyethylene which are used in the creation of detergents, surfactants, and different packaging elements. In the United States, 70% of all ethylene being produced comes from steam cracking, specifically of naptha while the remaining 30% is produced from cracking ethane. [2] In steam cracking, light hydrocarbons are heated to 750-950 °C. These high temperatures induce free radical reactions which are immediately quenched and stopped. This process takes large hydrocarbons and breaks them into smaller ones. The ethylene is then separated from the diverse mixture with compression and distillation. Due to the increased availability of natural gas in the United States, there has been in interest in tapping into natural gas as feed for this grossly consumed commodity chemical.

Since 1980, the catalytic oxidative coupling of methane (OCM) reaction to C_2 hydrocarbons has been studied in terms of best catalysts and operating conditions. Over the past 30 years, various studies have shown that OCM is a promising alternative to steam cracking, but it has not broken into the industrial market for a few reasons. First, OCM has a relatively low concentration of ethylene in the product stream as compared to the amount of reactant fed. It is hard to consider scaling up OCM without detailed chemistry about the C_2 yield of the most promising catalysts, which are not made widely available. Second, because OCM is only effective at very high temperatures and hydrocarbons are separated downstream at very low temperatures, this makes heat integration and efficient operation crucial to profitable operation.

The focus of this report is the implementation of the oxidative coupling of methane in a large-scale industrial plant, which has the potential for high profit due to the dropping natural gas prices and rising oil prices that affect traditional modes of ethylene production. Our primary objective was to design a plant that utilized OCM as means of producing 1 billion pounds per year of ethylene and capitalizing on the natural gas market. This is roughly a 2% increase in US capacity. Our plant design includes a reactor section, a separation train including cryogenic distillation and pressure swing adsorption, a refrigeration cycle, and rigorous heat integration. The product stream must contain only ethylene and ethane, to be sold to an olefin plant. In order to make this a profitable venture, the OCM reaction, operating conditions, and catalyst must be optimal. The following two factors form the basis of this plant design: a high temperature reactor with finely controlled operating conditions and an impeccable separations train that utilizes material and heat integration for the profitability of this process. Our plant will be located in the Gulf Coast for reasons discussed later in the report and will operate 330 days of every year.

Chemistry Background

The main chemistry behind the oxidative coupling of methane (OCM) is shown below.

$$CH_4 + \frac{1}{2} O_2 \rightarrow \frac{1}{2} C_2H_4 + H_2O \qquad (1)$$

This reaction is exothermic and has a standard heat of reaction of -175 kJ/mol, as seen in Table 1. To try to couple methane without an oxidant would prove to be futile as the endothermic reaction and thermodynamics would constrain the conversion greatly. Adding the oxidation aspect overcomes the thermodynamic restrictions and makes the reaction exothermic, as in Equation 1. However, the partial oxidation (Equation 2) and complete oxidation (Equation 3) of methane are much more thermodynamically favorable than the oxidative coupling. This can be seen from the corresponding Gibbs free energies in Table 1.

$$CH_4 + 3/2\ O_2 \rightarrow CO + 2\ H_2O \qquad (2)$$

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O \qquad (3)$$

Equation 2 is the partial oxidation and has a heat of reaction of -519 kJ/mol, and Equation 3 is the complete oxidation which is even more favorable with a heat of reaction of -801 kJ.mol. Both of these reactions produce combustion elements instead of the desired C_2 products. In order to operate the reactor section in a way that the C_2 yields are acceptable, the balance of the reactions above must be kept. This is the motivation behind the selection of the catalyst, LiMgO, which will be explained in the reactor component of Section 6.[3]

Table 1. Gibbs Free Energies and Enthalpies of Methane with Oxygen[4]

Reaction	ΔG^O_{298} (KJ/mol)	ΔH^O_{298} (KJ/mol)
$CH_4 + \frac{1}{2}O_2 \rightarrow \frac{1}{2}C_2H_4 + H_2O$	-143.0	-140.4
$CH_4 + \frac{1}{4}O_2 \rightarrow \frac{1}{2}C_2H_6 + \frac{1}{2}H_2O$	-64.0	-87.8
$CH_4 + \frac{3}{2}O_2 \rightarrow CO + H_2O$	-543.0	-518.7
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	-800.0	-801.3

Section 3- Project Charter

Project Charter – Group 1

Project Name: Oxidative Coupling of Methane to Ethylene

Project Champion: Gary Sawyer, Consultant – formerly ARCO, Lyondell-Basell

Project Leaders: Tyler Fini, Corey Patz, Rebecca Wentzel

Specific Goals: Design competitive plant and process to create 1 billion lb/yr (2% of US capacity) of ethylene from natural gas

Project Scope:

In Scope:

- Fully specified equipment lists (sizing, materials, etc) and subsequent process design
- Stoichiometric reactor model
- Catalyst specifications
- Ideal operating parameters (pressure, temperature, etc)
- Methods of separation
- Size and configuration of recycle loops
- Cost analysis based upon Capex and Opex

Out of Scope

- Kinetic reactor model
- Separation of ethylene from ethane

Deliverables:

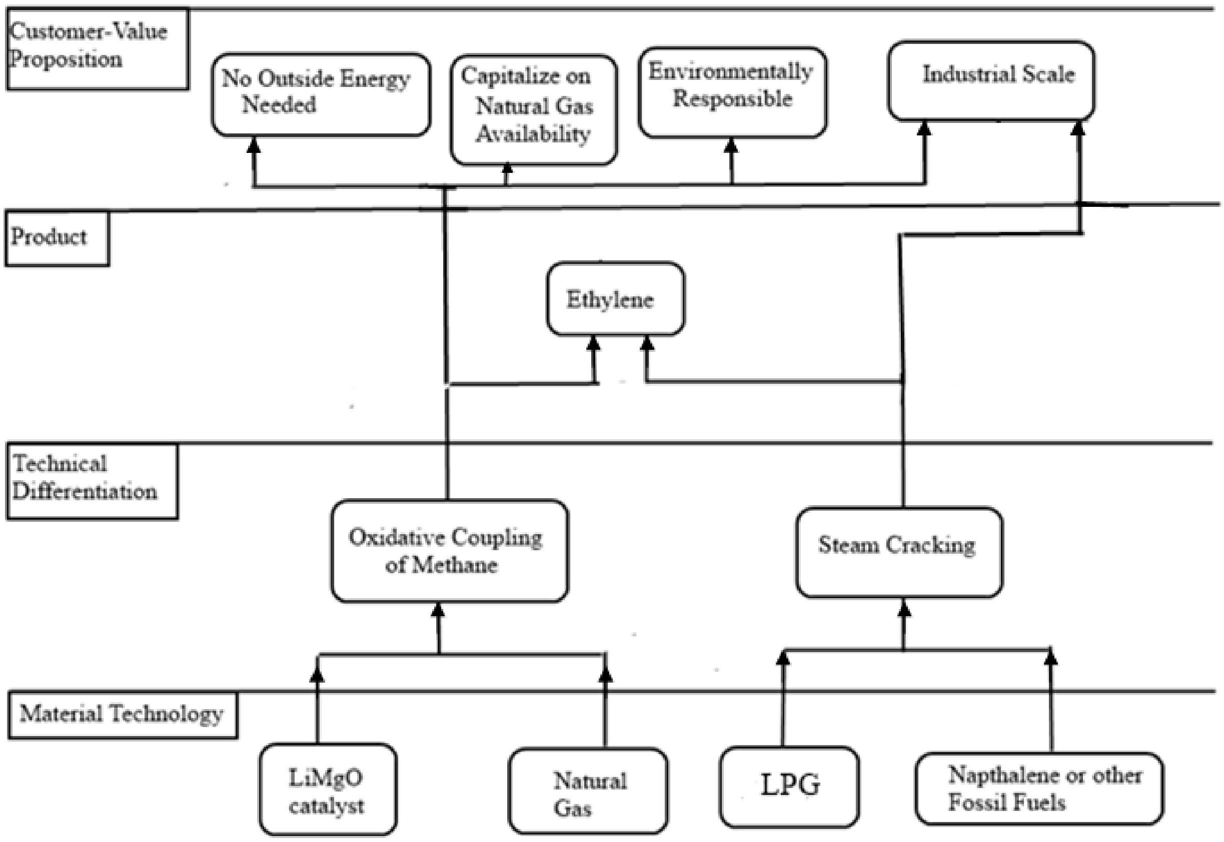
- Completed process model showing every piece of equipment and its specifications, including operating parameters
- Capital cost and final economic analyses demonstrating feasibility and profitability of the design
- Written report describing our findings/design
- PowerPoint presentation of our findings/design

Timeline:

- Weekly progress reports until final report submitted
- Written design report completed by Tuesday, April 15
- Oral presentation given on Wednesday, April 23

Section 4- Innovation Map

Innovation Map



The project being undertaken is to find a more economical and efficient process to create ethylene than traditional steam cracking, while decreasing energy intake with rigorous heat integration. The project is both technologically and market driven. The technologically driven aspect of the project concerns 1) the usage of the best behaving catalyst, LiMgO and 2) the ability to operate a self-sustaining process with regards to power generation. The process design is also market diven by customer value proposition such as 1) capitalizing on natural gas abundance, 2) envrironmental responsibility, 3) industrially scaled, and 4) economic profitability. The challenge of design lies within distinguishing the advantages of the technical differentiation of OCM and delivering upon the customer value propositions in an innovative and industrially feasible way.

Section 5- Market Analysis

As mentioned in the introduction, ethylene is in homogenous demand and is a building block molecule utilized for a wide array of purposes. Recalling the markets mentioned before, the OCM lies at the end of the value chain forming the base for other companies converting methane to ethylene.

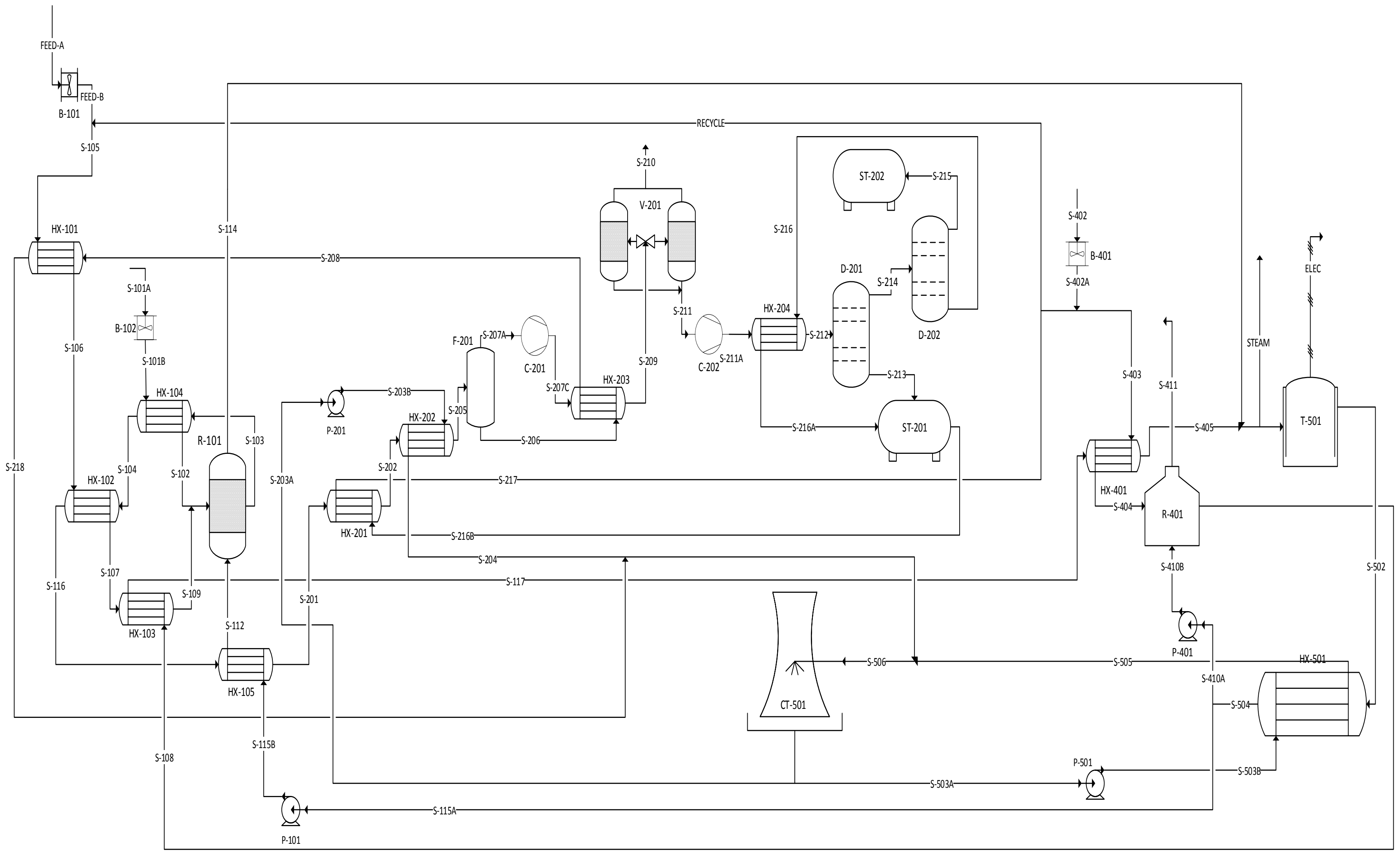
The advantages to using OCM to produce ethylene are numerous. OCM allows natural gas to be used as a source for the production of basic chemicals, mainly ethane and ethylene. Catalysts enable methane, a carbon building block, to combine into longer hydrocarbon chains. The OCM feedstock is relatively simple, natural gas and air, and produces a controlled number of products that can separated in a small number of separation processes. The OCM occurs at a pressure 96 psi and a temperature of 1292 °F. The single pass conversion of methane ranges from 22% to 34% with the selectively of ethylene to ethane of 10:1 to 1:2, respectively. Variation of the catalysts can be used in response to changing market conditions.

The production of ethylene through OCM and traditional steam cracking are both highly energy intensive, requiring large amounts of energy for cryogenic separation. The energy recovery within the OCM, to be discussed later, will draw from some of the technology implemented at steam cracking plants. An ethylene plant once running does not need to import its steam or electricity to power the process. Heat is recovered from the process in the form of high pressure steam to drive steam turbines. The other critical factor to success in a steam cracking plant is the recovery of methane. This will also play an important in making the OCM process economically viable by increasing the overall conversion of methane entering the plant.

According to research done by Siluria technologies, a company slated to launch a commercial OCM plant due to innovative catalyst screening technology, a "commercial-scale plant could achieve savings of $1bn/year in capital expense and operating expense over naphtha cracking and $250m over ethane cracking." The company went on in a press release to report that "oxidative coupling is competitive as long as the price of 1 bbl of oil exceeds 1MMBtu of natural gas by at least eight times…The ratio currently exceeds 20." Other reasons listed for why OCM is the new technology to invest in were the heat generation associated with the actual coupling reaction, which can be integrated to other units, as well as the simplicity of the products produced by OCM. OCM mostly produces ethylene and ethane, so the output is "simpler than cracking" which decreases costs.[5] While these claims have yet to be proved because the plant has not begun building or operation, Siluria highlights the advantages of OCM on an industrial scale but glosses over the feasibility aspect.

Section 6- Process Flow Diagram, Material Balances & Process Description

Overall Process Flow Diagram



Section 100: Reactor

This section outlines the main processes within the reactor section that take the feeds of methane and oxygen and react them to make ethane, ethylene, and combustion byproducts. The reaction section starts at the beginning of the process, with blowers B-101 and B-102 introducing methane and oxygen, respectively, into the system. The methane is preheated by HX-101, HX-102, and HX-103 and the oxygen is preheated by HX-104. HX-101 is heated by the residual cooling water from the flash separation unit in section 200, F-201. HX-102 and HX-104 are product feed economizers that combine the methane and oxygen with the products of the reactors for heat integration. HX-103 is heated by steam produced from the combustion cycle. The four heat exchangers provided the heat necessary to get the methane and oxygen to the required 700°C.

From HX-103 and HX-104, the methane and oxygen are fed in a ratio of 3:1 through each of 4 fixed bed catalytic reactors that are arranged in parallel, R-101 through R-104. Included inside of each reactor is a shell and tube heat exchanger that allows the reactors to operate isothermally, which is explained later in this section. HX-105 preheats the water introduced used in S-115A before it enters the reactors. These heat exchangers, RHX-101 through RHX-104, produce steam that is used throughout the process.

Following the reactors, the streams are all combined into S-103 which goes into HX-104. HX-104 cools the product mixture with the incoming oxygen feed, sends the resulting cooler stream, S-104, to the product feed economizer which then enters into the separation section.

Catalyst Selection

As research suggests, in order to have an OCM reactor that has a high conversion of methane as well as C_2 selectivity and yield, the reaction must occur at temperatures between 700-900 °C. Running a reactor at such high temperatures means low yields due to great quantities of CO and CO_2 formation as well as catalyst deactivation. A major area of research within the realm of OCM has been in trying to find the ideal catalyst that optimizes CH_4 conversion, and C_2 yield and selectivity. Using the work of Matsuura et. al, our process requires that we feed our CH_4 and O_2 in a 3:1 ratio with no diluents at 700 °C. Research with these conditions gave data of 13.3% CH_4 conversion, 94.8% O_2 conversion, 49% C_2 selectivity, and a C_2H_6/C_2H_4 ratio of 0.52.[6]

Reactor Design

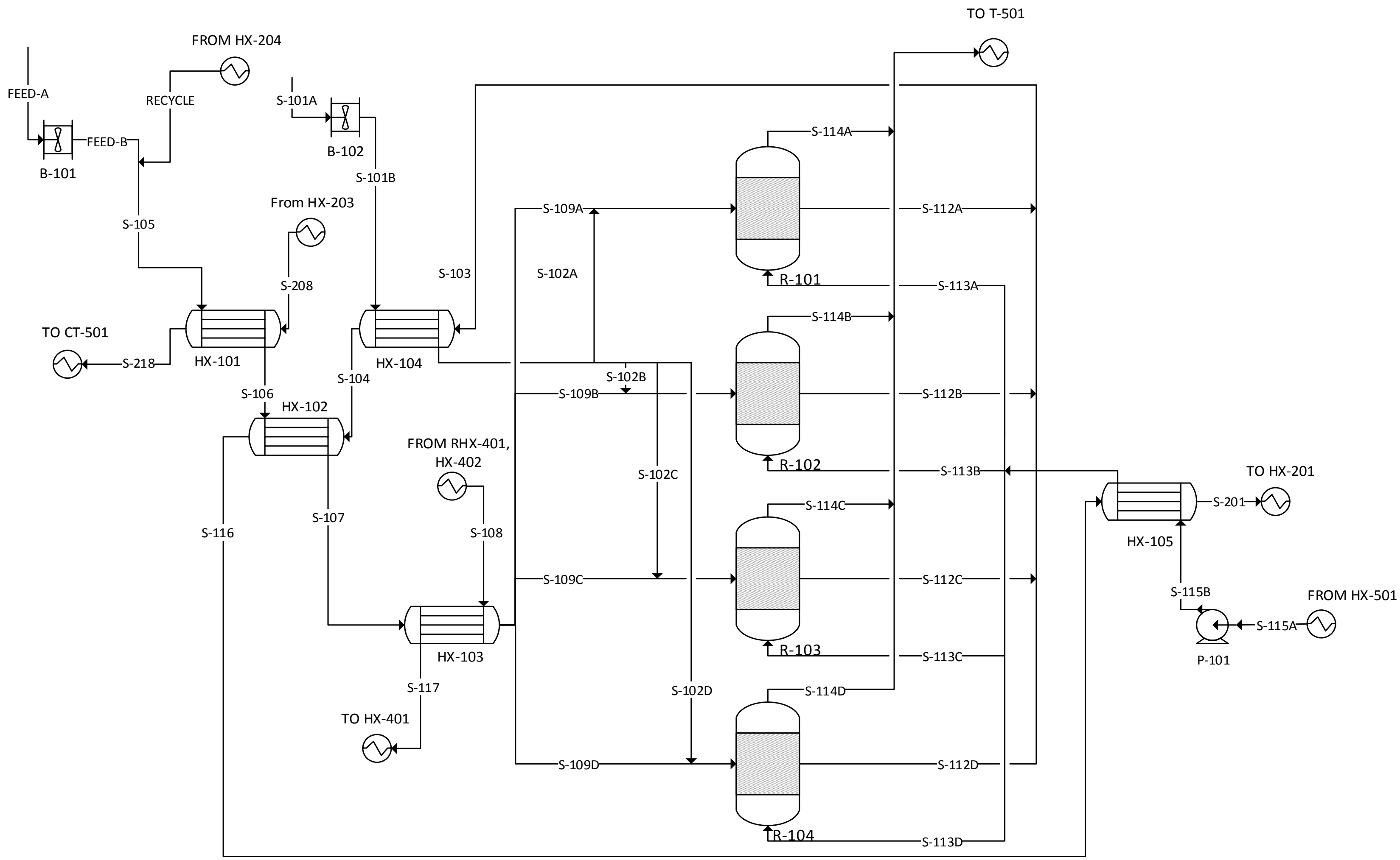
This process utilizes 4 fixed bed reactors with internal cooling, placed in parallel, packed with LiMgO catalyst to achieve OCM. The choice to run our reactors in parallel versus in series was guided by concern for safety and product control in running reactors at extremely high temperatures with explosive contents. In running reactors in series, there is less control about what goes into each subsequent reactor. The content of the later reactors depends solely on how well the previous reactors performed. It was decided that if one reactor were to fail in the process, the entire process would be detrimentally affected. Therefore, in selecting to run the reactors in parallel, a sense of control was gained in that there is control of amounts of feed and reactant entering each reactor specifically. Also, a spare reactor was included in parallel for cases where one of the other reactors is down.

The number of reactors was motivated by an evaluation of the temperature rise across the fixed bed. The shell and tube reactors are running isothermally, due to cooling inside of each reactor. The cooling water is pumped through the shell side to extract the heat produced in the exothermic reactions on the tube side. In absence of this cooling each of the 4 reactors would experience an approximate 500 °F increase per hour. This would cause marked instability within each reactor, simultaneously destroying the structural integrity of the reaction vessel and degrading the catalyst. As mentioned before, each reactor has a heat exchanger built inside that cools the reactor with cooling water, generating steam that is used in other parts of the process and maintaining the desired isothermal temperature profile.

The decision of using a fixed-bed catalytic reactor was motivated by upholding a balance of novelty with industrially feasibility. The choice for reactor was between using a fixed bed reactor, a fluidized bed reactor, or a membrane reactor. A study in 1997 compared the performance of OCM in a conventional fixed bed reactor and in a ceramic dense membrane reactor with LiMgO catalyst. The results of the fixed bed indicated that the maximum yield is obtained with the complete exhaustion of the oxygen supply to the reactor. The maximum C_2 yield at 750 °C is 20.7% at an optimal feed of 70% methane and 30% oxygen. The selectivity is 52.4%. A higher yield and selectivity can be obtained with higher operating temperature. However, due to the way the reactant mixture is fed to the reactor, it is unlikely that the yield will be greater than 30%. The main reason for this low yield is due to the fact that methane and oxygen are fed together to the reactor in one tube. A certain level of oxygen feed must be maintained in order to achieve reasonable conversion. The ceramic membrane reactor exhibited the possibility of achieving yield and selectivity beyond the limit of 20.7% yield and 52.4% selectivity at 750 °C of the conventional fixed-bed reactor. The improvement is obtained by limiting the oxygen concentration in the reactor to a very low level. The deep oxidation reaction of the C_2 product is significantly reduced. Consequently, the selectivity is higher and the yield is also greater. In the membrane reactor, the oxygen concentration is at almost a uniform low level and it appears to be able to achieve far better selectivity at the same yield.[7]

Key points taken away from this study are as follows. First, the membrane reactor seems to have better performance than the fixed bed. However, using membrane technology on such an industrial scale is still an unproven technology. Second, the reason the membrane reactor was so favorable was because it maintained very good control of oxygen, keeping it in optimal ratio with the methane and consuming the oxygen fully. What the fixed bed reactors accomplishes is a simulation of the achievements of a membrane reactor, or the idea of oxygen dosing. These ideas were modeled by having multiple fixed beds in parallel, introducing oxygen at the beginning of each fixed bed, and consuming the oxygen completely in each reactor.

Section 100 Reactor Section



Section 100 Reactor Section										
	FEED-A	FEED-B	RECYCLE	S-101	S-102	S-102A	S-102B	S-102C	S-102D	S-103
Temperature F	77	130	130	81	1202	1202	1202	1202	1202	1292
Pressure psia	65	87	87	115	115	115	115	115	115	87
Vapor Frac	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total Flow cuft/hr	2.49E+06	2.04E+06	3.15E+06	1.41E+06	4.37E+06	1.09E+06	1.09E+06	1.09E+06	1.09E+06	2.15E+07
Enthalpy Btu/hr	-9.05E+08	-8.92E+08	-1.38E+09	4.52E+04	2.42E+08	6.04E+07	6.04E+07	6.04E+07	6.04E+07	-5.39E+09
Mass Frac										
METHANE	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36
OXYGEN	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00
C2H4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
C2H6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
WATER	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	4.53E+05	4.53E+05	7.00E+05	8.98E+05	8.98E+05	2.24E+05	2.24E+05	2.24E+05	2.24E+05	2.04E+06

Section 100 Reactor Section										
	S-104	S-105	S-106	S-107	S-108	S-109	S-109A	S-109B	S-109C	S-109D
Temperature F	1119	130	286	1112	1670	1202	1202	1202	1202	1202
Pressure psia	87	87	87	87	218	87	87	87	87	87
Vapor Frac	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total Flow cuft/hr	1.94E+07	5.18E+06	6.59E+06	1.39E+07	2.63E+06	1.47E+07	3.69E+06	3.69E+06	3.69E+06	3.69E+06
Enthalpy Btu/hr	-5.63E+09	-2.27E+09	-2.16E+09	-1.39E+09	-2.24E+09	-1.28E+09	-3.20E+08	-3.20E+08	-3.20E+08	-3.20E+08
Mass Frac										
METHANE	0.36	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H6	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WATER	0.31	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	2.04E+06	1.15E+06	1.15E+06	1.15E+06	4.50E+05	1.15E+06	2.88E+05	2.88E+05	2.88E+05	2.88E+05

Section 100 Reactor Section										
	S-110A	S-110B	S-110C	S-110D	S-111A	S-111B	S-111C	S-111D	S-112	S-112A
Temperature F	1202	1202	1202	1202	4137	4137	4137	4137	269	1292
Pressure psia	87	87	87	87	87	87	87	87	218	87
Vapor Frac	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00
Total Flow cuft/hr	5.13E+06	5.13E+06	5.13E+06	5.13E+06	1.42E+07	1.42E+07	1.42E+07	1.42E+07	6.17E+04	5.40E+06
Enthalpy Btu/hr	-2.60E+08	-2.60E+08	-2.60E+08	-2.60E+08	-8.19E+07	-8.19E+07	-8.19E+07	-8.19E+07	-2.27E+10	-1.35E+09
Mass Frac										
METHANE	0.56	0.56	0.56	0.56	0.36	0.36	0.36	0.36	0.00	0.36
OXYGEN	0.44	0.44	0.44	0.44	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	0.00	0.00	0.00	0.00	0.06	0.06	0.06	0.06	0.00	0.06
C2H6	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.03	0.00	0.03
CO2	0.00	0.00	0.00	0.00	0.20	0.20	0.20	0.20	0.00	0.20
CO	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.03	0.00	0.03
WATER	0.00	0.00	0.00	0.00	0.31	0.31	0.31	0.31	1.00	0.31
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	5.13E+05	5.13E+05	5.13E+05	5.13E+05	5.13E+05	5.13E+05	5.13E+05	5.13E+05	3.40E+06	5.13E+05

Section 100 Reactor Section										
	S-112B	S-112C	S-112D	S-113A	S-113B	S-113C	S-113D	S-114A	S-114AB	S-114B
Temperature F	1292	1292	1292	269	269	269	269	1284	1284	1284
Pressure psia	87	87	87	218	218	218	218	218	218	218
Vapor Frac	1.00	1.00	1.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Total Flow cuft/hr	5.40E+06	5.40E+06	5.40E+06	1.54E+04	1.54E+04	1.54E+04	1.54E+04	4.05E+06	8.10E+06	4.05E+06
Enthalpy Btu/hr	-1.35E+09	-1.35E+09	-1.35E+09	-5.68E+09	-5.68E+09	-5.68E+09	-5.68E+09	-4.41E+09	-8.83E+09	-4.41E+09
Mass Frac										
METHANE	0.36	0.36	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	0.06	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H6	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.20	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WATER	0.31	0.31	0.31	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	5.13E+05	5.13E+05	5.13E+05	8.51E+05	8.51E+05	8.51E+05	8.51E+05	8.51E+05	1.70E+06	8.51E+05

Section 100 Reactor Section						
	S-114C	S-114D	S-115A	S-115B	S-116	S-117
Temperature F	1284	1284	95	95	482	1253
Pressure psia	218	218	15	218	87	218
Vapor Frac	1.00	1.00	0.00	0.00	1.00	1.00
Total Flow cuft/hr	4.05E+06	4.05E+06	5.54E+04	5.54E+04	1.15E+07	2.10E+06
Enthalpy Btu/hr	-4.41E+09	-4.41E+09	-2.34E+10	-2.34E+10	-6.40E+09	- 2.34E+09
Mass Frac						
METHANE	0.00	0.00	0.00	0.00	0.36	0.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	0.00	0.00	0.00	0.00	0.06	0.00
C2H6	0.00	0.00	0.00	0.00	0.03	0.00
CO2	0.00	0.00	0.00	0.00	0.20	0.00
CO	0.00	0.00	0.00	0.00	0.03	0.00
WATER	1.00	1.00	1.00	1.00	0.31	1.00
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	8.51E+05	8.51E+05	3.40E+06	3.40E+06	2.04E+06	4.50E+05

Section 200: Separations and Storage

Separations

This section outlines the procedures involved to isolate the desired ethylene and ethane products and to purify the methane for recycle. Because every component in the process stream, except water, is a gas at room temperature, ambient temperature or pressure separation techniques were not feasible. Therefore, a cryogenic distillation procedure involving two columns was chosen as the primary isolation method, with a flash vessel and adsorption process also being utilized. This four stage method effectively isolated the necessary components, although at a high cost. However, because of the challenges of separation, this high cost was necessary.

The separation section begins after the process stream leaves HX-105, the boiler-feed water preheater. The stream, at 212 °F, passes through two more heat exchangers and a flash to lower its temperature down to 95 °F and condense the water in the stream. Water is the only component in the stream that is a liquid at room temperature, making a condensation separation the simplest option for its removal. Also, because cryogenic separation processes will be used later on in the process, the water must be removed early on in the process. Because the stream will be cooled anyway for this cryogenic process, removing the water through cooling prevents the need for significant additional capital for another separation process.

The first heat exchanger (HX- 201) uses the cool methane that will be recycled or purged to cool the stream slightly. This process is more useful for warming the methane before the reactor and before the purge combustion than for cooling the process stream however. The second heat exchanger (HX-202) uses cooling water to bring the temperature down to the desired 95 °F, enabling the water to fall out as a liquid and be removed in the flash vessel (F-201). The cooling water is then sent to the cooling tower (CT-501) where its temperature is lowered by 35 °F.

Upon leaving the flash vessel, the stream is sent to a two stage compressor where the pressure of the stream is increased to 290 psi. This high pressure is necessary for the cryogenic process downstream. The compression causes an increase in temperature of 223 °F, thus requiring another heat exchanger to cool the process back down for the pressure swing adsorption step next. The outlet of the flash vessel (F-201) is used for cooling the stream, bringing its temperature up to 295 °F. Because of the greater than atmospheric pressure of the process stream, the water from the flash remains in the liquid phase even after cooling the stream after the compressor. This flash water was then used to preheat the methane feed to the reactor before being sent to the cooling tower, as described in Section 100.

The flash water brought the process stream down to 104 °F for pressure swing adsorption (PSA) for carbon dioxide and residual water removal. Carbon dioxide freezes at cryogenic temperatures, thus ruining cryogenic separation, so it was necessary to remove it earlier in the process. PSA utilizes adsorbents that selectively remove certain components from a process gas stream. It is a pressure swing adsorption because the adsorption takes place at a high pressure while the desorption takes place at a low pressure. The procedure begins with the process gas entering the vessel, where the desired component, carbon dioxide in this case, is adsorbed. However, some of the desired gas, which is the gas that is to be purified and not adsorbed, becomes trapped in the adsorbent. When the adsorbent reaches capacity of carbon dioxide, the inlet feed is stopped and the gas in the vessel is released from the vessel, thus lowering the pressure. This causes the adsorbed carbon dioxide to desorb. Once the process stream has left, a stream of gas with the adsorbent already removed enters the vessel at the opposite end of the vessel. As it enters, the pressure of the vessel increases and the desired gas that was trapped in the adsorbent is flushed out and released. This is then flushed with new process gas to continue the process. With one vessel, PSA is a batch process, but with more vessels, the operation can be done continuously, as each vessel is at a different phase in the adsorption or desorption process.

Several other methods exist for carbon dioxide separation, but PSA with activated alumina and zeolite 13X was chosen because of the efficacy of PSA and the relatively lower cost. Using an amine like monoethanolamine (MEA) was also considered, but due to the massive scale of this project, it was deemed too expensive. The MEA process involves regenerating the amine through heat while no heating was required for PSA. Also, MEA would not remove water from the stream, so a desiccant of some sort would still have to be used, while with PSA, a mixed bed of activated alumina and zeolite 13X could be used to remove all of the CO_2 and water. The final concern with MEA is that it is not effective enough for the complete removal of CO_2 that is required for the cryogenic separation. [8,9]

Due to the large amount of carbon dioxide that needs to be removed (424,079 lb/hr), very large vessels were required to hold all of the adsorbents. It is typical in industry to use 6 or 12 vessels full of adsorbent, with the relative amount of adsorbent decreasing with an increasing number of vessels. However, because of the scale, 13 vessels were required, as there is a maximum size of a pressure vessel that can be created. Also, the amount of activated alumina required is so small that the adsorbent in vessel is virtually only the zeolite.

The Ergun equation was used to determine the pressure drop across the system. The three equations involved in this calculation are presented below as (4), (5), and (6), where L is the length of the bed, D_p is the spherical of the packing, ρ is the density of the gas stream, μ is the dynamic viscosity, V_s is the superficial velocity, and ε is the void fraction.

$$f_p = \frac{150}{Gr_p} + 1.75 \tag{4}$$

$$f_p = \frac{\Delta p}{L} \frac{D_p}{\rho V_s^2} \left(\frac{\varepsilon^3}{1-\varepsilon} \right) \tag{5}$$

$$Gr_p = \frac{D_p V_s \rho}{(1-\varepsilon)\mu} \tag{6}$$

Because each vessel is identical, the volumetric flow rate was merely divided into 13 sections and the pressure drop for each individual vessel was calculated. Because of the pressure drop of 29.9 psi, an additional compressor, C-202, was added directly after this carbon dioxide separation to achieve the ideal operating pressure, 290 psi, of the subsequent towers.

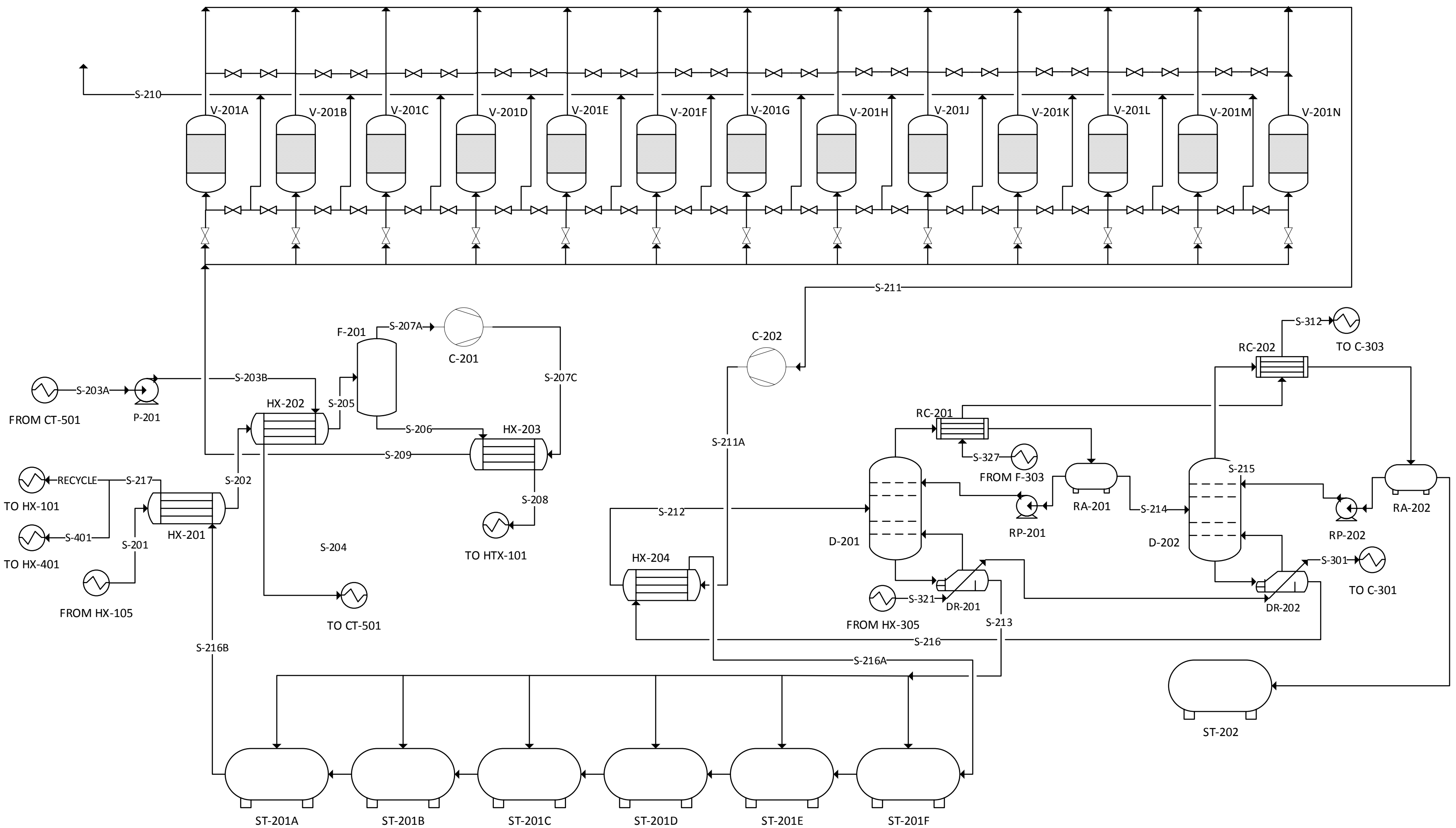
Following the PSA removal of carbon dioxide and water, the process stream is cooled to -94 °F by the liquid methane leaving the second distillation column (D-202). This temperature is the optimal temperature for the process stream to enter the first distillation column (D-201), for the least amount of combined heating and cooling is required. In this column, the ethane and ethylene products leave out of the bottom while the methane and carbon monoxide are sent out of the top. A total condenser was used for the distillate as this resulted in an overall lower combined heating and cooling requirement for the two towers. The product stream is sent to a series of storage tanks (ST-201) while the distillate is sent to the second distillation column to separate the methane and the carbon monoxide. The carbon monoxide leaves out of the top of this column at a temperature of -241 °F and a purity of 99.9%. This high purity results in a larger reboiler and taller column, but increases the value of the carbon monoxide product, which is sent to another storage tank (ST-202) and then sold. The methane is used for precooling the feed to D-201 and then for cooling the process stream before the flash (F-201) before being split, where 95% is recycled and 5% is sent to a combustor and burned for steam generation.

Pressure drops were neglected for both columns because they were quite small. Assuming a 4 psi pressure drop per 10 feet of height in each column and a standard drop of 10 psi for the valves present, this would result in less than 30 psi drop for the first tower and a less than 45 psi drop for the second tower.[10] The liquid ethylene and ethane stream from the bottom of the first column is sent straight to a storage tank, so a pressure drop has negligible effect on the design of the process. The same is for the carbon monoxide leaving the top of the second column. Because the top of the second column is liquid, the size of the pump and the utilities required to pump it back up to 290 psi would be negligible and the smaller pressure would have marginal effect on the separation process in D-202. Finally, the methane leaving the bottom of the second column is just used as a precooler before either being recycled or purged, where its pressure will drop anyway upon mixing with the other lower pressure streams.

A refrigeration cycle was used to achieve the very low temperatures required for cryogenic distillation. A cascade of propane, ethylene, and methane was utilized, which will be discussed further in section 300. The methane was used to cool the distillate for both columns while the propane was used for heating the bottom of the two columns. While the propane was not especially warm (about 65 °F), it provided enough heat for the reboiler requirements of the cryogenic columns. Also, because of the low temperatures, stainless steel could not be used for the columns, so Monel alloy 400 was used instead[11]. This nickel alloy is more expensive, but it can withstand the low temperatures required for cryogenic distillation.

Originally, only one column was planned to separate methane and the desired ethane and ethylene, for the carbon monoxide was to be oxidized into carbon dioxide and removed in the adsorption process. While carbon monoxide can be relatively simply selectively oxidized in the presence of some hydrocarbons, the double-bond in the ethylene makes it quite susceptible to oxidation. Therefore, this method was abandoned in favor of the second column.

Section 200 Separations and Storage Section



Section 200 Separation Section										
	S-201	S-202	S-203A	S-203B	S-204	S-205	S-206	S-207A	S-207B	S-207C
Temperature F	212	204	86	86	111	95	95	95	260	318
Pressure psia	87	87	15	22	22	87	87	87	218	290
Vapor Frac	0.77	0.75	0.00	0.00	0.00	0.65	0.00	1.00	1.00	1.00
Total Flow cuft/hr	6.28E+06	6.03E+06	1.75E+05	1.75E+05	1.78E+05	4.40E+06	1.01E+04	4.39E+06	2.29E+06	1.86E+06
Enthalpy Btu/hr	-7.09E+09	-7.15E+09	-7.45E+10	-7.45E+10	-7.41E+10	-7.46E+09	-4.26E+09	-3.20E+09	-3.10E+09	-3.06E+09
Mass Frac										
METHANE	0.36	0.36	0.00	0.00	0.00	0.36	0.00	0.52	0.52	0.52
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	0.06	0.06	0.00	0.00	0.00	0.06	0.00	0.09	0.09	0.09
C2H6	0.03	0.03	0.00	0.00	0.00	0.03	0.00	0.05	0.05	0.05
CO2	0.20	0.20	0.00	0.00	0.00	0.20	0.00	0.29	0.29	0.29
CO	0.03	0.03	0.00	0.00	0.00	0.03	0.00	0.05	0.05	0.05
WATER	0.31	0.31	1.00	1.00	1.00	0.31	1.00	0.01	0.01	0.01
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	2.04E+06	2.04E+06	1.08E+07	1.08E+07	1.08E+07	2.04E+06	6.20E+05	1.42E+06	1.42E+06	1.42E+06

Section 200 Separation Section										
	S-208	S-209	S-210	S-211	S-211A	S-212	S-213	S-214	S-215	S-216
Temperature F	296	104	104	104	123.1	-94	-12	-171	-241	-162
Pressure psia	87	290	290	260.2	290	290	290	290	290	290
Vapor Frac	0.00	1.00	0.95	1.00	1.00	1.00	0.00	0.00	0.00	0.00
Total Flow cuft/hr	1.14E+04	1.30E+06	1.80E+05	1.24E+06	1.15E+06	6.28E+05	7.17E+03	3.75E+04	1.87E+03	3.65E+04
Enthalpy Btu/hr	-4.12E+09	-3.21E+09	-1.66E+09	-1.56E+09	-1.55E+09	-1.66E+09	-2.02E+07	-1.82E+09	-1.22E+08	-1.69E+09
Mass Frac										
METHANE	0.00	0.52	0.00	0.74	0.74	0.74	0.00	0.92	0.00	1.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	0.00	0.09	0.00	0.13	0.13	0.13	0.65	0.00	0.00	0.00
C2H6	0.00	0.05	0.00	0.07	0.07	0.07	0.35	0.00	0.00	0.00
CO2	0.00	0.29	0.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.00	0.05	0.00	0.07	0.07	0.07	0.00	0.08	1.00	0.00
WATER	1.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	6.20E+05	1.42E+06	4.24E+05	9.98E+05	9.98E+05	9.98E+05	1.95E+05	8.03E+05	6.61E+04	7.37E+05

Section 200 Separation Section		
	S-217	S-218
Temperature F	130	150
Pressure psia	87	87
Vapor Frac	1.00	0.00
Total Flow cuft/hr	3.31E+06	1.04E+04
Enthalpy Btu/hr	-1.45E+09	-4.22E+09
Mass Frac		
METHANE	1.00	0.00
OXYGEN	0.00	0.00
C2H4	0.00	0.00
C2H6	0.00	0.00
CO2	0.00	0.00
CO	0.00	0.00
WATER	0.00	1.00
PROPANE	0.00	0.00
Total Flow lb/hr	7.37E+05	6.20E+05

Section 300: Refrigeration Cycle[12]

The refrigeration process is shown in Figure 3.4 accompanied with information concerning the streams contained in Table 3.4. The refrigeration cycle designed in this project is a propane, ethylene, and methane cascade to achieve the required temperatures for cryogenic separation of the hydrocarbon compounds produced in our process. This refrigeration cycle is based on the reverse Rankine cycle, where the gases in the system are compressed, reduced in temperature through several heat exchangers, and expanded in a Joule-Thompson Valve decreasing the temperature of the gas to establish a vapor-liquid equilibrium.

The compression of each gas and the temperature of reduction were determined through the use of a P-H (Pressure-Enthalpy) diagram. Figure 3.1 shows the P-H diagram of Propane, the enthalpy and pressure are measured on the y and x axes. Temperature isotherms are shown intersecting the liquid/vapor dome region. A straight line is then drawn across the diagram and using the lever rule, the vapor and liquid fractions are determined with lines intersecting on the left side (saturated liquid) and right side (saturated vapor). The peak of the dome is the critical point of the substance. The starting and ending temperatures of the propane in its liquid form are shown on the figure. The red line of the right side of the dome shows the temperature transition of the vapor component following the expansion. The P-H diagrams of the ethylene and methane in the refrigeration cascade mirror that of propane with the exception of lower temperature isotherms and higher pressures.

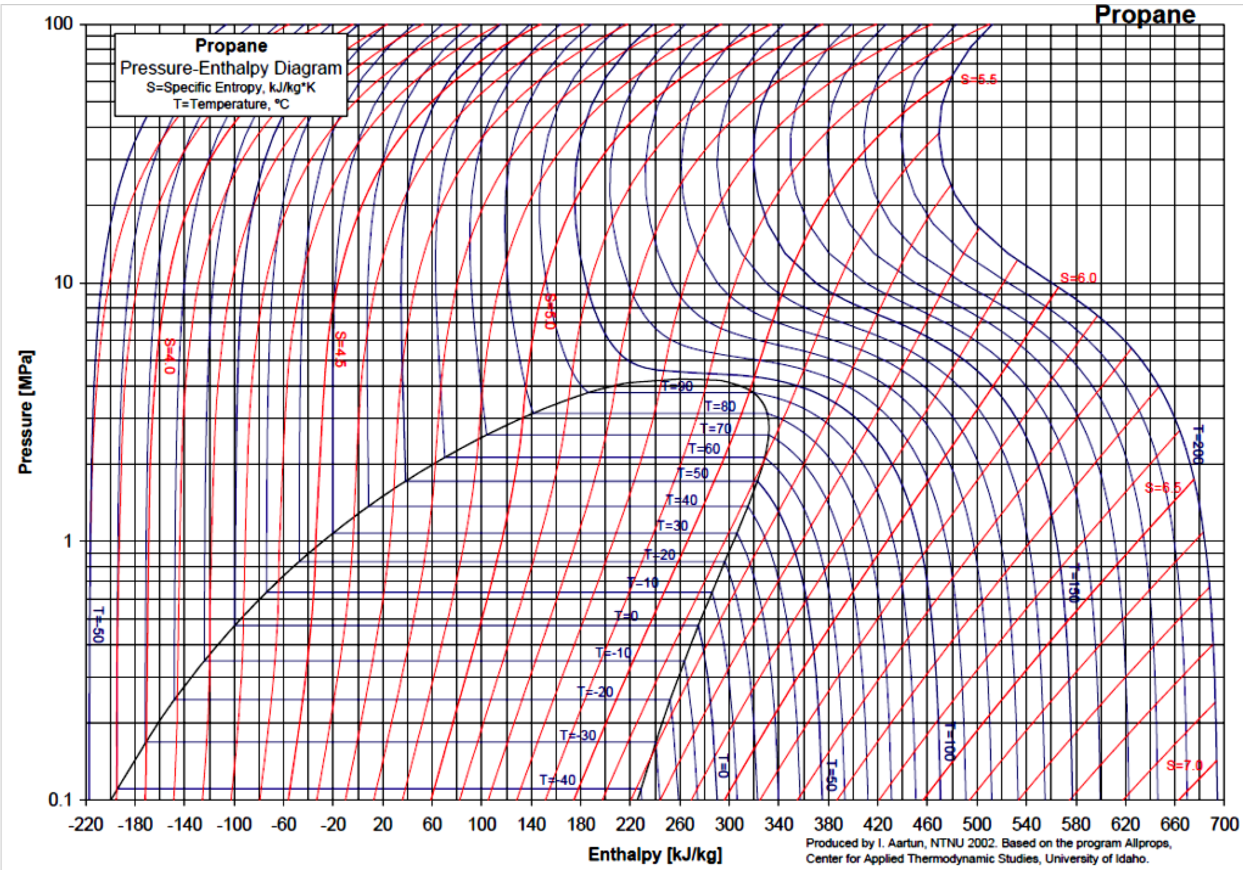


Figure 2. Propane Pressure Enthalpy Diagram

The temperature gradient for the refrigeration cycle is shown in Figure 3. The temperatures are charted alongside the quantity of heat capable of cooling within the process. The propane is on the warm side of the cycle reaching a cooling temperature of -39.8 °F. The ethylene transitions between the warm and cold side of the cycle with temperatures ranging from -30.0 °F to -151.8°F. The methane in the cold side of the cycle reaches its saturation temperature of -256.0 °F. The temperature ranges within the refrigeration cycle enable the cooling necessary for the cryogenic separations of the chemicals within the process.

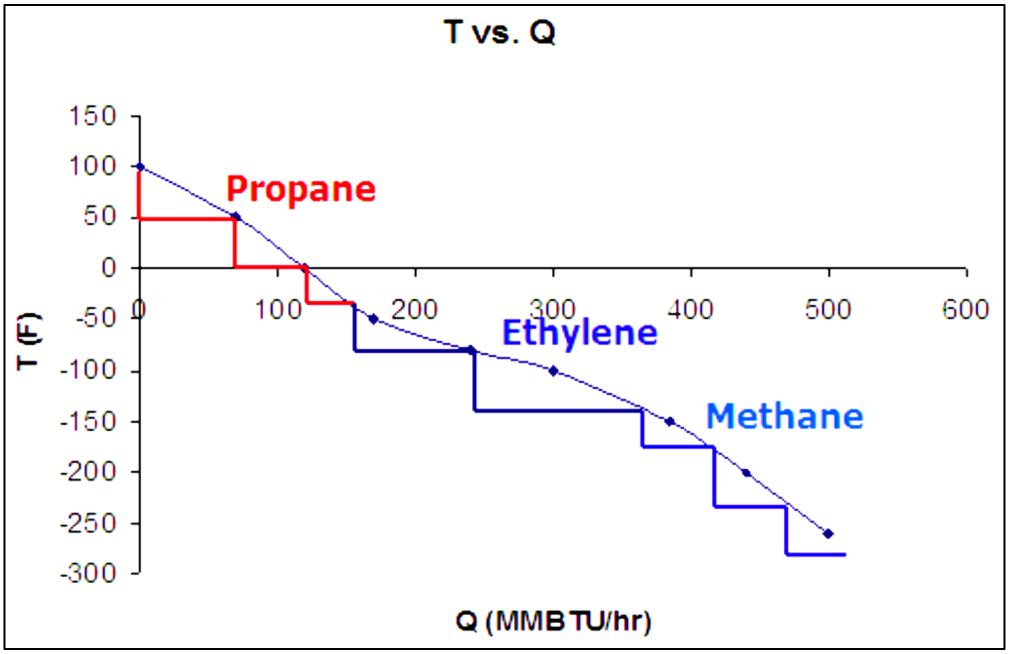


Figure 3 Refrigeration Cycle Temperature Cascade[11]

Propane Refrigeration

The latent heat of vaporization of propane is 180 BTU per pound coupled with its specific heat capacity in its vapor phase of 0.39 Btu per lb-°F. The propane enters the refrigeration cycle at a temperature of 31°F and is compressed to a pressure of 290.1 psi elevating it to a temperature of 276.7 °F. The propane is then cooled with cooling water at a temperature of 30°F in two heat exchangers, 8 tube passes and 2 shell passes, in parallel to reach a temperature of 87 °F. The propane then enters a Joule-Thompson valve reducing the pressure to 16.0 psi. The reduction in pressure pushes Propane into vapor-liquid equilibrium, with 0.3 of the propane remaining in the vapor phase. The propane proceeds to a flash vessel where the liquid and vapor phases are separated and then fed to the following heat exchanger. The propane chills the ethylene, increasing the propane vapor fraction to 0.47. The propane continues to a heat exchanger with methane increasing the vapor fraction of propane to 0.95. At this point, the propane is used for heating the reboiler of each distillation column, before reentering the refrigeration cycle.

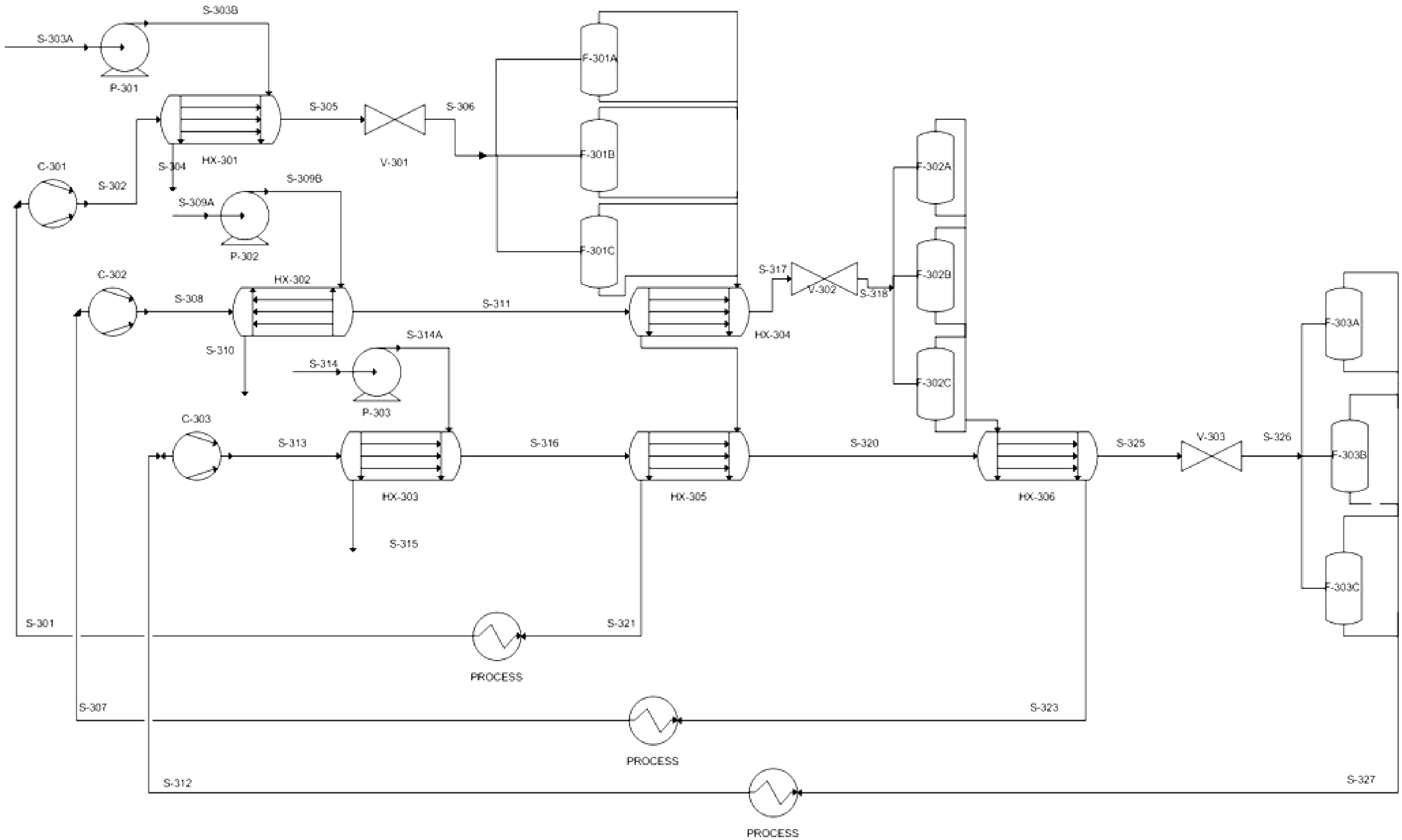
Ethylene Refrigeration

The latent heat of vaporization of ethylene is 207 Btu per pound paired with a specific heat capacity in its vapor phase of 0.32 Btu per lb-°F. The ethylene reenters the refrigeration cycle following the process at a temperature of -31.0 °F and is compressed to a pressure of 304.6 psi elevating it to a temperature of 382.4 °F. The ethylene is cooled with cooling water, in two parallel heat exchangers each with 8 tube and 2 shell passes, at a temperature of 30 °F to reduce its temperature to 87°F before entering a heat exchanger with propane at a temperature of -39.8 °F. The ethylene is chilled to a temperature of -30 °F and enters a Joule-Thompson valve reducing its pressure and temperature to 16.0 psi and -151.8 °F, respectively, with a vapor fraction of 0.37. The ethylene is then used to chill the last stage of the methane refrigeration to a temperature of -148.0 °F, increasing the vapor fraction of ethylene to 0.95.[11]

Methane Refrigeration

The latent heat of vaporization of methane is 219 Btu per pound with a specific heat capacity in its vapor phase of 0.54 Btu per lb-°F. The methane reenters the refrigeration cycle after the process at a temperature of -161.8 °F, it is compressed to a pressure of 304.6 psi elevating the temperature to 338.7 °F. Cooling water is then used within two 8 tube and 2 shell pass heat exchanger in parallel to lower the temperature of the methane to 87 °F. The methane then enters a heat exchanger with propane to reduce its temperature to -31.0 °C, followed by a heat exchanger with ethylene to lower it to a temperature of -151.8 °C. The methane is then expanded to a pressure of 16.0 psi through a Joule-Thompson valve lowering its temperature to saturation at -256.0 °F. The vapor fraction of the methane stream is 0.50, making the stream incredibly valuable utilizing its latent heat of vaporization in lieu of its specific heat capacity to provide cooling to the system. The methane stream is utilized in both condensing units of the cryogenic columns. [11]

Section 300 Refrigeration



Stream Table for Refrigeration Section 300										
	S-301	S-302	S-303A	S-303B	S-304	S-305	S-306	S-306A	S-306B	S-307
Temperature F	27.3	276.7	86.0	86.0	152.7	98.6	-39.8	-39.8	-39.8	-31.0
Pressure psia	16.0	290.1	14.5	21.8	21.8	290.1	16.0	16.0	16.0	16.0
Vapor Frac	1.00	1.00	0.00	0.00	0.30	0.00	0.47	1.00	0.00	1.00
Total Flow cuft/hr	3.46E+07	2.58E+06	3.18E+04	3.18E+04	1.11E+07	1.67E+05	1.38E+07	1.27E+07	1.19E+05	2.20E+07
Enthalpy Btu/hr	-4.96E+09	-4.49E+09	-1.35E+10	-1.35E+10	-1.25E+10	-5.55E+09	-5.55E+09	-2.59E+09	-2.95E+09	1.66E+09
Mass Frac										
PROPANE	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.00
ETHANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ETHYLENE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
METHANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WATER	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	4.76E6	4.76E6	7.20E6	7.20E6	7.20E6	4.76E6	4.76E6	2.22E6	2.53E6	2.16E6

Stream Table for Refrigeration Section 300										
	S-308	S-309A	S-309B	S-310	S-311	S-312	S-313	S-314A	S-314B	S-315
Temperature F	382.4	86	86	117.3	87.8	-161.7	338.7	86	86	111.0
Pressure psia	304.6	14.5	21.8	21.8	304.6	16.0	478.6	14.5	21.8	21.8
Vapor Frac	1.00	0.00	0.00	0.20	1.00	1.00	1.00	0.00	0.00	0.17
Total Flow cuft/hr	2.24E+06	1.33E+04	1.33E+04	2.95E+06	1.31E+06	1.96E+07	1.77E+06	1.19E+04	1.19E+04	2.25E+06
Enthalpy Btu/hr	2.02E+09	-5.47E+09	-5.47E+09	-5.17E+09	1.72E+09	-3.37E+09	-2.95E+09	-4.92E+09	-4.92E+09	-4.68E+09
Mass Frac										
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ETHANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ETHYLENE	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
METHANE	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WATER	0.00	1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	2.16E6	7.20E6	7.20E6	7.20E6	2.16E6	1.59E6	1.59E6	7.20E6	7.20E6	7.20E6

Stream Table for Refrigeration Section 300										
	S-316	S-317	S-318	S-318A	S-318B	S-319	S-320	S-321	S-322	S-323
Temperature F	86.0	-31.0	-151.8	-151.8	-151.8	-39.8	-31.0	-2.4	68.0	-91.7
Pressure psia	478.6	304.6	16.0	16.0	16.0	16.0	478.6	16.0	16.0	16.0
Vapor Frac	1.00	0.00	0.37	1.00	0.00	0.95	1.00	1.00	1.00	1.00
Total Flow ft^3/hr	1.15E+06	8.03E+04	5.80E+06	5.08E+06	6.05E+05	2.79E+07	8.31E+05	3.23E+07	3.77E+07	1.87E+07
Enthalpy Btu/hr	-3.19E+09	1.30E+09	1.30E+09	4.79E+08	8.16E+08	-5.12E+09	-3.30E+09	-5.01E+09	-4.88E+09	1.62E+09
Mass Frac										
PROPANE	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.00
ETHANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ETHYLENE	0.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	1.00
METHANE	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WATER	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	1.59E+06	2.16E+06	2.16E+06	8.01E+05	1.36E+06	4.76E+06	1.59E+06	4.76E+06	4.76E+06	2.16E+06

Stream Table for Refrigeration Section 300						
	S-324	S-325	S-326	S-326A	S-326B	S-327
Temperature F	-31.0	-148.0	-256.0	-256.0	-256.0	-139.0
Pressure psia	16.0	478.6	16.0	16.0	16.0	16.0
Vapor Frac	1.00	0.00	0.50	1.00	0.00	1.00
Total Flow cuft/hr	2.20E+07	9.05E+04	6.63E+06	6.63E+06	2.11E+04	2.12E+07
Enthalpy Btu/hr	1.66E+09	-3.63E+09	-3.63E+09	-1.82E+09	-1.82E+09	-3.36E+09
Mass Frac						
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00
ETHANE	0.00	0.00	0.00	0.00	0.00	0.00
ETHYLENE	1.00	0.00	0.00	0.00	0.00	0.00
METHANE	0.00	1.00	1.00	1.00	1.00	1.00
CO	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00
WATER	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	2164680.00	1591570.00	1591570.00	795000.00	795000.00	1591570.00

Section 400: Combustion

The overall conversion of methane within the process is 91.7%. The balance of methane, 8.26%, is sent for combustion to produce steam. Figure 4.1 is a ternary diagram mapping the percent composition of potential mixtures within the combustion chamber. For the combustion of methane within the process, coupled with the consideration that the process has an influx of pure oxygen, the lower flammability limit is 4.4% with an upper flammability limit of 41.2%.[13] At startup, pure oxygen will be fed in the mixture of methane to initiate combustion. Oxygen will then be fed in excess to ensure complete combustion of all methane leaving the recycle purge to produce steam for use in the process and generation of electricity via the turbine.

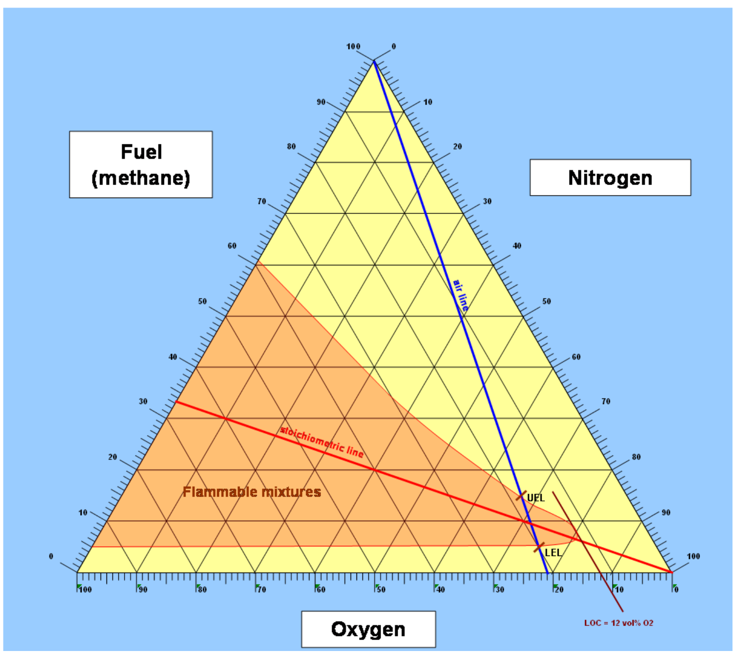
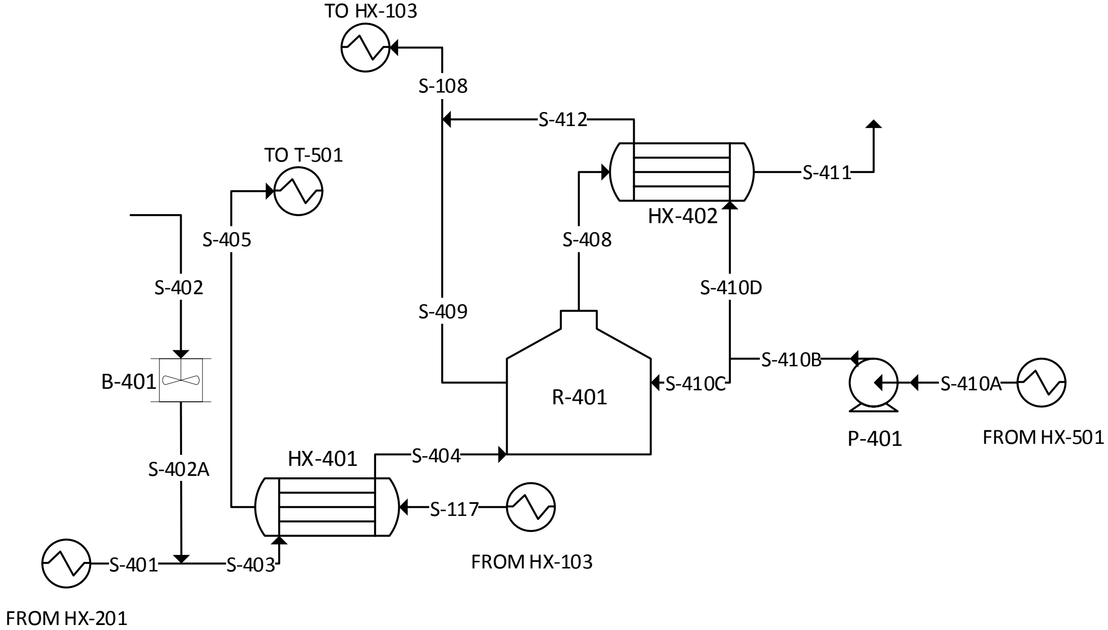


Figure 4 Flammability of Methane

The other consideration necessary for the combustion of methane is the auto-ignition temperature and adiabatic flame temperature. The auto-ignition temperature for methane is 1076 °F.[14] This translates into a requirement to preheat the feed into the combustion unit to this temperature at startup to begin the combustion process. Once the combustion has begun, a continual feed of methane will ensure this temperature is maintained. This is evident as shown in Table 1, the combustion of methane generates a large amount of heat. The other concern is the temperatures within the combustion unit, which is given through the adiabatic flame temperature of methane, 3542 °F. The cooling water heated through this process was brought to a temperature of 1602 °F.

The flue gas leaving this process is cooled using a heat exchanger with cooling water producing a flue stream temperature of 295 °F which is released to the surrounding the environment. The water leaving this process is also another high quality steam at a temperature of 1771 °F. The steam streams are combined and sent into the process and turbine.

Section 400 Combustion



Section 400 Combustion Section										
	S-401	S-402	S-403	S-404	S-405	S-406	S-408	S-409	S-410A	S-410B
Temperature F	130	81	98	1076	984	9184	4172	1602	95	95
Pressure psia	87	115	87	87	218	115	115	218	15	218
Vapor Frac	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
Total Flow cuft/hr	1.66E+05	2.52E+05	5.00E+05	1.38E+06	1.76E+06	6.58E+06	3.16E+06	1.52E+06	7.33E+03	7.33E+03
Enthalpy Btu/hr	-7.24E+07	8.06E+03	-7.24E+07	-7.62E+06	-2.41E+09	-8.18E+06	-5.13E+08	-1.35E+09	-3.10E+09	-3.10E+09
Mass Frac										
METHANE	1.00	0.00	0.19	0.19	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	0.00	1.00	0.81	0.81	0.00	0.08	0.08	0.00	0.00	0.00
C2H4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.51	0.51	0.00	0.00	0.00
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WATER	0.00	0.00	0.00	0.00	1.00	0.42	0.42	1.00	1.00	1.00
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	3.69E+04	1.60E+05	1.97E+05	1.97E+05	4.50E+05	1.97E+05	1.97E+05	2.70E+05	4.50E+05	4.50E+05

Section 400 Combustion Section				
	S-410C	S-410D	S-411	S-412
Temperature F	95	95	295	1771
Pressure psia	218	218	115	218
Vapor Frac	0.00	0.00	0.81	1.00
Total Flow cuft/hr	4.40E+03	2.93E+03	4.06E+05	1.10E+06
Enthalpy Btu/hr	-1.86E+09	-1.24E+09	-8.68E+08	-8.84E+08
Mass Frac				
METHANE	0.00	0.00	0.00	0.00
OXYGEN	0.00	0.00	0.08	0.00
C2H4	0.00	0.00	0.00	0.00
C2H6	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.51	0.00
CO	0.00	0.00	0.00	0.00
WATER	1.00	1.00	0.42	1.00
PROPANE	0.00	0.00	0.00	0.00
Total Flow lb/hr	2.70E+05	1.80E+05	1.97E+05	1.80E+05

Section 500: Electricity Generation

Turbine

A steam turbine operates through the segmented expansion of compressed steam, resulting in the reduction of pressure and temperature. Figure 5.1 shows a standard steam turbine where high energy steam enters the left side and is discharged on the right. The steam moves through the turbine spinning a series of propellers attached to magnets generating an inductive current that is converted into electricity through an alternator. The flow of energy is from thermal to mechanic to electric, and with each conversion there is a reduction in the amount of usable energy.

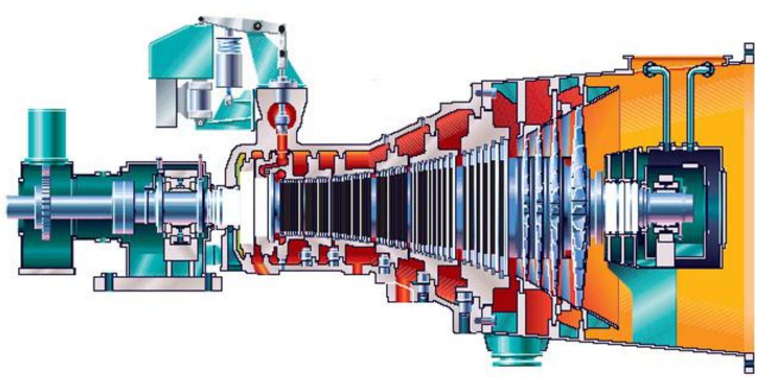


Figure 5 Steam Turbine

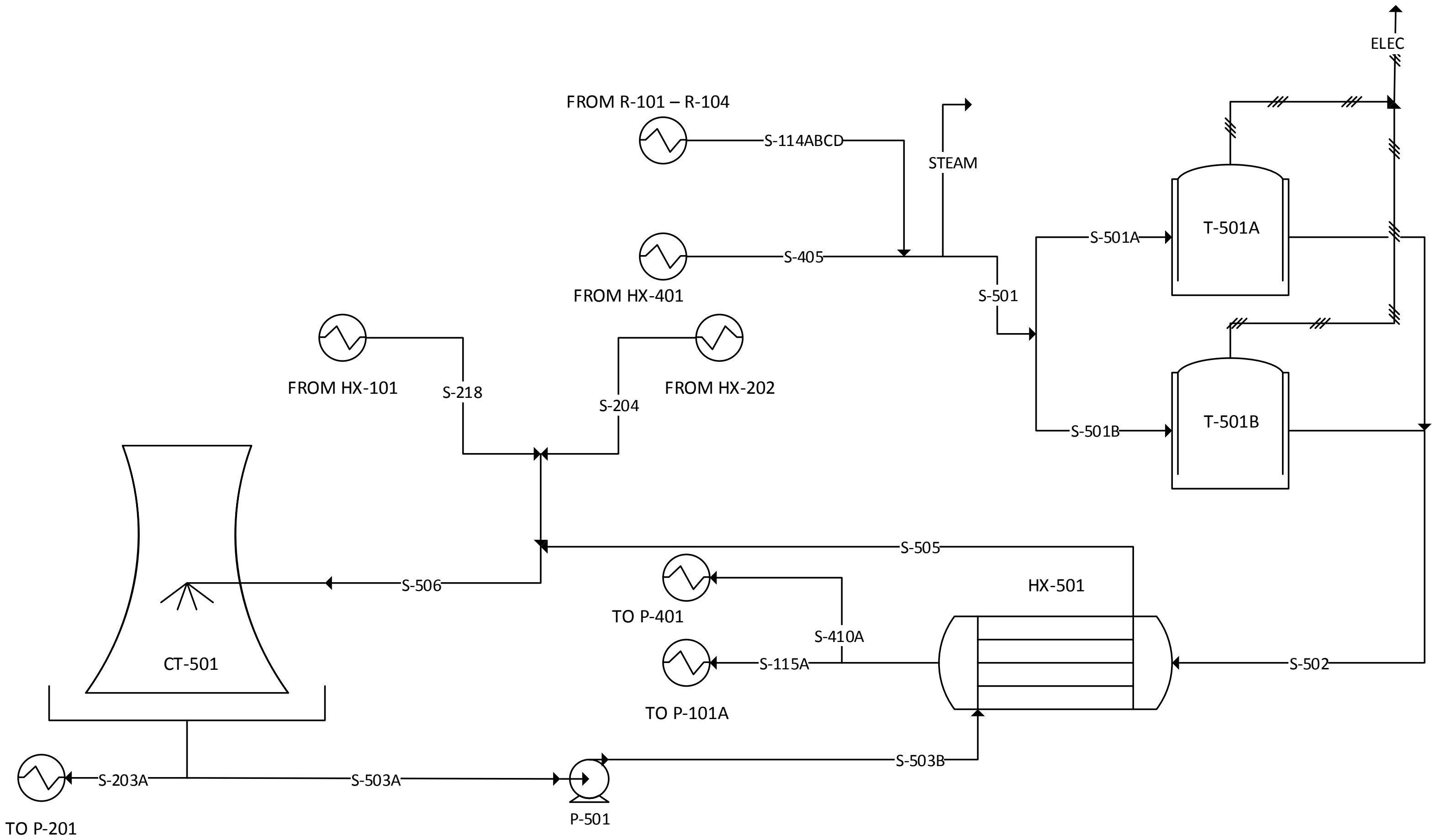
The net power remaining in the steam after its usage in the steam compressors of the refrigeration cycle, blowers in main process, and for preheating of streams is 277.610 MW. The recorded conversion of electricity from steam within the turbine is 0.40, translating to the generation of 111.045 MW of electricity. Four turbines of 28.33 MW capacities were selected for the conversion of steam to electricity. This enables appropriate scaling in the event of plant or distribution malfunction. The turbines are General Electric M5382C purchased and installed at a cost of $7.7 million. The electricity is distributed for use by pumps in the process, control operations, lighting, and other necessary plant functions. The remainder, 107.768 MW, is sent into the grid through a substation at a sale price of $0.085 per kWh. It is also noted that turbines require maintenance of $0.005 per kWh lending to a net price of $0.08 per kWh. [15]

Cooling Tower

Two concrete cooling towers are included to assist with cooling the large amount of water in the process. These also prevent the need to collect massive amounts of water for cooling as much of the water lives within the system as a result of the cooling towers. However, there is a small amount of water lost due to evaporation in the cooling towers, so the presence of these towers does not make the process entirely self-sufficient, but that reuptake is only about 2% of the overall flow rate of cooling water.

The cooling water itself is used in two applications, to cool the stream before F-201, the flash that removes water, and to condense and further cool the steam leaving the turbine. This cooled boiler-feed water can then be pumped to the combustor and the reactors for more steam generation. The cooling water itself only rises about 35 °F, making use of cooling towers feasible.

Section 500 Electricity Generation



Section 500 Electricity Generation Section							
	S-501	S-502	S-503A	S-503B	S-504	S-505	S-506
Temperature F	1252	185	86	86	95	123	122
Pressure psia	218	7	15	22	7	22	22
Vapor Frac	1.00	0.85	0.00	0.00	0.00	0.00	0.00
Total Flow cuft/hr	1.80E+07	1.73E+08	1.46E+06	1.46E+06	6.27E+04	1.49E+06	1.68E+06
Enthalpy Btu/hr	-2.01E+10	-2.27E+10	-6.20E+11	-6.20E+11	-2.65E+10	-6.17E+11	-6.95E+11
Mass Frac							
METHANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2H6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WATER	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PROPANE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Flow lb/hr	3.86E+06	3.86E+06	9.01E+07	9.01E+07	3.86E+06	9.01E+07	1.02E+08

Section 7- Energy Balance and Utility Requirements

An important specification set forth by profitable ethylene plants is to minimize energy usage and to operate self-sufficiently in energy. This entails recycling as much water and heat as possible in the form of energy integration across the sections of the OCM process. This section summarizes utility requirements by type and details the self-sufficiency of the plant.

Utility Requirements

Without the integration, the process required electricity, steam at 150 psig and 450 psig, cooling water, and refrigeration to -238 °F. Due to the excess heat generated in maintaining the reactors at isothermal conditions, all the process steam was substituted for boiler feed water. The steam produced was in large excess and utilized to power a turbine providing the electricity needs for the plant as well. As a feature of the integration, the boiler feed water and the cooling water live within the process requiring an upfront purchase and minor replenishing on an annual basis. In order to achieve the refrigeration temperatures needed, a cascade of propane, ethylene, and methane living in an integrated cycle was used.

Steam Integration

Energy integration within the process was attained through the formation of steam in The total energy extracted from the process through steam totaled 735.319 MW, removing the amount needed to power the blowers and compressors with a mechanical efficiency of 0.75 leaves a balance of 277.610 MW. The balance is sent through a turbine with a conversion efficiency of 0.40 to produce a total of 111.045 MW of electricity. Removing the amount needed within the process leaves 107.768 MW available for sale to the grid. The utilities of the system are summarized in the following table.

Energy Requirements of Process				
Equipment	Description	Utility (MW/yr)	Source	
Section 100				
B101	Blower	3.73	Steam	
B102	Blower	0.60	Steam	
P101	Pump	0.71	Electricity	
		5.04		*Net Section 100*
Section 200				
P201	Pump	0.02	Electricity	
RP201	Reflux Pump	0.066	Electricity	
RP202	Reflux Pump	2.36	Electricity	
C201	Compressor	40.32	Steam	
C202	Compressor	2.68	Steam	
		45.446		*Net Section 200*
Section 300				
P301	Pump	0.01	Electricity	
P302	Pump	0.006	Electricity	
P303	Pump	0.005	Electricity	
C301	Compressor	79.86	Steam	
C302	Compressor	104.80	Steam	
C303	Compressor	125.29	Steam	
		309.971		*Net Section 300*
Section 400				
B401	Blower	0.11	Steam	
P401	Pump	0.10	Electricity	
		0.21		*Net Section 400*
Totals				
Total Electricity		**3.277**		
Total Steam		**356.780**		
Total Utilities		**360.007**		

Utilities Living in the Process

All utilities were provided for within the process with associated annual losses. A total of 90.1 million lbs of cooling water and 9.86 million lbs of process water are circulated through the system. The process water is used to generate steam that is utilized to power compressors before entering a steam turbine to produce electricity. The cooling water is used in the process when the temperatures are not effective for steam generation. The refrigeration cascade uses 5.13, 2.16, and 1.59 million lbs of propane, ethylene, and methane, respectively. The amount lost per year was assumed as 5%, with the exception of the water sent to the cooling tower were marked losses are attributable to evaporation, discussed in the process description of Section 500. A summary of the utilities living within the process is summarized in the following table.

Utilities in Process						
Material	**Purpose**	**Amount within System (lb)**	**Price ($/lb)**	**Purchased Cost**	**Amount Lost (lb/yr)**	**Replenish Cost**
Cooling Water	Cooling	1.22E8	0.000628	$ 76,930	1.81E10	$ 11,368,650
Boiler Water	Steam	9.86E6	0.000215	$ 2,119	7.83E4	$17
Propane	Refrigeration	5.13E6	0.948	$3,750,000	2.46E5	$234,000
Ethylene	Refrigeration	2.16E6	-	-	1.08E5	-
Methane	Refrigeration	1.59E6	-	-	7.95E5	-

Reactor Section

As mentioned in the Process Description of Section 100 of the process, prior to entering the fixed bed reactors, the feed streams of new and recycled methane, alongside oxygen are preheated to 1292 °F and pressurized to 6 bar to meet the requirements outlined in literature. The feed is heated through the use of a product and feed economizer, with additional heating provided through the steam produced to maintain the reactors at 1292 °F. The blowers feeding the methane and oxygen to the reactors are powered with steam produced in the reactions outlined in Table 7.1.

The catalyst requires a set of specific criteria to maintain the optimal conversion of methane to ethylene and ethane in lieu of the more thermodynamically favorable combustion process. Recall that in Section 6, the reactors were described as having internal cooling within the reactor. Using boiler feed water to provide the needed cooling generates steam. The steam produced on each shell side of the reactor is at a temperature of 1284 °F and is utilized throughout the process in the form of heating, powering steam compressors, and the generation of electricity in a steam turbine.

The products leaving the reactor are used in a product-feed economizer to partially pre-heat the feeds to the reactor section. Prior to entering the separation section, the products need to be cooled to 27.3 °C. The cooling water that is sent to the reactors is preheated as it is used to cool the product stream to 212 °F. Additional cooling is provided through residual sensible cooling from the methane leaving the second column in the refrigeration cycle before it returns to the cycle as well as more cooling water.

Separation Section

The products enter a flash vessel where the water condenses out of the system leaving a dry product stream. The product stream is then compressed to a pressure of 290 psi elevating the temperature to 318 °F. The water separated from the flash is pumped through a heat exchanger to reduce the temperature of the product stream to 104 °F before entering the adsorption column. Thirteen vessels utilize a system of valves and blowers, powered with steam, to extract the CO_2 and residual water vapor from the product stream. The product stream leaving the adsorption column is chilled to a temperature of -94 °F using the bottoms products of the second column.

Each cryogenic column uses a pump, reboiler, and condensing unit to achieve the desired separation. The reboiler of the first and second column uses the propane produced in the refrigeration cycle to reach a temperature of -12 and -162 °F, respectively. The condensing unit of the first and second column uses the methane of the refrigeration cycle to reach temperatures of -171 and -241 °F, respectively. The remaining cooling capabilities of the methane are used to assist in lowering the temperature of the feed to the first column. Two pumps located at the bottom of the columns used to pump reflux back to the top of the column are used to regain pressure losses attributed to the tower, piping, and head loss. The pumps are powered through electricity generated with the steam produced in the process.

Refrigeration Section

The refrigeration cycle is the system with highest energy demands resultant of a high degree of compression. The propane, ethylene, and methane compressor consume 80, 105, and 125 MW of power. The power is provided through the large quantity of steam produced through the reactor and combustion section of the process. The cooling provided through the refrigeration cycle meets the amount needed within the system to enable cryogenic separation, with the remainder used to provide storage cooling within the process.

Combustion Section

The methane leaving the bottom of the second column is recycled back into the system. The methane has to be warmed prior to mixing in the reactor section or being sent to combustion. The cooling capacity of the methane is utilized in the temperature maintenance of the 5 ethylene and ethane storage vessels returning to the system at 32 °F. The methane is mixed with oxygen prior to further heating using the steam produced in the reactor section to a temperature of 984 °F. The methane is combusted in the reactor, generating an additional steam stream. The flue gases of the combustion leave the process at 295 °F, while the steam leaves at a temperature of 1771 °F to assist in heating of the process to its conversion to electricity.

Storage

The ethane and ethylene are stored at a temperature of -12 °F and pressure of 290 psi. It is required to have at least 3 days of storage for the products of the process with the consideration of the temperature profile; average of 85.3 °F at the location of Baytown, Texas cooling will be needed to ensure that the ethylene and ethane does not vaporize compromising the structural integrity of the storage vessels. The cooling is provided through the methane leaving the bottom of column 2; additional cooling can be provided with the purchase of outside liquid propane to run through the cooling system.

Section 8- Process Economics

Process Economics

At an ethylene price of \$0.62/lb, an ethane price of \$0.42/lb, a methane price of \$0.10/lb, and an oxygen price of \$0.02/lb, the process is profitable within an ROI of 6.79%.[16] Included in this return on investment is the sale of the byproducts of carbon monoxide at \$0.04/lb and electricity at \$0.08/kwh. The profitability measures are summarized in the following table. The inputs leading up to this finding are outlined in the following sections: materials, equipment cost estimates, utility requirements, cost summaries, and cash flows. Although the process is profitable, increased conversion of methane alongside increased selecitivity to C_2 hydrocarbons will increase the ROI.

Table 8.1

Profitability Measures

The Internal Rate of Return (IRR) for this project is	25.61%
The Net Present Value (NPV) of this project in 2015 is	\$ 517,165,400

ROI Analysis (Third Production Year)

Annual Sales	**558,000,000**
Annual Costs	**(174,607,204)**
Depreciation	**(69,822,450)**
Income Tax	**(116,021,028)**
Net Earnings	**197,549,318**
Total Capital Investment	**915,567,267**
ROI	**21.58%**

Materials

The primary inputs to the process were 453,000 lbs per hour of methane and 898,000 lbs per hour of oxygen. This allows for 35 days per year of down time for the plant. This translates to the production of 126,750 lbs per hour of ethylene to achieve the required 1 billion lbs per year. One year has been alloted for construction of the facility. The price of the inputs are $0.10 per lb of methane and $0.02 per lb of oxygen. The price of methane has a marked impact on the cost of the plant and have in the past fluctuated widely. However in recent years, the price has stabilized lending to stability in its pricing for these assessments.

Equipment Cost

Equipment costs are a large portion of the overall initial capital investment totaling $600 million. The largest expenditure was on the refrigeration cycle used for cyrogenic separation at 61.5% of the total cost of the process. This was largely due to the cost of the multistage compressors needed within the cycle with a combined estimated cost of $241 million. The separation section compromised 16.1% of the total cost largely due to the cost of columns and associated components. The reactor section was estimated at a cost comprising 5.82% of the total cost of process, the bulk of the cost was associated with the heat exchangers needed to maintain the isothermal conditions within the reactors. The breakdown of the cost of each section follows.

Table 8.2

Total Process Cost Summary

Percent Section 100	$ 34,973,679	5.82%
Percent Section 200	$ 97,164,090	16.1%
Percent Section 300	$ 369,369,353	61.5%
Percent Section 400	$ 55,804,870	9.29%
Percent Section 500	$ 59,558,635	9.92%
Total Cost	**$ 600,360,871**	**100.00%**

Table 8.3

Section 100 Equipment Costs

Equipment Description	Type	Purchase Cost	Bare Module Factor	Bare Module Cost	
B-101	Fabricated Equipment	$837,526	1.00	$	837,526
BFW-01	Compound in System	$130,759	1.00	$	130,760
CW-01	Compound in System	$1689	1.00	$	1,689
HX-101	Fabricated Equipment	$443,365	7.31	$	3,240,998
HX-102	Fabricated Equipment	$1,072,618	7.40	$	7,937,373
HX-103	Fabricated Equipment	$33,621	7.16	$	240,726
HX-104	Fabricated Equipment	$48,918	7.01	$	342,915
HX-105	Fabricated Equipment	$53,086	7.01	$	372,133
HX-106	Fabricated Equipment	$456,708	7.31	$	3,338,535
P-101	Process Machinery	$41,795	20.10	$	840,080
R-101/2/3/4	Catalysts	$6,221,204	1.00	$	6,221,204
R-101/2/3/4 5	Fabricated Equipment	$3,133,425	3.05	$	9,556,946
RHX-101/2/3/4	Fabricated Equipment	$272,090	7.03	$	1,912,793
		Total Cost for Section 100		**$**	**34,973,678**

Table 8.4

Section 200 Equipment Costs

Equipment Description	Type	Purchase Cost	Bare Module Factor	Bare Module Cost
C-201	Process Machinery	$7,467,878	2.30	$ 17,176,119
C-201	Process Machinery	$6,174,762	2.30	$ 14,201,953
C-202	Process Machinery	$1,369,035	2.30	$ 3,148,781
D-201	Fabricated Equipment	$1,093,303	4.16	$ 4,548,140
D-202	Fabricated Equipment	$2,297,774	4.16	$ 9,558,740
DC-201	Fabricated Equipment	$98,662	8.14	$ 803,109
DC-202	Fabricated Equipment	$58,821	8.04	$ 472,921
DR-201	Fabricated Equipment	$28,409	7.87	$ 223,579
DR-202	Fabricated Equipment	$31,337	7.90	$ 247,562
F-201	Fabricated Equipment	$340,182	3.03	$ 1,030,751
HX-201	Fabricated Equipment	$41,200	6.98	$ 287,576
HX-202	Fabricated Equipment	$544,901	7.66	$ 3,505,530
HX-203	Fabricated Equipment	$886,891	7.66	$ 6,793,585
HX-204	Fabricated Equipment	$59,016	8.04	$ 474,489
HX-205	Fabricated Equipment	$59,016	8.04	$ 474,489
P-201	Process Machinery	$74,170	6.30	$ 467,270
P-202	Process Machinery	$17,328	1.00	$ 17,328
RA-201	Fabricated Equipment	$332,016	3.05	$ 1,012,649
RA-202	Fabricated Equipment	$448,784	3.05	$ 1,368,791
RP-201	Process Machinery	$5,273	8.30	$ 43,766
RP-202	Process Machinery	$7,974	36.10	$ 287,861
V-201	Fabricated Equipment	$4,076,520	4.16	$ 16,958,323
V-201	Catalysts	$17,010,420	1.00	$ 17,010,420
		Total Cost for Section 200		**$ 100,312,871**

Table 8.5

Equipment Costs Section 300

Equipment Description	Type	Purchase Cost	Bare Module Factor	Bare Module Cost
C-301	Process Machinery	$37,378,265	2.15	$ 80,363,270
C-302	Process Machinery	$37,378,265	2.15	$ 80,363,270
C-303	Process Machinery	$37,378,265	2.15	$ 80,363,270
F-301	Fabricated Equipment	$719,612	3.05	$ 2,194,817
F-302	Fabricated Equipment	$428,865	3.05	$ 1,308,038
F-303	Fabricated Equipment	$595,686	3.05	$ 1,816,842
HX-301/2/3	Fabricated Equipment	$14,924,202	6.70	$ 99,992,153
HX-304	Fabricated Equipment	$1,131,677	7.30	$ 8,261,242
HX-305	Fabricated Equipment	$165,595	7.30	$ 1,208,844
HX-306	Fabricated Equipment	$1,169,530	7.30	$ 8,537,569
P-301	Process Machinery	$4,833	6.30	$ 30,448
P-302	Process Machinery	$4,640	6.30	$ 29,232
P-303	Process Machinery	$4,492	6.30	$ 28,300
PR-01	Compound in System	$1,249,246	3.90	$ 4,872,059
		Total Cost for Section 300		**$ 369,369,353**

Table 8.6

Equipment Costs Section 400

Equipment Description	Type	Purchase Cost	Bare Module Factor	Bare Module Cost	
HX-401	Fabricated Equipment	$24,563	7.09	$	174,152
HX-402	Fabricated Equipment	$48,450	7.23	$	350,294
K-401	Fabricated Equipment	$315,639	6.37	$	2,010,620
P-401	Process Machinery	$6,917	6.30	$	43,577
R-401	Fabricated Equipment	$8,921,711	2.58	$	23,018,014
RHX-401	Fabricated Equipment	$22,154	7.06	$	156,407
T-401/2/3/4	Process Machinery	$30,000,000	1.00	$	30,000,000
		Total Cost of Section 400		**$**	**55,804,870**

Table 8.7

Equipment Costs Section 500

HX-501 AB	Fabricated Equipment	$4,350,008	6.56	$	28,551,508
Pump-501 ABCD	Process Machinery	$935,480	6.30	$	5,893,520
V-501/2/3/4/5/6	Storage	$9,572,136	1.00	$	9,572,136
CT-501	Storage	$13,894,042	1.00	$	13,894,042
V-508	Fabricated Equipment	$1,647,429	1.00	$	1,647,429
		Total Cost of Section 500		**$**	**9,558,635**

Utility Requirements

The designed plant is self-sustaining. The only required utilities are the replacement of cooling and boiler feed water, propane, ethylene, and methane living within the system. The quantities of each flowing within the system were summarized in the energy and utility section. The electricity used to power the pumps within the system is supplied through steam powered turbines in the combustion section.

Cost Summaries

The variable costs, working capital, fixed costs, and investment summary are presented in the following tables taken to specifications outlined in SSLW Table 23.1. The variable costs of the plant totaled $34.3 million primarily composed of the purchase of raw materials, $265 million. The sale of byproducts and electricity produced in our plant provided $302.3 million to offset the cost of purchasing raw materials and general expenses.

Table 8.8
Variable Cost Summary

Variable Costs at 100% Capacity:				
General Expenses				
	Selling / Transfer Expenses:		$	18,600,000
	Direct Research:		$	29,760,000
	Allocated Research:		$	3,100,000
	Administrative Expense:		$	12,400,000
	Management Incentive Compensation:		$	7,750,000
Total General Expenses			$	71,610,000
Raw Materials	$0.265000	per lb of Ethylene	$	265,000,000
Byproducts	$0.153211	per lb of Ethylene		($243,310,800)
Utilities	-$0.059008	per lb of Ethylene		($59,008,331)
Total Variable Costs			**$**	**34,290,869**

Working Capital

The working capital of the plant was based on the requirement of three days storage of produced materials. The storage of raw of materials was unnecessary for that plant as the natural gas and oxygen are piped directly into the plant. The total capital investment of the plant is equal to $906.5 million.

Table 8.9
Working Capital

	2016	2017	2018
Accounts Receivable	$ 22,931,507	$ 11,465,753	$ 11,465,753
Cash Reserves	$ 3,134,112	$ 1,567,056	$ 1,567,056
Accounts Payable	$ (7,618,870)	$ (3,809,435)	$ (3,809,435)
Ethylene Inventory	$ 2,293,151	$ 1,146,575	$ 1,146,575
Raw Materials	$ 653,425	$ 326,712	$ 326,712
Total	**$ 21,393,324**	**$ 10,696,662**	**$ 10,696,662**
Present Value at 15%	*$ 18,602,890*	*$ 8,088,213*	*$ 7,033,229*

Total Capital Investment **$ 906,504,951**

Fixed Costs

The fixed costs of the plant are largely composed of the maintenance and operations of the plant at $80.6 and $30.8 million, respectively. The total fixed cost of operation is $143.7 million.

Table 8.9

Fixed Cost Summary

<u>Operations</u>			
	Direct Wages and Benefits	$	25,480,000
	Direct Salaries and Benefits	$	3,822,000
	Operating Supplies and Services	$	1,528,800
	Technical Assistance to Manufacturing	$	-
	Control Laboratory	$	-
	Total Operations	**$**	**30,830,800**
<u>Maintenance</u>			
	Wages and Benefits	$	35,067,078
	Salaries and Benefits	$	8,766,770
	Materials and Services	$	35,067,078
	Maintenance Overhead	$	1,753,354
	Total Maintenance	**$**	**80,654,280**
<u>Operating Overhead</u>			
	General Plant Overhead:	$	5,192,645
	Mechanical Department Services:	$	1,755,260
	Employee Relations Department:	$	4,315,015
	Business Services:	$	5,412,053
	Total Operating Overhead	**$**	**16,674,973**
<u>Property Taxes and Insurance</u>			
	Property Taxes and Insurance:	$	15,585,368
<u>Other Annual Expenses</u>			
	Rental Fees (Office and Laboratory Space):	$	-
	Licensing Fees:	$	-
	Miscellaneous:	$	-
	Total Other Annual Expenses	**$**	**-**
<u>Total Fixed Costs</u>		**$**	**143,745,422**

Investment Summary

The bare module cost of the plant is equal to $600.3 million, largely composed of the purchase of fabricated equipment and process machinery at $292.9 million and $219.8 million. The direct permanent investment includes the bare module cost alongside the cost of site preparations and service facilities at $660.3 million. The total depreciable capital of the plant is $779.2 million. The total permanent investment for the plant totaled $872.7 million.

Table 8.10

Investment Summary

Bare Module Costs				
Fabricated Equipment	$	292,930,589		
Process Machinery	$	219,862,137		
Spares	$	-		
Storage	$	81,346,941		
Other Equipment	$	-		
Catalysts	$	6,221,204		
Computers, Software, Etc.	$	-		
Total Bare Module Costs:			**$**	**600,360,871**
Direct Permanent Investment				
Cost of Site Preparations:	$	30,018,044		
Cost of Service Facilities:	$	30,018,044		
Allocated Costs for utility plants and related facilities:	$	-		
Direct Permanent Investment			**$**	**660,396,958**
Total Depreciable Capital				
Cost of Contingencies & Contractor Fees	$	118,871,452		
Total Depreciable Capital			**$**	**779,268,410**
Total Permanent Investment				
Cost of Land:	$	15,585,368		
Cost of Royalties:	$	-		
Cost of Plant Start-Up:	$	77,926,841		
Total Permanent Investment - Unadjusted			$	872,780,619
Site Factor				1.00
Total Permanent Investment			**$**	**872,780,619**

Cash Flows

The most important features of the cash flow summary are the initial capital costs, the year of positive cash flow, and the final net present value. The summary shows that the process has a positive cash flow within the first year of operation, $122.5 million. The process exhibits a positive cumulative net present value within the seventh year of operation. The final net present value is $517.2 million. With this knowledge investment is recommended.

Table 8.11						
Cash Flow Summary 1/2						
Year	**Percentage of Design Capacity**	**Product Unit Price**	**Sales**	**Capital Costs**	**Working Capital**	**Var Costs**
2015	0%		-	-	-	-
2016	0%		-	(872,780,600)	(21,393,300)	-
2017	45%	$0.62	279,000,000	-	(10,696,700)	(15,430,900)
2018	68%	$0.62	418,500,000	-	(10,696,700)	(23,146,300)
2019	90%	$0.62	558,000,000	-	-	(30,861,800)
2020	90%	$0.62	558,000,000	-	-	(30,861,800)
2021	90%	$0.62	558,000,000	-	-	(30,861,800)
2022	90%	$0.62	558,000,000	-	-	(30,861,800)
2023	90%	$0.62	558,000,000	-	-	(30,861,800)
2024	90%	$0.62	558,000,000	-	-	(30,861,800)
2025	90%	$0.62	558,000,000	-	-	(30,861,800)
2026	90%	$0.62	558,000,000	-	-	(30,861,800)
2027	90%	$0.62	558,000,000	-	-	(30,861,800)
2028	90%	$0.62	558,000,000	-	-	(30,861,800)
2029	90%	$0.62	558,000,000	-	-	(30,861,800)
2030	90%	$0.62	558,000,000	-	-	(30,861,800)
2031	90%	$0.62	558,000,000	-	-	(30,861,800)
2032	90%	$0.62	558,000,000	-	-	(30,861,800)
2033	90%	$0.62	558,000,000	-	-	(30,861,800)
2034	90%	$0.62	558,000,000	-	-	(30,861,800)
2035	90%	$0.62	558,000,000	-	-	(30,861,800)
2036	90%	$0.62	558,000,000	-	42,786,600	(30,861,800)

Table 8.12							
Cash Flow Summary 2/2							
Year	**Fixed Costs**	**Depreciation**	**Taxible Income**	**Taxes**	**Net Earnings**	**Cash Flow**	**Cumulative Net Present Value at 15%**
2015	-	-	-	-	-	-	-
2016	-	-	-	-	-	(894,173,900)	(777,542,600)
2017	(143,745,400)	(155,853,700)	(36,030,000)	13,331,100	(22,698,900)	122,458,100	(684,946,600)
2018	(143,745,400)	(249,365,900)	2,242,400	(829,700)	1,412,700	240,081,900	(527,088,900)
2019	(143,745,400)	(149,619,500)	233,773,300	(86,496,100)	147,277,200	296,896,700	(357,337,200)
2020	(143,745,400)	(89,771,700)	293,621,100	(108,639,800)	184,981,300	274,753,000	(220,736,400)
2021	(143,745,400)	(89,771,700)	293,621,100	(108,639,800)	184,981,300	274,753,000	(101,953,100)
2022	(143,745,400)	(44,885,900)	338,506,900	(125,247,600)	213,259,400	258,145,200	(4,906,800)
2023	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	74,052,300
2024	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	142,712,300
2025	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	202,416,600
2026	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	254,333,500
2027	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	299,478,600
2028	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	338,735,200
2029	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	372,871,300
2030	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	402,554,900
2031	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	428,366,800
2032	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	450,811,900
2033	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	470,329,300
2034	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	487,301,000
2035	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	241,537,500	502,059,000
2036	(143,745,400)	-	383,392,800	(141,855,300)	241,537,500	284,324,100	517,165,400

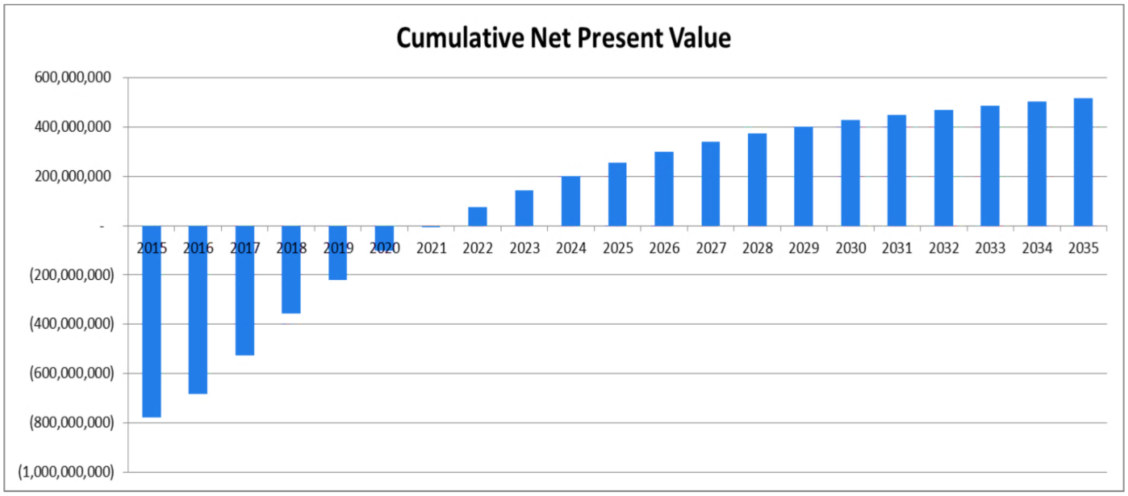


Chart 8.1

Sensitivity Analysis

The most significant variable and revenue driving costs will be examined for bottom-line impact in order to prepare for different operation scenarios. The main drivers for the OCM process are the conversion of methane and the prices of methane, ethylene, and ethane. Internal rate of return (IRR) are shown for product price against variable costs, fixed costs, and total permanent investment. These measures are designed to demonstrate the robustness of the OCM process. The product price variation is taken within 20%, the fluctuation seen for the price of ethylene in the market. It is the case in the following figures that as the product price decreases and the associated cost increases the IRR decreases.

This figure demonstrates the relationship between the product price and variables costs in the range of 20% of their current value. The IRR is positive within these ranges of product price and variable costs shown in Table 8.13.

Table 8.13 IRR Product Price vs. Variable Cost

Product Price						Variable Costs					
	$27,432,695	$28,804,330	$30,175,965	$31,547,599	$32,919,234	***$34,290,869***	$35,662,504	$37,034,138	$38,405,773	$39,777,408	$41,149,043
$0.50	19.37%	19.29%	19.21%	19.13%	19.05%	18.96%	18.88%	18.80%	18.72%	18.64%	18.56%
$0.52	20.76%	20.68%	20.60%	20.52%	20.44%	20.36%	20.29%	20.21%	20.13%	20.05%	19.97%
$0.55	22.11%	22.03%	21.95%	21.88%	21.80%	21.72%	21.65%	21.57%	21.50%	21.42%	21.34%
$0.57	23.42%	23.35%	23.27%	23.20%	23.12%	23.05%	22.97%	22.90%	22.83%	22.75%	22.68%
$0.60	24.71%	24.63%	24.56%	24.49%	24.42%	24.34%	24.27%	24.20%	24.12%	24.05%	23.98%
$0.62	25.97%	25.89%	25.82%	25.75%	25.68%	25.61%	25.54%	25.47%	25.39%	25.32%	25.25%
$0.64	27.20%	27.13%	27.06%	26.99%	26.92%	26.85%	26.78%	26.71%	26.64%	26.57%	26.50%
$0.67	28.41%	28.34%	28.27%	28.20%	28.14%	28.07%	28.00%	27.93%	27.86%	27.79%	27.72%
$0.69	29.60%	29.54%	29.47%	29.40%	29.33%	29.26%	29.19%	29.13%	29.06%	28.99%	28.92%
$0.72	30.78%	30.71%	30.64%	30.57%	30.51%	30.44%	30.37%	30.30%	30.24%	30.17%	30.10%
$0.74	31.93%	31.86%	31.80%	31.73%	31.67%	31.60%	31.53%	31.47%	31.40%	31.33%	31.27%

This figure shows the relationship between the product price and fixed costs in the range of 20% of their current value. The IRR is positive within these ranges of product price and fixed costs shown in Table 8.14.

Table 8.14 IRR Product Price vs. Fixed Cost

Product Price						Fixed Costs					
	$114,996,338	$120,746,154	$126,495,971	$132,245,788	$137,995,605	***$143,745,422***	$149,495,239	$155,245,056	$160,994,873	$166,744,690	$172,494,506
$0.50	21.07%	20.65%	20.23%	19.81%	19.39%	18.96%	18.54%	18.11%	17.68%	17.25%	16.81%
$0.52	22.43%	22.02%	21.61%	21.19%	20.78%	20.36%	19.95%	19.53%	19.11%	18.69%	18.26%
$0.55	23.75%	23.35%	22.94%	22.54%	22.13%	21.72%	21.32%	20.91%	20.49%	20.08%	19.67%
$0.57	25.04%	24.65%	24.25%	23.85%	23.45%	23.05%	22.65%	22.24%	21.84%	21.44%	21.03%
$0.60	26.31%	25.92%	25.53%	25.13%	24.74%	24.34%	23.95%	23.55%	23.15%	22.76%	22.36%
$0.62	27.55%	27.16%	26.78%	26.39%	26.00%	25.61%	25.22%	24.83%	24.44%	24.04%	23.65%
$0.64	28.77%	28.39%	28.00%	27.62%	27.23%	26.85%	26.46%	26.08%	25.69%	25.30%	24.92%
$0.67	29.97%	29.59%	29.21%	28.83%	28.45%	28.07%	27.68%	27.30%	26.92%	26.54%	26.16%
$0.69	31.15%	30.77%	30.39%	30.02%	29.64%	29.26%	28.89%	28.51%	28.13%	27.75%	27.37%
$0.72	32.31%	31.93%	31.56%	31.19%	30.81%	30.44%	30.07%	29.69%	29.32%	28.94%	28.57%
$0.74	33.45%	33.08%	32.71%	32.34%	31.97%	31.60%	31.23%	30.86%	30.49%	30.11%	29.74%

This figure shows the relationship between the total permanent investment and the product price in the range of 20% of their current value. The IRR is positive within these ranges of product price and total permanent investment shown in Table 8.15.

Table 8.15 IRR Product Price vs. Total Permanent Investment

		Total Permanent Investment										
		$698,224,495	$733,135,720	$768,046,945	$802,958,170	$837,869,394	***$872,780,619***	$907,691,844	$942,603,069	$977,514,293	$1,012,425,518	$1,047,336,743
Product Price	$0.50	30.29%	27.53%	25.05%	22.82%	20.80%	18.96%	17.28%	15.73%	14.30%	12.98%	11.74%
	$0.52	32.11%	29.24%	26.67%	24.36%	22.27%	20.36%	18.62%	17.03%	15.55%	14.19%	12.92%
	$0.55	33.89%	30.92%	28.25%	25.86%	23.69%	21.72%	19.93%	18.28%	16.76%	15.35%	14.05%
	$0.57	35.64%	32.55%	29.80%	27.32%	25.08%	23.05%	21.19%	19.49%	17.93%	16.48%	15.14%
	$0.60	37.35%	34.16%	31.31%	28.75%	26.44%	24.34%	22.43%	20.68%	19.07%	17.58%	16.20%
	$0.62	39.02%	35.73%	32.79%	30.15%	27.77%	25.61%	23.64%	21.83%	20.18%	18.65%	17.23%
	$0.64	40.67%	37.28%	34.25%	31.53%	29.08%	26.85%	24.82%	22.96%	21.26%	19.69%	18.23%
	$0.67	42.30%	38.81%	35.69%	32.88%	30.36%	28.07%	25.98%	24.07%	22.32%	20.71%	19.22%
	$0.69	43.90%	40.30%	37.10%	34.22%	31.62%	29.26%	27.12%	25.16%	23.36%	21.71%	20.18%
	$0.72	45.48%	41.78%	38.49%	35.53%	32.86%	30.44%	28.24%	26.23%	24.39%	22.69%	21.12%
	$0.74	47.03%	43.24%	39.86%	36.82%	34.08%	31.60%	29.34%	27.28%	25.39%	23.65%	22.05%

Changes in the variable price do not have as much of a marked effect on the IRR as the fixed costs and total permanent investment. It is expected in coming years that the price of ethylene will increase as its traditional raw material, naphthalene, is expected to increase in price in response to decrease in supply. This translates to an optimistic view on the IRR for the OCM plant.

Comparison to Traditional Ethylene Plants

The average total depreciable capital associated with a traditional ethylene plant (naphthalene cracking) is $681MM.[17] The total depreciable capital for the OCM plant is $779 MM which is $98MM greater. The total permanent investment for a typical cracking plant is $855MM, while the total permanent investment for the OCM plant is $872MM.[17] The OCM plant falls within range of typical ethylene plant costs, but is marginally more expensive.

Additional Economic Considerations

Transportation of Materials

The location of the plant will be near an olefins plant where the ethylene will be removed and the ethane will be reformed to ethylene. The ethylene will be piped directly into an olefins plant. The natural gas will be piped into the plant from the piping network. The oxygen used will be bought from air separations facility typically found near olefin plants and piped into the process.

Catalyst Modification

The research concerning catalysts for use in the OCM process is ongoing. The catalyst chosen for our plant is from research performed in 2001. If the price of methane remains low, research will continue on catalysts used in OCM. If a catalyst becomes available with a higher conversion of methane and greater selectivity of ethylene to ethane, it would be advantageous to seriously consider exchanging catalysts as it will greatly reduce the cost of utilities and increase the amount of product.

Section 9- Safety and Other Considerations

Safety

Because methane is one of the major chemicals of concern in this process, it is necessary to note that the Occupational Safety & Healthy Administration (OSHA) classifies it as not only an asphyxiant but also an explosive. [18] This warning resonates with the primary risk associated with all combustible gases, the possibility of explosions. Because oxidative coupling must take place at temperatures around 700 °C, this process will always be operating above the auto ignition temperature of methane of 580 °C. Methane can form explosive mixtures between the lower explosive limit (LEL) of 5% by volume and the upper explosive limit (UEL) of 15% by volume.[19] Careful consideration was taken in checking the concentrations of each stream in the process to see if this regime of flammability was avoided. Likewise, ethane is classified by OSHA as an asphyxiant and explosive, with a LEL of 3% and an UEL of 12.4%. Similarly, ethylene has flammability concerns when it is between 2.7% and 36% volume of mixture. To take care of these concerns, our process starves the ethylene of oxygen, thereby making the mixtures too lean to combust. The kinetics of OCM in methane excess, studied by Geerts et. al, has shown oxidative coupling to be of strong preference over combustion in experimental reaction vessels.[20] In order to detect a methane leak, OSHA recommends detector tubes for AUER or Drager that can detect the presence of methane at 5000 ppm. There are equivalent detectors for the other hydrocarbons as well which will be used.

Another safety concern in the process is the high pressure reached throughout it, most notably in the distillation and compression units. To check for any deviation from design pressures, control valves can be placed throughout the process, with the dual function of monitoring and venting material to relieve pressure. In reference to the extremely high temperatures of the reactor section and the extremely low temperatures of part of the separation train, proper inspection and maintenance of the reactors and the cryogenic units is crucial and there must be a high frequency of inspections at the beginning of operation in order to compile reliable vessel performance. During regularly scheduled maintenance, any build up in process equipment and piping will be prevented. Also, stainless steel material will be used throughout the process to inhibit corrosion and Monel will be used to withstand the cryogenic processing units.

Environmental Considerations

The only streams leaving the process are S-210 and S-411. Every other stream feeds back into the process. S-210 consists of carbon dioxide that is removed with the pressure swing adsorption. S-411comes from the combustion process and has mass fractions of 0.60 water vapor, 0.3 carbon dioxide, 0.06 oxygen, and less than 1% methane and C_2 product. The EPA does not currently regulate carbon dioxide output, however during the lifetime of this plant, it could certainly be regulated and then our plant would be made to comply with the environmental standards.

The environmental concerns of this process will be analyzed with regards to the US standards of pollution control. The primary environmental concerns are with regard to the quality of the air purged from the system and process of cooling water intake. No solid waste is produced in this process so there will be no compliance issues with the Federal Hazardous and Solid Waste Amendments (HSWA) set forth by the Resource Conservation and Recovery Act (RCRA). [21]

The only air quality concern regulated under the Clean Air ACT (CAA) is due to the formation of CO in the process. Current EPA standards regulating CO are to not exceed a level of 35 ppm combined with a 1-hour averaging time.[22] The CO released to the environment is so minimal that it easily meets this standard. This is the case because the CO produced in this process is sold to a user near Baytown, Texas and is stored in storage tank ST-502.

With respect to the quality of cooling water, the process and plant will be guided by abiding section 316b of the Clean Water Act (CWA). This section requires that industrial facilities like this plant obtain National Pollutant Discharge Elimination System (NPDES) permits for cooling water intake structures, to ensure that the plant is using the best technology available for location, design, and capacity of the plant.[23] 316b also explains how the withdrawal of cooling water by industrial facilities like this plant in Baytown should not detrimentally effect aquatic life from where the cooling water is drawn. There is no concern with quality of cooling water leaving the system because the cooling water lives within the system, whether for cooling or power purposes.

Location

The plant will be located in Baytown, Texas. A Gulf Coast location was chosen for three reasons. First, the location needed to be near an olefin plant to sell the ethylene/ethane product mixture to and the petrochemical industry is hugely invested in the Gulf Coast already. Second, the location needed to be easily connected to a natural gas pipeline for feed to the plant. The Gulf Coast has an abundance of pipelines to tap into. Third, due to the vast amounts of cooling water needed for the process, the location needed to be near a water source like a lake or river for water supply.

Additionally, Dow Chemical Company has six ethylene crackers in the United States, split between three sites located in Texas and Louisiana. ExxonMobil has the 4th largest ethylene production complex, that produces 2,197,000 tonnes per year and it is located in Baytown, Texas.[24] The fact that such a large scale operation found success in Baytown is proof that it is a suitable location for an ethylene plant. In conclusion, if this plant is to be competitive economically, it has to be located where the competition is.

Start Up

Due to the extensive heat integration in the process, plant startup is complex. For instance, between the various feeds to the reactors and combustor, a total of five preheaters are required, all using later streams in the process as the heat source. To combat this issue, the combustor will be used to provide heating requirements for the process until the process has achieved a steady-state equivalent state.

First the natural gas will be fed directly to the combustor, with an amount of oxygen, the create steam. This steam will first be used to preheat the combustor with HX-401, before being sent to the four preheaters to the reactors (HX-101 through HX-104). Although not all of these heat exchangers at steady state use steam for cooling, all of the heat exchangers are made of stainless steel and can handle steam rather than a process gas being sent through them. Additionally, because all of the process gas streams used for heating contain considerable amounts of water, any residual water present in the heat exchangers upon switching to the normal process gas should not impact the overall mass balances in the system.

While this solves the heating requirements, there are also cooling requirements involved, particularly HX-204. This precooler before the column D-201 uses the liquid methane leaving the second column to cool the process stream. To combat this, significant amounts of liquid nitrogen will be trucked in to cool the stream to -94 F. The two other primary cooling requirements are the precoolers before F-201, the water flash, and the cooling for the top of each distillation column. For the precoolers, HX-201 and HX-202, more cooling water will be used to offset HX-201, which uses the cool methane from the bottom of the second column after it has cooled the feed to the column and chilled the product storage tanks. Therefore, HX-201 will just be bypassed and HX-202 will be used solely for this cooling. The heat exchanger was sized to account for this additional amount of cooling water required at start up. For the tower cooling, the refrigeration cycle providing the cooling is self-contained in terms of start up and does not require later steps in the process to achieve the temperature for the columns. Therefore, this cooling will not change between start up and while at steady state.

Maintenance

The operating year was chosen to be 330 days per year to allow for slightly over a month total throughout the year for maintenance operations. A number of additional cautions and expenses have been considered for proper maintenance of the overall process.

An additional reactor/heater exchanger system (R-105/RX-105) was included in the capital costs for the plant, allowing for maintenance of an individual reactor without stopping the entire system or reducing the amount of product created. Because the reactor catalyst needs to be switched every 90 days, this is extremely important for continuous operation throughout the year.

The large number of vessels for the PSA process also means that the adsorbents can be switched out in an individual vessel without upsetting the overall process. However, because these adsorbents have a life of three years, replacing these catalysts is much less of a concern.

The two process just described are the only instances in the process of a catalyst or adsorbent that requires periodic replacement. While boiler-feed water will be replaced infrequently to help protect the equipment, the entire plant will be shut down for the process.

Any other maintenance of the equipment will occur during this period as well. Also, due to careful materials selections, mostly extensive usage of stainless steel and monel, maintenance of process equipment should be relatively minor.

Section 10- Equipment List and Unit Descriptions

Equipment List

Section 100: Reactor	Section 200: Separations		Section 300: Refrigeration	Section 400: Combustion	Section 500: Electricity
B-101	C-201	ST-202	C-301	B-401	CT-501
B-102	C-202	V-201	C-302	CM-401	HX-501
HX-101	D-201		C-303	HX-401	P-501
HX-102	D-202		F-301	HX-402	T-501
HX-103	DA-201		F-302	RHX-402	
HX-104	DA-202		F-303	P-402	
HX-105	DR-201		HX-301		
P-101	DR-202		HX-302		
R-101	F-201		HX-303		
R-102	HX-201		HX-304		
R-103	HX-202		HX-305		
R-104	HX-203		HX-306		
R-105	HX-204		P-301		
RHX-101	RC-201		P-302		
RHX-102	RC-202		P-303		
RHX-103	RP-201				
RHX-104	RP-202				
RHX-105	P-201				
	ST-201				

Unit Descriptions

Section 100:

B-101 is a blower that increases the pressure of the methane feed of Stream 1. It increases the pressure from 64.7 psi to 87 psi, while increasing the temperature from 77°F to 129.6°F. The inlet volumetric flow rate is 2,493,180 cuft/hr and the outlet volumetric flow rate is 2,036,520 cuft/hr. The blower is made from Cast Iron. The steam required to power the blower is 12,725,546 BTU/hr which is supplied from within the process. The bare module cost is $837,526.

B-102 is a blower that increases the pressure of the oxygen feed from 100 psi to 105 psi. The temperature increases from 81.1°F to 91.6°F. The inlet volumetric flow rate is 1,622,200 cuft/hr and the outlet volumetric flow rate is 1,575,170 cuft/hr. The blower is made of Cast Iron. The steam required to power the blower is 2,049 MBTU/hr which is supplied from within the process. The bare module cost is $199,139.

HX-101 is a shell and tube heat exchanger that serves as a first preheater for the methane feed. It takes stream X and cools it from 295.8°F to 150°F on the tube side, and the shell side goes from 129.6°F to 286°F. The heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 886. There are 4 tube passes, 2 shell passes, and the area available for heat transfer is 48,986 ft^2. The heat duty is 105,849 MBTU/hr. The bare module cost is $3,241,254 and the annual utility cost is zero because the utilities are provided from within the system.

HX-102 is a shell and tube heat exchanger that serves as the second preheater for the methane feed. It takes stream X and cools it from 1137.6°F to 482°F on the tube side, and the shell side goes from 286°F to 1133.1°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 856. There are 8 tube passes, 2 shell passes, and the area available for heat transfer is 106,065 ft^2. The heat duty is 801,852 MBTU/hr. The bare module cost is $7,937,373 and the annual utility cost is zero because the utilities are provided from within the system.

HX-103 is a shell and tube heat exchanger that serves as the third and final preheater for the methane feed. It takes stream X and cools it from 1652.3°F to 1334.6°F on the tube side, and the shell side goes from 1133.2°F to 1202°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is one tube and shell pass each and the area available for heat transfer is 1,749 ft^2. The heat duty is 81,001 MBTU/hr. The bare module cost is $240,726 and the annual utility cost is zero because the utilities are provided from within the system.

HX-104 is a shell and tube heat exchanger that serves as the first preheater for the oxygen feed. It takes stream X and cools it from 221.2°F to 184.7°F on the tube side, and the shell side goes from 81.1°F to 205°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 3,517 ft^2. The heat duty is 24,822 MBTU/hr. The bare module cost is $342,915 and the annual utility cost is zero because the utilities are provided from within the system.

HX-105 is a shell and tube heat exchanger that serves as the second preheater for the oxygen feed. It takes stream X and cools it from 1292°F to 1137.6°F on the tube side, and the shell side goes from 205°F to 1202°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 4,020 ft^2. The heat duty is 216,868 MBTU/hr. The bare module cost is $372,133 and the annual utility cost is zero because the utilities are provided from within the system.

P-101 is a multistage centrifugal pump that pumps boiler-feed water for the cooling of the reactor section. The pump is made of stainless steel and has 5 stages and a volumetric flow rate of 51,456 cuft/hr. It has a pressure rise of 648.1 psi while generating a head of 456 ft. The electricity requirement to run the pump is 884 hp and the pump efficiency is 0.86. The pump has a bare module cost of $208,975.

R-101 is a fixed bed catalytic reactor with an internal shell and tube heat exchanger, RHX-101. The reactor serves to facilitate the oxidative coupling of methane to form ethylene and ethane with the use of LiMgO catalyst, and operating at conditions of 1292°F and 87 psi. The reactor is made of Stainless Steel, weights 52,596 lb, has a diameter of 11.5 ft, a length of 34 ft and a wall thickness of 0.82 inches. The catalyst has total weight of 4080 kg per reactor and a lifetime of 90 days, so it must be changed 4 times in the course of 330 days of operation. The bare module cost of the reactor is $2,012,792 and the annual catalyst cost is $1,555,301

R-102 is a fixed bed catalytic reactor with an internal shell and tube heat exchanger, RHX-102. The reactor serves to facilitate the oxidative coupling of methane to form ethylene and ethane with the use of LiMgO catalyst, and operating at conditions of 1292°F and 87 psi. The reactor is made of Stainless Steel, weights 52,596 lb, has a diameter of 11.5 ft, a length of 34 ft and a wall thickness of 0.82 inches. The catalyst has total weight of 4080 kg per reactor and a lifetime of 90 days, so it must be changed 4 times in the course of 330 days of operation. The bare module cost of the reactor is $2,012,792 and the annual catalyst cost is $1,555,301.

R-103 is a fixed bed catalytic reactor with an internal shell and tube heat exchanger, RHX-103. The reactor serves to facilitate the oxidative coupling of methane to form ethylene and ethane with the use of LiMgO catalyst, and operating at conditions of 1292°F and 87 psi. The reactor is made of Stainless Steel, weights 52,596 lb, has a diameter of 11.5 ft, a length of 34 ft and a wall thickness of 0.82 inches. The catalyst has total weight of 4080 kg per reactor and a lifetime of 90 days, so it must be changed 4 times in the course of 330 days of operation. The bare module cost of the reactor is $2,012,792 and the annual catalyst cost is $1,555,301.

R-104 is a fixed bed catalytic reactor with an internal shell and tube heat exchanger, RHX-104. The reactor serves to facilitate the oxidative coupling of methane to form ethylene and ethane with the use of LiMgO catalyst, and operating at conditions of 1292°F and 87 psi. The reactor is made of Stainless Steel, weights 52,596 lb, has a diameter of 11.5 ft, a length of 34 ft and a wall thickness of 0.82 inches. The catalyst has total weight of 4080 kg per reactor and a lifetime of 90 days, so it must be changed 4 times in the course of 330 days of operation. The bare module cost of the reactor is $2,012,792 and the annual catalyst cost is $1,555,301.

R-105 is a fixed bed catalytic reactor with an internal shell and tube heat exchanger, RHX-105. The reactor serves to facilitate the oxidative coupling of methane to form ethylene and ethane with the use of LiMgO catalyst, and operating at conditions of 1292°F and 87 psi. The reactor is made of Stainless Steel, weights 52,596 lb, has a diameter of 11.5 ft, a length of 34 ft and a wall thickness of 0.82 inches. The catalyst has total weight of 4080 kg per reactor and a lifetime of 90 days, so it must be changed 4 times in the course of 330 days of operation. The bare module cost of the reactor is $2,012,792 and the annual catalyst cost is $1,555,301.

RHX-101 is a shell and tube exchanger that provides cooling inside R-101 to maintain isothermal temperature. The shell side goes from 217.6°F to 1265°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 4,182 ft^2. The heat duty is 1,266,843 MBTU/hr. The bare module cost is $382,685 and the annual utility cost is zero because the utilities are provided from within the system.

RHX-102 is a shell and tube exchanger that provides cooling inside R-102 to maintain isothermal temperature. The shell side goes from 217.6°F to 1265°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 4,182 ft^2. The heat duty is 1,266,843 MBTU/hr. The bare module cost is $382,685 and the annual utility cost is zero because the utilities are provided from within the system.

RHX-103 is a shell and tube exchanger that provides cooling inside R-103 to maintain isothermal temperature. The shell side goes from 217.6°F to 1265°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 4,182 ft^2. The heat duty is 1,266,843 MBTU/hr. The bare module cost is $382,685 and the annual utility cost is zero because the utilities are provided from within the system.

RHX-104 is a shell and tube exchanger that provides cooling inside R-104 to maintain isothermal temperature. The shell side goes from 217.6°F to 1265°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is

4,182 ft^2. The heat duty is 1,266,843 MBTU/hr. The bare module cost is $382,685 and the annual utility cost is zero because the utilities are provided from within the system.

RHX-105 is a spare shell and tube exchanger that provides cooling inside the reactor to maintain isothermal temperature. The shell side goes from 217.6°F to 1265°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 4,182 ft^2. The heat duty is 1,266,843 MBTU/hr. The bare module cost is $382,685 and the annual utility cost is zero because the utilities are provided from within the system.

Section 200:

C-201 is a multi-stage compressor that compresses gases in Stream 35 after F-01 for further separation processes. It takes the stream from 87 psi to 290 psi and the temperature goes from 81.1°F to 573.8 °F. The inlet volumetric flow rate is 4,319,060 cuft/hr and the outlet volumetric flow rate is 1,833,550 cuft/hr. It is made from Cast-Iron/Carbon Steel and has 2 stages. The steam requirement to power the compressor is 135,572,203 BTU/hr, which is supplied from within the steam generation of the process. The bare module cost of the compressor is $31,378,071.

C-202 is a single stage compressor that compresses gases in S-211 after the carbon dioxide separation. It takes the stream from 260.2 psi to 290 psi and the temperature goes from 104°F to 123.2°F. The inlet volumetric flow rate is 1,2424,870 cuft/hr and the outlet volumetric flow rate is 1,154,090 cuft/hr. It is made from Cast-Iron/Carbon Steel. The steam requirement to power the compressor is 9,146 BTU/hr which is supplied from within the steam generation of the process. The bare module cost of the compressor is $3,148,781.

D-201 is a Sieve Tray Distillation Tower operating at cryogenic conditions for the purpose of separating ethane and ethylene products from the rest of Stream 39. It is made of Monel. The column has 18 trays with a tray spacing of 2 ft, and it has as a height of 46 ft, a diameter of 9.5 ft, and a weight of 98,396 lb. The column is operating with a reflux ratio of 0.597. The distillate is removed at a temperature of -170.9°F and the bottoms is taken off at a temperature of -12.3°F. The bare module cost of the column is $4,548,140.

D-202 is a Sieve Tray Distillation Tower operating at cryogenic conditions for the purpose of separating methane from carbon monoxide in Stream 41 for recycling. It is made of Monel. The column has 37 trays with a tray spacing of 2 ft and a total height of 86 ft. The column has a diameter of 11.5 ft and a weight of 257,562 lb. It operates at a reflux ratio of 11.1. The distillate is removed at -241°F and the bottoms is taken off at -161.9°F. The bare module cost of the tower is $9,558,740.

DA-201 is a reflux accumulator for column D-201. It is made Monel-400 to withstand cryogenic conditions. It has a diameter of 9 ft and a height of 20 ft and weighs 44,334 lb. It operates at a pressure of 290 psi and has a wall thickness of 1.27 in, allowing for corrosion. The bare module cost of the reflux accumulator is $1,012,729.

DA-202 is a reflux accumulator for column D-202. It is made Monel-400 to withstand cryogenic conditions. It has a diameter of 10 ft and a height of 26 ft and weighs 67,795 lb. It operates at a pressure of 290 psi and has a wall thickness of 1.53 in, allowing for corrosion. The bare module cost of the reflux accumulator is $1,367,540.

DR-201 is a reboiler heat exchanger for column D-201. It is made from Monel due to cryogenic conditions. The tubes are 20 ft in length and the area available for heat transfer is 1,192 ft2. The reboiler utilizes countercurrent flow, has 934 tubes, and one shell and tube pass each. The heat duty is 19,449 MBTU/hr. The bare module cost of this reboiler is $223,579 and the utility cost per year is zero because utilities are provided from within the system.

DR-202 is a reboiler heat exchanger for column D-202. It is made from Monel due to cryogenic conditions. The tubes are 20 ft in length and the area available for heat transfer is 1,139 ft2. The reboiler utilizes countercurrent flow, has 934 tubes, and one shell and tube pass each. The heat duty is 49,613 MBTU/hr. The bare module cost of this reboiler is $247,562 and the utility cost per year is zero because utilities are provided from within the system.

F-201 is a flash column that removes water from S-205 and thus from the process. Most of the water is separated into stream S-206. The remainder will be separated out later with pressure swing adsorption. The flash operates at 87 psi and 27.3 °F. It is made of Stainless Steel. The vessel has a height of 12.5 ft, a diameter of 16.5 ft and a weight of 60,383 lb. The bare module cost of the tower is $1,019,790.

HX-201 is a shell and tube exchanger that serves as the first cooler to help with removal of water from the flash vessel. The tube side goes from 212°F to 203.7°F and the shell side goes from 0°F to 129.6°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 2,606 ft^2. The heat duty is 522,823 MBTU/hr. The bare module cost is $287,576 and the annual utility cost is zero because the utilities are provided from within the system.

HX-202 is a shell and tube exchanger that serves as a second cooler to help with removal of water from the flash vessel. The tube side goes from 203.7°F to 95°F and the shell side goes from 86°F to 173.1°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 856. There are 8 tube passes, 2 shell passes and the area available for heat transfer is 119,964 ft^2. The heat duty is 316,905 MBTU/hr. The bare module cost is $9,474,547 and the annual utility cost is zero because the utilities are provided from within the system.

HX-203 is a shell and tube exchanger that serves as cooler after the compressor CM-401. The tube side goes from 317.9°F to 104°F and the shell side goes from 95°F to 295.8°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 886. There are 4 tube passes, 2 shell passes and the area available for heat transfer is 90,510 ft^2. The heat duty is 145,141 MBTU/hr. The bare module cost is $6,793,585 and the annual utility cost is zero because the utilities are provided from within the system.

HX-204 is a shell and tube exchanger that serves as a cooler of Stream WHAT into Column WHAT. The tube side goes from 104°F to -64°F and the shell side goes from -161.9°F to -161.4°F. The countercurrent heat exchanger is made of Monel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 tube and shell pass each and the area available for heat transfer is 4,745 ft^2. The heat duty is 102,776 MBTU/hr. The bare module cost is $474,489 and the annual utility cost is zero because the utilities are provided from within the system.

RC-201 is the condenser heat exchanger for column D-201. It is made from Monel, due to cryogenic conditions.

The tubes are 20 ft in length, and the area available for heat transfer is 9,706 ft^2 . The condenser utilizes countercurrent flow, has 934 tubes, and one shell and tube pass each. The heat duty is 196,335 MBTU/hr. The bare module cost of this condenser is $803,109 and the utility cost per year is zero because the utilities are provided from within the system.

RC-202 is the condenser heat exchanger for column D-202. It is made from Monel due to cryogenic conditions. The tubes are 20 ft in length, and the area available for heat transfer is 4721 ft^2. The condenser utilizes countercurrent flow, has 934 tubes and one shell and tube pass each. The heat duty is 45,006 MBTU/hr. The bare module cost is $472,921 and the annual utility cost is zero because the utilities are provided from within the system.

RP-201 is a single stage centrifugal pump that pumps liquid propane for cooling in D-201. The pump is made of Monel to withstand cryogenic conditions and has a volumetric flow rate of 22,814 cuft/hr. It has a pressure rise of 42 psi while generating a head of 96 ft. The electricity requirement to run the pump is 89 hp and the pump efficiency is 0.86. The pump has a bare module cost of $66,539.

RP-202 is a two-stage centrifugal pump that pumps liquid propane for cooling in D-202. The pump is made of Monel to withstand cryogenic conditions and has a volumetric flow rate of 20,697 cuft/hr. It has a pressure rise of 59.6 psi while generating a head of 137 ft. The electricity requirement to run the pump is 3,169 hp and the pump efficiency is 0.86. The pump has a bare module cost of $287,861.

P-201 is a centrifugal pump that pumps cooling water through HX-201. It is made of stainless steel to prevent corrosion. The pump has a volumetric flow rate of 35,376 cuft/hr and a pressure change of 7.3 psi while generating a head of 16.4 ft. The electricity requirement to run the pump is 22 hp and the pump efficiency of 0.86. The bare module cost of the pump is $41,750.

ST-201 is comprised of 6 storage tanks of volume 86,048 cuft each. These tanks store a composition of 0.3491 Ethane, 0.6472 Ethylene and the remainder Methane. They are operated at 290 psi and 0°F and are made out of Stainless Steel. Each has a diameter of 90.7 ft. The bare module cost for all 6 tanks is $9,572,203.

ST-202 is a storage tank of volume 89,596 cuft. This tank stores a mixture of mass fraction 0.999444 carbon monoxide and remainder methane. The tank is operated at -241°F and 290 psi and is made out of Stainless Steel. It has a diameter of 84.5 ft and the bare module cost is $1,647,316.

V-201 is a series of 13 identical vertical pressure vessels that serve the purpose of separating carbon dioxide out of S-209 through pressure swing adsorption. S-210 gets the entirety of the carbon dioxide. The vessels operate at 96.8°F and 290 psi. The vessels are made of low-alloy steel and each weigh 151,112 lbs, have a diameter of 12.5 ft, a length of 39 ft, and a wall thickness of 1.899 in. The vessels utilize two different catalysts, Zeolite 13x and Activated Alumina, to separate out remaining water and carbon dioxide. The total bare module cost of all 13 vessels is $1,413,195 and the annual catalyst cost is $850,571.

Section 300:

C-301 is a multi-stage compressor that compresses methane in Stream 301 for refrigeration. It takes the stream from 16 psi to 188.5 psi and the temperature goes from 68°F to 280.7°F. The inlet volumetric flow rate is 34,580,00 cuft/hr and the outlet volumetric flow rate is 3,860,000 cuft/hr. It is made from Cast-Iron/Carbon Steel and has 5 stages. The steam requirement to power the compressor is 149,650 hp which is supplied from within the steam generation of the process. The bare module cost of the compressor is $80,363,270.

C-302 is a multi-stage compressor that compresses ethylene in Stream 307 for the refrigeration cycle. It takes the stream from 16 psi to 304.5 psi and the temperature goes from -31°F to 382.3°F. The inlet volumetric flow rate is 21,900,000 cuft/hr and the outlet volumetric flow rate is 2,240,000 cuft/hr. It is made from Nickel Alloy and has 5 stages. The steam requirement to power the compressor is 140,551 hp which is supplied from within the steam generation of the process. The bare module cost of the compressor is $80,363,270.

C-303 is a multi-stage compressor that compresses methane in Stream 312 for the refrigeration cycle. It takes the stream from 16 psi to 478.6 psi and the temperature goes from -139°F to 385.4°F. The inlet volumetric flow rate is 21,100,000 cuft/hr and the outlet volumetric flow rate is 1,880,000 cuft/hr. It is made from Nickel Alloy and has 5 stages. The steam requirement to power the compressor is 180,537 hp which is supplied from within the steam generation of the process. The bare module cost of the compressor is $80,363,270.

F-301 is a flash column that separates S-306 into liquid and vapor phases. It is made of Monel-400. The vessel has a height of 27.5 ft, a diameter of 25.5 ft and a weight of 126,812 lb. The overhead and bottoms are both removed at -39.8°F. The bare module cost of the tower is $2,194,819.

F-302 is a flash column that separates S-318 into liquid and vapor phases. It is made of Monel-400. The vessel has a height of 28 ft, a diameter of 18.5 ft and a weight of 63,662 lb. The overhead and bottoms are both removed at -151.7°F. The bare module cost of the tower is $1,308,040.

F-303 is a flash column that separates S-326 into liquid and vapor phases. It is made of Monel-400. The vessel has a height of 12 ft, a diameter of 28.5 ft and a weight of 126,812 lb. The overhead and bottoms are both removed at -256°F. The bare module cost of the tower is $2,194,819.

HX-301 is a shell and tube heat exchanger that cools Stream S-302 for expansion in parallel with what? It is made from Stainless Steel. The tubes are 20 ft in length and the area available for heat transfer is 144,493 ft2. The heat exchanger utilizes countercurrent flow, has 982 tubes, 2 shell passes, and 6 tube passes. The heat duty is 145,000MBTU/hr. The bare module cost is $33,330,717 and the utility cost per year is $4,464,489.

HX-302 is a shell and tube heat exchanger that cools Stream S-308 for expansion in parallel with what? It is made from Stainless Steel. The tubes are 20 ft in length and the area available for heat transfer is 143,493 ft2. The heat exchanger utilizes countercurrent flow, has 982 tubes, 2 shell passes, and 6 tube passes. The heat duty is 145,000MBTU/hr. The bare module cost is $33,330,717 and the utility cost per year is $3,937,006.

HX-303 is a shell and tube heat exchanger that cools Stream S-313 for expansion. It is made from Stainless Steel. The tubes are 20 ft in length and the area available for heat transfer is 140,562 ft2. The heat exchanger utilizes countercurrent flow, has 982 tubes, 2 shell passes, and 6 tube passes. The heat duty is 148,950 MBTU/hr. The bare module cost is $33,330,717 and the utility cost per year is $3,543,304.

HX-304 is a shell and tube heat exchanger that cools Stream S-311 for expansion. It is made from Monel due to cryogenic temperatures. The tubes are 20 ft in length and the area available for heat transfer is 111,249 ft2. The heat exchanger utilizes countercurrent flow, has 982 tubes, 2 shell passes, and 6 tube passes. The heat duty is 422,000 MBTU/hr. The bare module cost is $8,261,242 and the utility cost per year is zero due to utilities being supplied from within the system.

HX-305 is a shell and tube heat exchanger that cools Stream S-316 for expansion. It is made from Monel due to cryogenic temperatures. The tubes are 20 ft in length and the area available for heat transfer is 23,782 ft2. The heat exchanger utilizes countercurrent flow, has 914 tubes, 2 shell passes, and 1 tube pass. The heat duty is 110,600 MBTU/hr. The bare module cost is $1,208,844 and the utility cost per year is zero due to utilities being supplied from within the system.

HX-306 is a shell and tube heat exchanger that cools Stream S-320 for expansion. It is made from Monel due to cryogenic temperatures. The tubes are 20 ft in length and the area available for heat transfer is 113,869 ft2. The heat exchanger utilizes countercurrent flow, has 982 tubes, 2 shell passes, and 8 tube passes. The heat duty is 322,000 MBTU/hr. The bare module cost is $8,537,569 and the utility cost per year is zero due to utilities being supplied from within the system.

P-301 is a single stage centrifugal pump that pumps cooling water to HX-301. The pump is made of Stainless Steel and has a volumetric flow rate of 1880.2 gpm .It has a pressure rise of 7.25 psi while generating a head of 16.4 ft. The electricity requirement to run the pump is 24899 BTU/hr and the pump efficiency is 0.86. The pump has a bare module cost of $30,488.

P-302 is a single stage centrifugal pump that pumps cooling water to HX-302. The pump is made of Stainless Steel and has a volumetric flow rate of 1682.3 gpm .It has a pressure rise of 7.25 psi while generating a head of 16.4 ft. The electricity requirement to run the pump is 24899 BTU/hr and the pump efficiency is 0.86. The pump has a bare module cost of $29,232.

P-303 is a single stage centrifugal pump that pumps cooling water to HX-303. The pump is made of Stainless Steel and has a volumetric flow rate of 1488.6 gpm. It has a pressure rise of 7.25 psi while generating a head of 16.4 ft. The electricity requirement to run the pump is 24899 BTU/hr and the pump efficiency is 0.86. The pump has a bare module cost of $28,300.

Section 400:

B-401 is a blower that increases the pressure of the oxygen feed for the purge in Stream 9. It increases the pressure from 100 psi to 105 psi and the temperature from 81.1 to 91.6°F. The inlet volumetric flow rate is 289,122 cuft/hr and the outlet volumetric flow rate is 280,741 cuft/hr. The blower is made of Cast Iron. The steam required to power the blower is 365 MBTU/hr which is supplied from within the process. The bare module cost of the blower is $51,806.

HX-401 is a shell and tube exchanger that serves to preheat the feed to the combustor (BLOCK NAME). The tube side goes from 1334.6°F to 1068.6°F and the shell side goes from 98.1°F to 1076°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 shell and tube pass each and the area available for heat transfer is 572 ft^2. The heat duty is 64,817 MBTU/hr. The bare module cost is $174,152 and the annual utility cost is zero because the utilities are provided from within the system.

HX-402 is a shell and tube exchanger that extracts heat from the flue gas to generate steam. The tube side goes from 4172°F to 295°F and the shell side goes from 86.1°F to 1753.7°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 shell and tube pass each and the area available for heat transfer is 3,461 ft^2. The heat duty is 354,526 MBTU/hr. The bare module cost is $350,294 and the annual utility cost is zero because the utilities are provided from within the system.

R-401 is a combustor that combusts the methane from the purge, Stream 57A, for steam generation. It is made from Cr-Mo Alloy Steel and has a bare module cost of $23,107,234.

RHX-401 is a shell and tube exchanger that extracts heat from the combustor to generate steam. The shell side temperature goes from 86.1°F to 1583.9°F. The countercurrent heat exchanger is made of stainless steel and the tubes are 20 ft in length, with the total number of tubes equaling 934. There is 1 shell and tube pass each and the area available for heat transfer is 690 ft^2. The heat duty is 505,123 MBTU/hr. The bare module cost is $156,407 and the annual utility cost is zero because the utilities are provided from within the system.

Section 500:

CT-501 is made up of 2 cooling tower units that cool water in S-506A prior to releasing it from the process in S-509. The temperature goes from 121.9°F to 86°F. The cooling towers are made of concrete, have 4,182 gpm of evaporative losses and a wet bulb temperature of 100°F. The bare module cost for the two units is $13,894,042.

HX-501 is made up of 2 shell and tube heat exchangers that condense S-502 after the T-401. The heat exchangers are made from Stainless Steel. The tubes are 20 ft in length and the area available for heat transfer is 185,587 ft^2. The heat exchangers utilize countercurrent flow, have

886 tubes each, 2 shell passes, and 4 tube passes each. The heat duty is 3,840,260 MBTU/hr. The bare module cost is $14,275,754 and the utility cost per year is zero due to utilities being supplied from within the system.

P-501A-D are identical pumps that pump cooling water in S-503A for the turbine condenser. Each pump demonstrates a pressure rise of 7.3 psi while giving a head of 16.9 ft and having a volumetric flow rate of 364,689 cuft/hr. Each pump is made of Stainless Steel, has 10 stages each, a pump efficiency of 0.86, and consumes 224 hp of power. The bare module cost for each pump is $1,473,380.

T-501 is a series of 4 steam turbines that take the steam in S-501 and convert it to electricity, with an efficiency of 0.4. The turbines operate at inlet conditions of 217.6 psi and 1252.5 °F and at outlet conditions of 7.3 psi and 184.7 °F. The turbines are made of Stainless Steel, have a power range of 26.75 MW and a speed range of 5100 rpm. The bare module cost is $30,000,000 and the annual operating cost is zero because the steam is supplied from within the process.

Section 11-Specification Sheets

Section 100:

B-101		
Block Type: Blower		
Function: Increases pressure of methane feed		
Materials:	*Inlet*	*Outlet*
Stream	FEED-A	FEED-B
Operating Conditions:		
Pressure (psi)	64.7	87
Temperature (°F)	77	129.6
Volumetric Flow Rate (ft^3/hr)	2493180	2036520
Design Data:		
Construction Material	Cast Iron	
Number of Stages	1	
Interstage Cooling	None	
Consumed Power (BTU/hr)	12,725,546	
Power Source	Steam	
Purchase Cost:	$837,526	
Bare Module Cost:	$837,526	
Annual Operating Cost:	0	

B-102		
Block Type: Blower		
Function: Increases pressure of oxygen feed		
Materials:	*Inlet*	*Outlet*
Stream	S-101A	S-101B
Operating Conditions:		
Pressure (psi)	100	105
Temperature (°F)	81.1	91.6
Volumetric Flow Rate (ft^3/hr)	1622200	1575170
Design Data:		
Construction Material	Cast Iron	
Number of Stages	1	
Interstage Cooling	None	
Consumed Power (MBTU/hr)	2,049	
Power Source	Steam	
Purchase Cost:	$199,139	
Bare Module Cost:	$199,139	
Annual Operating Cost:	0	

HX-101		
Block Type: Heat Exchanger		
Function: First preheater for methane feed		
Tube:	*Inlet*	*Outlet*
Stream	S-208	S-218
Temperature (°F)	295.8	150
Pressure (psi)	87	87
Shell:		
Stream	S-105	S-106
Temperature (°F)	129.6	286
Pressure (psi)	87	87
Operating Conditions:		
Tube Flow Rate (lb/hr)	619518	
Shell Flow Rate (lb/hr)	1152950	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	886	
Number of Tube Passes	4	
Number of Shell Passes	2	
Transfer Area (ft^2)	48986	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	14.89	
Heat Duty (MBTU/hr)	105849	
Purchase Cost:	$443,365	
Bare Module Cost:	$3,241,254	
Annual Utilities Cost:	0	

HX-102		
Block Type: Heat Exchanger		
Function: Second preheater for methane feed		
Tube:	*Inlet*	*Outlet*
Stream	S-104	S-116
Temperature (°F)	1137.6	482
Pressure (psi)	87	87
Shell:		
Stream	S-106	S-107
Temperature (°F)	286	1133.1
Pressure (psi)	87	87
Operating Conditions:		
Tube Flow Rate (lb/hr)	2042030	
Shell Flow Rate (lb/hr)	1152950	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	856	
Number of Tube Passes	8	
Number of Shell Passes	2	
Transfer Area (ft^2)	106065	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	20.51	
Heat Duty (MBTU/hr)	801852	
Purchase Cost:	$1,072,618	
Bare Module Cost:	$7,937,373	
Annual Utilities Cost:	0	

HX-103		
Block Type: Heat Exchanger		
Function: Final preheater for methane feed		
Tube:	*Inlet*	*Outlet*
Stream	S-107	S-109
Temperature (°F)	1652.3	1334.6
Pressure (psi)	217.6	217.6
Shell:		
Stream	S-108	S-117
Temperature (°F)	1133.2	1202
Pressure (psi)	87	87
Operating Conditions:		
Tube Flow Rate (lb/hr)	450382	
Shell Flow Rate (lb/hr)	1152950	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	1749	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	145	
Heat Duty (MBTU/hr)	81001	
Purchase Cost:	$33,621	
Bare Module Cost:	$240,726	
Annual Utilities Cost:	0	

HX-104		
Block Type: Heat Exchanger		
Function: First preheater for oxygen feed		
Tube:	*Inlet*	*Outlet*
Stream	S-103	S-104
Temperature (°F)	221.2	184.7
Pressure (psi)	16	16
Shell:		
Stream	S-101B	S-102B
Temperature (°F)	81.1	205
Pressure (psi)	114.7	114.7
Operating Conditions:		
Tube Flow Rate (lb/hr)		583695
Shell Flow Rate (lb/hr)		897689
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	3517	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	193	
Heat Duty (MBTU/hr)	24822	
Purchase Cost:	$48,918	
Bare Module Cost:	$342,915	
Annual Utilities Cost:	0	

HX-105		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Second preheater for oxygen feed		
Tube:	*Inlet*	*Outlet*
Stream	S-116	S-201
Temperature (°F)	*1292*	*1137.6*
Pressure (psi)	*87*	*87*
Shell:		
Stream	S-115B	S-113
Temperature (°F)	205	1202
Pressure (psi)	114.7	114.7
Operating Conditions:		
Tube Flow Rate (lb/hr)	2042030	
Shell Flow Rate (lb/hr)	897689	
Design Data:		
Construction Material	Stainless Steel/Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4020	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	348	
Heat Duty (MBTU/hr)	216868	
Purchase Cost:	$53,086	
Bare Module Cost:	$372,133	
Annual Utilities Cost:	0	

P-101		
Block Type: Pump **Function:** Pumps boiler-feed water for reactor cooling		
Materials:	*Inlet*	*Outlet*
Stream	S-115A	S-115B
Operating Conditions:		
Pressure Rise (psi)	203	
Pressure Head (ft)	456	
Flow Rate (ft^3/hr)	51456	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	5	
Pump Efficiency	0.86	
Consumed Power (hp)	884	
Power Source	Electricity	
Purchase Cost:	$208,975	
Bare Module Cost:	$208,975	
Annual Operating Cost:	0	

R-101			
Block Type: Fixed Bed Catalytic Reactor with internal shell and tube HX			
Function: facilitate Oxidative coupling of methane to form ethylene/ethane			
Materials:	*Inlet*	*Outlet*	
Stream	S-109A	S-112A	
Mass Flow (lb/hr)	514,208	514,208	
Volumetric Flow (ft^3/hr)	$5.38x10^6$	$5.42x10^6$	
Breakdown (Mass Frac):			
Methane	0.563	0.365	
Oxygen	0.436	0	
Ethylene	0.0001	0.062	
Ethane	0	0.033	
Carbon Dioxide	0	0.202	
Carbon Monoxide	0	0.032	
Water	0	0.306	
Operating Conditions	Temperature (°F)	Pressure (psi)	
	1292	87	
Interior Equipment	RHX-101		
Design Data:			
Construction Material	Stainless Steel 304	Catalyst	LiMgO
Vessel Weight (lb)	52,596	Catalyst Weight (kg)	4080
Volume (ft^3)		Catalyst Cost	$0.003545/kg
Diameter (ft)	11.5	Catalyst Life	90 days
Length (ft)	34		
Wall Thickness (in)	0.82		
Purchase Cost:	$659,932		
Bare Module Cost:	$2,012,792		
Annual Catalyst Cost:	$1,555,301		

R-102			
Block Type: Fixed Bed Catalytic Reactor with internal shell and tube HX			
Function: facilitate Oxidative coupling of methane to form ethylene/ethane			
Materials:	*Inlet*	*Outlet*	
Stream	S-109B	S-112B	
Mass Flow (lb/hr)	514,208	514,208	
Volumetric Flow (ft^3/hr)	$5.38x10^6$	$5.42x10^6$	
Breakdown (Mass Frac):			
Methane	0.563	0.365	
Oxygen	0.436	0	
Ethylene	0.0001	0.062	
Ethane	0	0.033	
Carbon Dioxide	0	0.202	
Carbon Monoxide	0	0.032	
Water	0	0.306	
Operating Conditions	Temperature (°F)	Pressure (psi)	
	1292	87	
Interior Equipment	RHX-102		
Design Data:			
Construction Material	Stainless Steel 304	Catalyst	LiMgO
Vessel Weight (lb)	52,596	Catalyst Weight (kg)	4080
Volume (ft^3)		Catalyst Cost	$0.003545/kg
Diameter (ft)	11.5	Catalyst Life	90 days
Length (ft)	34		
Wall Thickness (in)	0.82		
Purchase Cost:	$659,932		
Bare Module Cost:	$2,012,792		
Annual Catalyst Cost:	$1,555,301		

R-103			
Block Type: Fixed Bed Catalytic Reactor with internal shell and tube HX			
Function: facilitate Oxidative coupling of methane to form ethylene/ethane			
Materials:	*Inlet*	*Outlet*	
Stream	S-109C	S-112C	
Mass Flow (lb/hr)	514,208	514,208	
Volumetric Flow (ft^3/hr)	$5.38x10^6$	$5.42x10^6$	
Breakdown (Mass Frac):			
Methane	0.563	0.365	
Oxygen	0.436	0	
Ethylene	0.0001	0.062	
Ethane	0	0.033	
Carbon Dioxide	0	0.202	
Carbon Monoxide	0	0.032	
Water	0	0.306	
Operating Conditions	Temperature (°F) 1292	Pressure (psi) 87	
Interior Equipment	RHX-103		
Design Data:			
Construction Material	Stainless Steel 304	Catalyst	LiMgO
Vessel Weight (lb)	52,596	Catalyst Weight (kg)	4080
Volume (ft^3)		Catalyst Cost	$0.003545/kg
Diameter (ft)	11.5	Catalyst Life	90 days
Length (ft)	34		
Wall Thickness (in)	0.82		
Purchase Cost:	$659,932		
Bare Module Cost:	$2,012,792		
Annual Catalyst Cost:	$1,555,301		

R-104			
Block Type: Fixed Bed Catalytic Reactor with internal shell and tube HX **Function:** facilitate Oxidative coupling of methane to form ethylene/ethane			
Materials:	*Inlet*	*Outlet*	
Stream	S-109D	S-112D	
Mass Flow (lb/hr)	514,208	514,208	
Volumetric Flow (ft^3/hr)	5.38×10^6	5.42×10^6	
Breakdown (Mass Frac):			
Methane	0.563	0.365	
Oxygen	0.436	0	
Ethylene	0.0001	0.062	
Ethane	0	0.033	
Carbon Dioxide	0	0.202	
Carbon Monoxide	0	0.032	
Water	0	0.306	
Operating Conditions	Temperature (°F) 1292	Pressure (psi) 87	
Interior Equipment	RHX-104		
Design Data:			
Construction Material	Stainless Steel 304	Catalyst	LiMgO
Vessel Weight (lb)	52,596	Catalyst Weight (kg)	4080
Volume (ft^3)		Catalyst Cost	\$0.003545/kg
Diameter (ft)	11.5	Catalyst Life	90 days
Length (ft)	34		
Wall Thickness (in)	0.82		
Purchase Cost:	\$659,932		
Bare Module Cost:	\$2,012,792		
Annual Catalyst Cost:	\$1,555,301		

R-105			
Block Type: Spare Fixed Bed Catalytic Reactor with internal shell and tube HX			
Function: facilitate Oxidative coupling of methane to form ethylene/ethane			
Materials:	*Inlet*	*Outlet*	
Stream	-	-	
Mass Flow (lb/hr)	514,208	514,208	
Volumetric Flow (ft^3/hr)	$5.38x10^6$	$5.42x10^6$	
Breakdown (Mass Frac):			
Methane	0.563	0.365	
Oxygen	0.436	0	
Ethylene	0.0001	0.062	
Ethane	0	0.033	
Carbon Dioxide	0	0.202	
Carbon Monoxide	0	0.032	
Water	0	0.306	
Operating Conditions	Temperature (°F) 1292	Pressure (psi) 87	
Interior Equipment	RHX-105		
Design Data:			
Construction Material	Stainless Steel 304	Catalyst	LiMgO
Vessel Weight (lb)	52,596	Catalyst Weight (kg)	4080
Volume (ft^3)		Catalyst Cost	$0.003545/kg
Diameter (ft)	11.5	Catalyst Life	90 days
Length (ft)	34		
Wall Thickness (in)	0.82		
Purchase Cost:	$659,932		
Bare Module Cost:	$2,012,792		
Annual Catalyst Cost:	$1,555,301		

RHX-101		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Cooling in reactor to maintain isothermal temperature		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	1292	1292
Pressure (psi)	87	87
Shell:		
Stream	-	-
Temperature (°F)	217.6	1265
Pressure (psi)	217.6	217.6
Operating Conditions:		
Tube Flow Rate (lb/hr)	512659	
Shell Flow Rate (lb/hr)	851222	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4182	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	301	
Heat Duty (MBTU/hr)	1266843	
Purchase Cost:	$54,418	
Bare Module Cost:	$382,685	
Annual Utilities Cost:	0	

RHX-102		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Cooling in reactor to maintain isothermal temperature		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	1292	1292
Pressure (psi)	87	87
Shell:		
Stream	-	-
Temperature (°F)	217.6	1265
Pressure (psi)	217.6	217.6
Operating Conditions:		
Tube Flow Rate (lb/hr)	512659	
Shell Flow Rate (lb/hr)	851222	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4182	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	301	
Heat Duty (MBTU/hr)	1266843	
Purchase Cost:	$54,418	
Bare Module Cost:	$382,685	
Annual Utilities Cost:	0	

RHX-103		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Cooling in reactor to maintain isothermal temperature		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	1292	1292
Pressure (psi)	87	87
Shell:		
Stream	-	-
Temperature (°F)	217.6	1265
Pressure (psi)	217.6	217.6
Operating Conditions:		
Tube Flow Rate (lb/hr)	512659	
Shell Flow Rate (lb/hr)	851222	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4182	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	301	
Heat Duty (MBTU/hr)	1266843	
Purchase Cost:	$54,418	
Bare Module Cost:	$382,685	
Annual Utilities Cost:	0	

RHX-104		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Cooling in reactor to maintain isothermal temperature		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	1292	1292
Pressure (psi)	87	87
Shell:		
Stream	-	-
Temperature (°F)	217.6	1265
Pressure (psi)	217.6	217.6
Operating Conditions:		
Tube Flow Rate (lb/hr)	512659	
Shell Flow Rate (lb/hr)	851222	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4182	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	301	
Heat Duty (MBTU/hr)	1266843	
Purchase Cost:	$54,418	
Bare Module Cost:	$382,685	
Annual Utilities Cost:	0	

RHX-105		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Spare exchanger for cooling in reactor		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	1292	1292
Pressure (psi)	87	87
Shell:		
Stream	-	-
Temperature (°F)	217.6	1265
Pressure (psi)	217.6	217.6
Operating Conditions:		
Tube Flow Rate (lb/hr)	512659	
Shell Flow Rate (lb/hr)	851222	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4182	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	301	
Heat Duty (MBTU/hr)	1266843	
Purchase Cost:	$54,418	
Bare Module Cost:	$382,685	
Annual Utilities Cost:	0	

Section 200:

C-201		
Block Type: Compressor		
Function: Compresses gas for further separation processes		
Materials:	*Inlet*	*Outlet*
Stream	S-207A	S-207C
Operating Conditions:		
Pressure (psi)	87	290
Temperature (°F)	81.1	573.8
Volumetric Flow Rate (ft^3/hr)	4,319,060	1,833,550
Design Data:		
Construction Material	Cast-Iron/Carbon Steel	
Number of Stages	2	
Interstage Cooling	None	
Consumed Power (BTU/hr)	135,572,203	
Power Source	Steam	
Purchase Cost:	$13,642,640	
Bare Module Cost:	$31,378,071	
Annual Operating Cost:	0	

C-202		
Block Type: Compressor		
Function: Compresses gas after carbon dioxide separation		
Materials:	*Inlet*	*Outlet*
Stream	S-211	S-211A
Operating Conditions:		
Pressure (psi)	260.2	290
Temperature (°F)	104	123.2
Volumetric Flow Rate (ft^3/hr)	1,242,870	1,154,090
Design Data:		
Construction Material	Cast-Iron/Carbon Steel	
Number of Stages	1	
Interstage Cooling	None	
Consumed Power (BTU/hr)	9,146	
Power Source	Steam	
Purchase Cost:	$1,369,035	
Bare Module Cost:	$3,148,781	
Annual Operating Cost:	0	

D-201			
Block Type: Sieve Tray Distillation Tower			
Function: Separates ethane and ethylene products from rest of stream			
Materials:	*Feed*	*Distillate*	*Bottoms*
Stream	S-212	S-214	S-213
Phase	Vapor	Liquid	Liquid
Mass Flow (lb/hr)	1,011,801	816,533	195,268
Volumetric Flow (ft^3/hr)	637653	38190	7172
Temperature (°F)	-94	-170.9	-12.3
Breakdown (lb/hr)			
Breakdown (lb/hr)			
Ethane	68165	11	68154
Methane	749275	748525	749
Ethylene	127640	1276	126364
Carbon Monoxide	66720	66720	0
Operating Conditions:			
Condenser Pressure (psi)	290		
Condenser Temperature (°F)	-170.9		
Reboiler Pressure (psi)	290		
Reboiler Temperature (°F)	-12.3		
Reflux ratio	0.597		
Design Data:			
Construction Material	Monel	Tray Efficiency	0.39
Weight (lb)	98396	Number of Trays	18
Diameter (ft)	9.5	Feed Stage	8
Height (ft)	46	Tray Spacing (ft)	2

Exterior Components:	
Reboiler	DR-201
Reflux Accumulator	DA-201
Pump	RP-201
Condenser	RC-201
Purchase Cost:	$1,093,303
Bare Module Cost:	$4,548,140
Annual Operating Cost:	0

D-202			
Block Type: Sieve Tray Distillation Tower			
Function: Separates methane for recycling from carbon monoxide			
Materials:	*Feed*	*Distillate*	*Bottoms*
Stream	S-214	S-215	S-301
Phase	Liquid	Liquid	Liquid
Mass Flow (lb/hr)	816,533	66,091	750,442
Volumetric Flow (ft^3/hr)	38190	1868	37211
Temperature (°F)	-170.9	-241	-161.9
Breakdown (lb/hr)			
Ethane	68165	11	68154
Methane	749275	748525	749
Ethylene	127640	1276	126364
Carbon Monoxide	66720	66720	0
Operating Conditions:			
Condenser Pressure (psi)	290		
Condenser Temperature (°F)	-161.9		
Reboiler Pressure (psi)	290		
Reboiler Temperature (°F)	-241		
Reflux ratio	11.1		
Design Data:			
Construction Material	Monel	Tray Efficiency	0.35
Weight (lb)	257562	Number of Trays	37
Diameter (ft)	11.5	Feed Stage	8
Height (ft)	86	Tray Spacing (ft)	2
Exterior Components:			

Reboiler	DR-202
Reflux Accumulator	DA-202
Pump	RP-202
Condenser	RC-202
Purchase Cost:	$2,297,774
Bare Module Cost:	$9,558,740
Annual Operating Cost:	0

DA-201		
Block Type: Reflux accumulator of D-201		
Function: serves as distribution point for reflux and distillate		
Operating Conditions:		
Operating Pressure (psi)	290	
Temperature (°F)	-12.3	
Design Data:		
	Construction Material	Monel
	Weight (lb)	44334
	Diameter (ft)	9
	Height (ft)	20
Purchase Cost:	$332,042	
Bare Module Cost:	$1,012,729	
Annual Operating Cost:		0

DA-202		
Block Type: Reflux accumulator of D-202		
Function: serves as distribution point for reflux and distillate		
Operating Conditions:		
Operating Pressure (psi)	290	
Temperature (°F)	-161.9	
Design Data:		
	Construction Material	Monel
	Weight (lb)	67795
	Diameter (ft)	10
	Height (ft)	26
Purchase Cost:	$448,374	
Bare Module Cost:	$1,367,540	
Annual Operating Cost:	0	

DR-201		
Block Type: Heat Exchanger		
Function: Reboiler for D-201		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	39	27.3
Pressure (psi)	16	16
Shell:		
Stream	-	-
Temperature (°F)	-94	-58.5
Pressure (psi)	290	290
Operating Conditions:		
Tube Flow Rate (lb/hr)	4374730	
Shell Flow Rate (lb/hr)	1011800	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	1192	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	1397	
Heat Duty (MBTU/hr)	19449	
Purchase Cost:	$28,409	
Bare Module Cost:	$223,579	
Annual Utilities Cost:	0	

DR-202		
Block Type: Heat Exchanger		
Function: Reboiler for D-202		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	68	39
Pressure (psi)	16	16
Shell:		
Stream	-	-
Temperature (°F)	-170.9	-165.8
Pressure (psi)	290	290
Operating Conditions:		
Tube Flow Rate (lb/hr)	4374730	
Shell Flow Rate (lb/hr)	816533	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	1501	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	1139	
Heat Duty (MBTU/hr)	49613	
Purchase Cost:	$31,337	
Bare Module Cost:	$247,562	
Annual Utilities Cost:	0	

F-201			
Block Type: Flash Vessel			
Function: Removes water from the process stream			
Materials:	*Feed*	*Overhead*	*Bottoms*
Stream	S-205	S-207A	S-206
Phase	Mixed	Vapor	Liquid
Mass Flow (lb/hr)	2054789	1432676	622720
Volumetric Flow (cuft/hr)	4326610	4319060	10058.1
Breakdown (lb/hr):			
Methane	748669	749275	1.5
Ethylene	127641	127640	0.4
Ethane	68165	68165	0.1
Carbon Dioxide	415339	415313	26
Carbon Monoxide	66720	66720	0
Water	628255	5563	622691
Operating Conditions:			
Pressure (psi)	87	87	87
Temperature (°F)	27.3	27.3	27.3
Design Data:			
Construction Material	Stainless Steel		
Weight (lb)	60383		
Volume (gal)	19995		
Diameter (ft)	16.5		
Height (ft)	12.5		
Purchase Cost:	$245,142		
Bare Module Cost:	$1,019,790		
Annual Operating Cost:	0		

HX-201		
Block Type: Heat Exchanger		
Function: First cooler to assist with removal of water through flash vessel		
Tube:	*Inlet*	*Outlet*
Stream	S-201	S-202
Temperature (°F)	212	203.7
Pressure (psi)	87	87
Shell:		
Stream	S-216B	S-217
Temperature (°F)	0	129.6
Pressure (psi)	87	87
Operating Conditions:		
Tube Flow Rate (lb/hr)	2054800	
Shell Flow Rate (lb/hr)	750443	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	2606	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	154	
Heat Duty (MBTU/hr)	522823	
Purchase Cost:	$41,200	
Bare Module Cost:	$287,576	
Annual Utilities Cost:	0	

HX-202		
Block Type: Heat Exchanger		
Function: Second cooler to assist with removal of water through flash vessel		
Tube:	*Inlet*	*Outlet*
Stream	S-202	S-205
Temperature (°F)	203.7	95
Pressure (psi)	87	87
Shell:		
Stream	S-203B	S-204
Temperature (°F)	86	173.1
Pressure (psi)	21.8	21.8
Operating Conditions:		
Tube Flow Rate (lb/hr)	2042030	
Shell Flow Rate (lb/hr)	3152670	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	856	
Number of Tube Passes	8	
Number of Shell Passes	2	
Transfer Area (ft^2)	119964	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	24.6	
Heat Duty (MBTU/hr)	316905	
Purchase Cost:	$1,236,886	
Bare Module Cost:	$9,474,547	
Annual Utilities Cost:	0	

HX-203		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Cooler after the compressor		
Tube:	*Inlet*	*Outlet*
Stream	S-207C	S-209
Temperature (°F)	317.9	104
Pressure (psi)	290	209
Shell:		
Stream	S-206	S-208
Temperature (°F)	95	295.8
Pressure (psi)	87	87
Operating Conditions:		
Tube Flow Rate (lb/hr)	1422510	
Shell Flow Rate (lb/hr)	615918	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	886	
Number of Tube Passes	4	
Number of Shell Passes	2	
Transfer Area (ft^2)	90510	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	7.5	
Heat Duty (MBTU/hr)	145141	
Purchase Cost:	$886,891	
Bare Module Cost:	$6,793,585	
Annual Utilities Cost:	0	

HX-204		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Cools inlet into column		
Tube:	*Inlet*	*Outlet*
Stream	S-211	S-212
Temperature (°F)	104	-64
Pressure (psi)	290	290
Shell:		
Stream	S-216	S-216A
Temperature (°F)	-161.9	-161.4
Pressure (psi)	290	290
Operating Conditions:		
Tube Flow Rate (lb/hr)	998432	
Shell Flow Rate (lb/hr)	750443	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4745	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	109	
Heat Duty (MBTU/hr)	102776	
Purchase Cost:	$59,016	
Bare Module Cost:	$474,489	
Annual Utilities Cost:	0	

RC-201		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Condenser heat exchanger for D-201		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	-94	-113.4
Pressure (psi)	290	290
Shell:		
Stream	-	-
Temperature (°F)	-255.9	-177.55
Pressure (psi)	16	16
Operating Conditions:		
Tube Flow Rate (lb/hr)	14778500	
Shell Flow Rate (lb/hr)	1591570	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	9706	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	1042	
Heat Duty (MBTU/hr)	196335	
Purchase Cost:	$98,662	
Bare Module Cost:	$803,109	
Annual Utilities Cost:	0	

RC-202		
IDENTIFICATION: Heat Exchanger		
FUNCTION: Condenser heat exchanger for D-202		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	-170.8	-209.7
Pressure (psi)	290	290
Shell:		
Stream	-	-
Temperature (°F)	-255.9	-255.9
Pressure (psi)	16	16
Operating Conditions:		
Tube Flow Rate (lb/hr)	1099410	
Shell Flow Rate (lb/hr)	1591570	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	4721	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	225	
Heat Duty (MBTU/hr)	45006	
Purchase Cost:	$58,821	
Bare Module Cost:	$472,921	
Annual Utilities Cost:	0	

RP-201		
Block Type: Pump		
Function: Pumps liquid propane for cooling in D-201		
Materials:	*Inlet*	*Outlet*
Stream	-	-
Operating Conditions:		
Pressure Rise (psi)	42	
Pressure Head (ft)	96	
Flow Rate (cuft/hr)	22814	
Design Data:		
Construction Material	Monel	
Number of Stages	1	
Pump Efficiency	0.86	
Consumed Power (hp)	89	
Power Source	Electricity	
Purchase Cost:	$8,050	
Bare Module Cost:	$66,539	
Annual Operating Cost:	0	

RP-202		
Block Type: Pump		
Function: Pumps liquid propane for cooling in D-202		
Materials:	*Inlet*	*Outlet*
Stream	-	-
Operating Conditions:		
Pressure Rise (psi)	59.6	
Pressure Head (ft)	137	
Flow Rate (cuft/hr)	20697	
Design Data:		
Construction Material	Monel	
Number of Stages	2	
Pump Efficiency	0.86	
Consumed Power (hp)	3169	
Power Source	Electricity	
Purchase Cost:	$7,974	
Bare Module Cost:	$287,861	
Annual Operating Cost:	0	

P-201		
Block Type: Pump **Function:** Pumps cooling water		
Materials:	*Inlet*	*Outlet*
Stream	S-203A	S-203B
Operating Conditions:		
Pressure Rise (psi)	7.3	
Pressure Head (ft)	16.9	
Flow Rate (ft^3/hr)	35376	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	5	
Pump Efficiency	0.86	
Consumed Power (hp)	107	
Power Source	Electricity	
Purchase Cost:	$74,170	
Bare Module Cost:	$467,270	
Annual Operating Cost:	0	

ST-201	
Block Type: Storage Tank	
Number of Units: 6	
Function: Store Products	
Materials:	
Mass Fraction:	
Ethane	0.3491
Ethylene	0.6472
Methane	0.0038
Operating Conditions:	
Pressure (psi)	290
Temperature (°F)	0
Design Data:	
Construction Material	Stainless Steel
Volume (cuft)	86048
Diameter (ft)	90.7
Purchase Cost:	$ 9,572,202
Bare Module Cost:	$ 9,572,203
Annual Operating Cost:	$ -

ST-202	
Block Type: Storage Tank	
Number of Units: 1	
Function: Store Products	
Materials:	
Mass Fraction:	
Carbon Monoxide	0.999444
Methane	0.000556
Operating Conditions:	
Pressure (psi)	290
Temperature (°F)	-241
Design Data:	
Construction Material	Stainless Steel
Volume (cuft)	89656
Diameter (ft)	84.5
Purchase Cost:	$ 1,647,316.00
Bare Module Cost:	$ 1,647,316.00
Annual Operating Cost:	$ 0

V-201				
Block Type: Vertical Pressure Vessels **Number of Units:** 13 **Function:** Separates out carbon dioxide through pressure swing adsorption				
Materials:	*Inlet*	*Outlet 1*	*Outlet 2*	
Stream	S-209	S-210	S-211	
Mass Flow (lb/hr)	1432680	420877	1011800	
Volumetric Flow (ft^3/hr)	1833550	266680	1564780	
Breakdown (lb/hr):				
Methane	835739	0	835739	
Ethylene	127640	0	127640	
Ethane	68164	0	68164	
Carbon Dioxide	415315	415315	0	
Carbon Monoxide	66720.39	0	66720.39	
Water	6020	6020	0	
Operating Conditions:				
Temperature(°F)	96.8			
Pressure (psi)	290			
Design Data:				
Construction Material	Low-alloy Steel	Catalyst	Zeolite 13X	Activated Alumina
Vessel Weight (lbs)	151112	Catalyst Diameter (mm)	3	1.6
Diameter (ft)	12.5	Catalyst Weight (lb)	1092054	3220
Length (ft)	39	Catalyst Cost	2548562	3150
Wall Thickness (in)	1.899	Catalyst Life (yr)	3	3
Purchase Cost:	$339,710			
Bare Module Cost:	$1,413,195			
Annual Catalyst Cost:	$850,571			

Section 300:

C-301		
Block type: Compressor		
Function: Compress Methane for Refrigeration		
Materials:	*Inlet*	*Outlet*
Stream	S-301	S-302
Operating Conditions:		
Pressure (psi)	16.0	188.5
Temperature (°F)	68.0	280.7
Volumetric Flow Rate (ft^3/hr)	34,580,000	3,860,000
Design Data:		
Construction Material	Cast Iron	
Number of Stages	5	
Interstage Cooling	None	
Consumed Power (hp)	149650	
Power Source	Steam	
Purchase Cost:	$ 7,378,265.00	
Bare Module Cost:	$ 80,363,270.00	
Annual Operating Cost:	0	

C-302		
Block Type: Compressor		
Function: Compress Ethylene for Refrigeration Cycle		
Materials:	*Inlet*	*Outlet*
Stream	S-307	S-308
Operating Conditions:		
Pressure (psi)	16	304.5
Temperature (°F)	-31	382.3
Volumetric Flow Rate (ft^3/hr)	21,900,000	2,240,000
Design Data:		
Construction Material	Nickel Alloy	
Number of Stages	5	
Interstage Cooling	None	
Consumed Power (hp)	140551	
Power Source	Steam	
Purchase Cost:	$ 37,378,265.00	
Bare Module Cost:	$ 80,363,270.00	
Annual Operating Cost:	0	

C-303		
Block Type: Compressor		
Function: Compress Methane for Refrigeration Cycle		
Materials:	*Inlet*	*Outlet*
Stream	S-312	S-313
Operating Conditions:		
Pressure (psi)	16	478.6
Temperature(°F)	-139	385.4
Volumetric Flow Rate (ft^3/hr)	21,100,000	1,880,000
Design Data:		
Construction Material	Nickel Alloy	
Number of Stages	5	
Interstage Cooling	None	
Consumed Power (HP)	180537	
Power Source	Steam	
Purchase Cost:	$	37,378,265.00
Bare Module Cost:	$	80,363,270.00
Annual Operating Cost:	$	-

F-301			
Block Type: Flash **Function:** Separate Vapor and Liquid Phases			
Materials:	*Feed*	*Overhead*	*Bottoms*
Stream	S-306	S-306A	S-306B
Phase	MIX	VAP	LIQ
Mass Flow (lb/hr)	4,374,730	2,053,463	2,316,100
Volumetric Flow (L/hr)	361,000,000	3,380,000	361,000,000
Breakdown Mass Frac:			
Ethylene	0	0	0
Methane	0	0	0
Propane	1	1	1
Water	0	0	0
Operating Conditions:			
Pressure (psi)	16	16	16
Temperature (°F)	-39.8	-39.8	-39.8
Equilibirium	Vapor-Liquid Equilibrium		
Design Data:			
Construction Material	Monel-400		
Weight (lb)	126812		
Volume (gal)	113292		
Diameter (ft)	25.5		
Height (ft)	27.5		
Purchase Cost:	$ 719,612.00		
Bare Module Cost:	$ 2,194,819.00		
Annual Operating Cost:	0		

F-302			
Block Type: Flash **Function:** Separate Liquid and Vapor Phases			
Materials:	*Feed*	*Overhead*	*Bottoms*
Stream	S-318	S-318A	S-318B
Phase	MIX	VAP	LIQ
Mass Flow (lb/hr)	2,160,000.00	799,000.00	1,360,800.00
Volumetric Flow (L/hr)	164,323,000.00	164,323,000.00	1,714,000.00
Breakdown Mass Frac:			
Ethylene	1	1	1
Methane	0	0	0
Propane	0	0	0
Water	0	0	0
Operating Conditions:			
Pressure (psi)	16	16	16
Temperature(°F)	-151.7	-151.7	-151.7
Equilibirium	Vapor-Liquid Equilibrium		
Design Data:			
Construction Material	Monel-400		
Weight (lb)	63662		
Volume (gal)	56298		
Diameter (ft)	18.5		
Height (ft)	28		
Purchase Cost:	$ 428,865.00		
Bare Module Cost:	$ 1,308,040.00		
Annual Operating Cost:	0		

F-303			
Block Type: Flash			
Function: Separate Vapor and Liquid Phases			
Materials:	*Feed*	*Overhead*	*Bottoms*
Stream	S-326	S-326A	S-326B
Phase	MIX	VAP	LIQ
Mass Flow (lb/hr)	1,591,570	795,785	791,010
Volumetric Flow (L/hr)	187,650,000	188,000,000	59,714
Breakdown Mass Frac:			
Ethylene	0	0	0
Methane	1	1	1
Propane	0	0	0
Water	0	0	0
Operating Conditions:			
Pressure (psi)	15.9	15.9	15.9
Temperature(°F)	-256	-256	-256
Equilibirium	Vapor-Liquid Equilibrium		
Design Data:			
Construction Material	Monel-400		
Weight (lb)	126812		
Volume (gal)	57263		
Diameter (ft)	28.5		
Height (ft)	12		
Purchase Cost:	$ 719,612.00		
Bare Module Cost:	$ 2,194,819.00		
Annual Operating Cost:	0		

HX-301		
Block Type: Heat Exchanger in Parallel		
Function: Cool Stream S-302 for Expansion		
Tube:	*Inlet*	*Outlet*
Stream	S-302	S-305
Temperature (°F)	280.7	99
Pressure (psi)	188.5	188.5
Shell:		
Stream	S-303	S-304
Temperature (°F)	81.1	178
Pressure (psi)	14.5	14.5
Operating Conditions:		
Tube Flow Rate (lb/hr)	4,374,730	
Shell Flow Rate (lb/hr)	900,764	
Design Data:		
Construction Material	Stainless Steel/Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	982	
Number of Tube Passes	6	
Number of Shell Passes	2	
Transfer Area (ft^2)	144,493	
Overall Heat Transfer Coefficient ($Btu/hr\text{-}ft^2\text{-}R$)	149.6	
Heat Duty (MBTU/hr)	145,000	
Purchase Cost:	$ 4,974,734.00	
Bare Module Cost:	$ 33,330,717.00	
Annual Utilities Cost:	$ 4,464,489.04	

HX-302		
Block Type: Heat Exchanger in Parallel		
Function: Cool Stream S-308 for Expansion		
Tube:	*Inlet*	*Outlet*
Stream	S-308	S-311
Temperature (°F)	382.3	87.8
Pressure (psi)	304.56	304.56
Shell:		
Stream	S-309	S-310
Temperature (°F)	81.1	215.7
Pressure (psi)	14.5	14.5
Operating Conditions:		
Tube Flow Rate (lb/hr)	2,160,000	
Shell Flow Rate (lb/hr)	794,338	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	982	
Number of Tube Passes	6	
Number of Shell Passes	2	
Transfer Area (ft^2)	143,493	
Overall Heat Transfer Coefficient ($Btu/hr\text{-}ft^2\text{-}R$)	151.6	
Heat Duty (MBTU/hr)	149,500	
Purchase Cost:	$ 4,974,734	
Bare Module Cost:	$ 33,330,717	
Annual Utilities Cost:	$ 3,937,006	

HX-303		
Block Type: Heat Exchanger in Parallel		
Function: Cool Stream S-313 for Expansion		
Tube:	*Inlet*	*Outlet*
Stream	S-313	S-316
Temperature (°F)	385.3	86
Pressure (psi)	478.6	478.6
Shell:		
Stream	S-314	S-315
Temperature (°F)	81.1	215.7
Pressure (psi)	14.5	14.5
Operating Conditions:		
Tube Flow Rate (lb/hr)	1,591,570	
Shell Flow Rate (lb/hr)	714,904	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	982	
Number of Tube Passes	6	
Number of Shell Passes	2	
Transfer Area (ft^2)	140,562	
Overall Heat Transfer Coefficient (Btu/hr-ft^2-R)	154	
Heat Duty (MBTU/hr)	148,950	
Purchase Cost:	$ 4,974,734	
Bare Module Cost:	$ 33,330,717	
Annual Utilities Cost:	$ 3,543,304	

HX-304		
Block Type: Heat Exchanger		
Function: Cool Stream S-311 for Expansion		
Tube:	*Inlet*	*Outlet*
Stream	S-311	S-317
Temperature (°F)	87.8	-31
Pressure (psi)	304.5	304.5
Shell:		
Stream	S-306	S-319
Temperature (°F)	-39.8	-39.8
Pressure (psi)	16	16
Operating Conditions:		
Tube Flow Rate (lb/hr)	2,160,000	
Shell Flow Rate (lb/hr)	4,370,000	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	982	
Number of Tube Passes	6	
Number of Shell Passes	2	
Transfer Area (ft^2)	111,249	
Overall Heat Transfer Coefficient (Btu/hr-ft^2-R)	149.6	
Heat Duty (MBTU/hr)	422,000	
Purchase Cost:	$ 1,131,677	
Bare Module Cost:	$ 8,261,242	
Annual Utilities Cost:	0	

HX-305		
Block Type: Heat Exchanger		
Function: Cool Stream S-316 for Expansion		
Tube:	*Inlet*	*Outlet*
Stream	S-316	S-320
Temperature (°F)	86	-31
Pressure (psi)	478.6	478.6
Shell:		
Stream	S-319	S-321
Temperature (°F)	-39.8	-39.8
Pressure (psi)	16	16
Operating Conditions:		
Tube Flow Rate (lb/hr)	1,591,000	
Shell Flow Rate (lb/hr)	4,370,000	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	914	
Number of Tube Passes	1	
Number of Shell Passes	2	
Transfer Area (ft^2)	23,782	
Overall Heat Transfer Coefficient ($Btu/hr\text{-}ft^2\text{-}R$)	149.6	
Heat Duty (MBTU/hr)	110,600	
Purchase Cost:	$ 165,595	
Bare Module Cost:	$ 1,208,844	
Annual Utilities Cost:	0	

HX-306		
Block Type: Heat Exchanger		
Function: Cool Stream S-320 for Expansion		
Tube:	*Inlet*	*Outlet*
Stream	S-320	S-325
Temperature (°F)	-31	-148
Pressure (psi)	478.6	478.6
Shell:		
Stream	S-318	S-323
Temperature (°F)	-151.7	-91.6
Pressure (psi)	16	16
Operating Conditions:		
Tube Flow Rate (lb/hr)	1,590,000	
Shell Flow Rate (lb/hr)	2,160,000	
Design Data:		
Construction Material	Monel/Monel	
Flow Direction	Countercurrent	
Number of Tubes	982	
Number of Tube Passes	8	
Number of Shell Passes	2	
Transfer Area (ft^2)	113,869	
Overall Heat Transfer Coefficient ($Btu/hr\text{-}ft^2\text{-}R$)	149.6	
Heat Duty (MBTU/hr)	322,000	
Purchase Cost:	$ 1,169,530	
Bare Module Cost:	$ 8,537,569	
Annual Utilities Cost:	0	

P-301		
Block Type: Pump		
Function: Pump Cooling Water to HX-301		
Materials:	*Inlet*	*Outlet*
Stream	S-303A	S-303B
Operating Conditions:		
Pressure Rise (psi)	7.25	
Pressure Head (ft)	16.4	
Flow Rate (gpm)	1880.2	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	0.86	
Consumed Power (BTU/hr)	24899.1	
Power Source	Electricity	
Purchase Cost:	$4,833.00	
Bare Module Cost:	$30,488.00	
Annual Operating Cost:	0	

P-302		
Block Type: Pump		
Function: Pump Cooling Water to HX-302		
Materials:	*Inlet*	*Outlet*
Stream	S-309A	S-309B
Operating Conditions:		
Pressure Rise (psi)	7.25	
Pressure Head (ft)	16.4	
Flow Rate (gpm)	1682.3	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	0.86	
Consumed Power (BTU/hr)	22116.1	
Power Source	Electricity	
Purchase Cost:	$ 4,640.00	
Bare Module Cost:	$ 29,232.00	
Annual Operating Cost:	0	

P-303		
Block Type: Pump **Function:** Pump Cooling Water to HX-303		
Materials:	*Inlet*	*Outlet*
Stream	S-314A	S-314B
Operating Conditions:		
Pressure Rise (psi)	7.25	
Pressure Head (ft)	16.4	
Flow Rate (gpm)	1488.6	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	0.86	
Consumed Power (BTU/hr)	20071.8	
Power Source	Electricity	
Purchase Cost:	$4,492.00	
Bare Module Cost:	$28,300.00	
Annual Operating Cost:	0	

Section 400:

B-401		
Block Type: Blower		
Function: Increases pressure of oxygen feed for purge		
Materials:	*Inlet*	*Outlet*
Stream	S-402	S-402A
Operating Conditions:		
Pressure (psi)	100	105
Temperature (°F)	81.1	91.6
Volumetric Flow Rate (ft^3/hr)	289122	280741
Design Data:		
Construction Material	Cast Iron	
Number of Stages	1	
Interstage Cooling	None	
Consumed Power (MBTU/hr)	365	
Power Source	Steam	
Purchase Cost:	$51,806	
Bare Module Cost:	$51,806	
Annual Operating Cost:	0	

R-401		
Block Type: Combustor		
Function: Combusts purge methane for steam generation		
Materials:	*Inlet*	*Outlet*
Stream	S-404	S-408
Mass Flow (lb/hr)	196249	196249
Volumetric Flow (ft^3/hr)	358300	139569
Breakdown (lb/hr):		
Methane	37424.39	374.2439
Oxygen	158727	10926.84
Ethylene	63.81904	63.81904
Ethane	0.5322281	0.5322281
Carbon Dioxide	0	101639
Carbon Monoxide	33.36018	33.36018
Water	0	83211.22
Operating Conditions:		
Duty	0	
Pressure (psi)	114.7	
Design Data:		
Construction Material	Cr-Mo Alloy Steel	
Purchase Cost:	$8,921,712	
Bare Module Cost:	$23,107,234	
Annual Operating Cost:	0	

HX-401		
Block Type: Heat Exchanger		
Function: Preheats the feed to the combustor		
Tube:	*Inlet*	*Outlet*
Stream	S-117	S-405
Temperature (°F)	1334.6	1068.6
Pressure (psi)	217.6	217.6
Shell:		
Stream	S-403	S-404
Temperature (°F)	98.1	1076
Pressure (psi)	87	87
Operating Conditions:		
Tube Flow Rate (lb/hr)	450382	
Shell Flow Rate (lb/hr)	196848	
Internal Components:	RHX-401	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	572	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	353	
Heat Duty (MBTU/hr)	64817	
Purchase Cost:	$24,563	
Bare Module Cost:	$174,152	
Annual Utilities Cost:	0	

HX-402		
Block Type: Heat Exchanger		
Function: Extracts heat from flue gas to generate steam		
Tube:	*Inlet*	*Outlet*
Stream	S-408	S-411
Temperature (°F)	4172	295
Pressure (psi)	114.7	114.7
Shell:		
Stream	S-410D	S-412
Temperature (°F)	86.1	1753.7
Pressure (psi)	217.6	217.6
Operating Conditions:		
Tube Flow Rate (lb/hr)	196848	
Shell Flow Rate (lb/hr)	180153	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	3461	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	26	
Heat Duty (MBTU/hr)	354526	
Purchase Cost:	$48,450	
Bare Module Cost:	$350,294	
Annual Utilities Cost:	0	

P-401		
Block Type: Pump		
Function: Pumps boiler-feed water for combustor		
Materials:	*Inlet*	*Outlet*
Stream	S-410A	S-410B
Operating Conditions:		
Pressure Rise (psi)	203	
Pressure Head (ft)	473	
Flow Rate (ft^3/hr)	7294	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	0.76	
Consumed Power (hp)	141	
Power Source	Electricity	
Purchase Cost:	$6,917	
Bare Module Cost:	$43,578	
Annual Operating Cost:	0	

RHX-401		
Block Type: Heat Exchanger		
Function: Extracts heat from the combustor to generate steam		
Tube:	*Inlet*	*Outlet*
Stream	-	-
Temperature (°F)	4172	4172
Pressure (psi)	114.7	114.7
Shell:		
Stream	-	-
Temperature (°F)	86.1	1583.9
Pressure (psi)	217.6	217.6
Operating Conditions:		
Tube Flow Rate (lb/hr)	196848	
Shell Flow Rate (lb/hr)	270229	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	934	
Number of Tube Passes	1	
Number of Shell Passes	1	
Transfer Area (ft^2)	690	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	488	
Heat Duty (MBTU/hr)	505123	
Purchase Cost:	$22,154	
Bare Module Cost:	$156,407	
Annual Utilities Cost:	0	

Section 500:

CT-501		
Block Type: Cooling Tower **Number of Units:** 2 **Function:** Cool Water Prior to Outlet		
Materials:		
	Inlet	*Outlet*
Stream	S-506A	S-509
Operating Conditions:		
Temperature (°F)	121.9	86
Flow Rate (GPM)	209082	209082
Design Data:		
Construction Material	Concrete	
Evaporation Losses (gpm)	4182	
Wet Bulb (°F)	85	
Purchase Cost:	$ 13,894,042	
Bare Module Cost:	$ 13,894,042	
Annual Operating Cost:	$ 0	

HX-501		
Block Type: Heat Exchanger		
Number of Units: 2		
Function: Condenser after turbine		
Tube:	*Inlet*	*Outlet*
Stream	S-502	S-504
Temperature (°F)	184.7	95
Pressure (psi)	7.3	7.3
Shell:		
Stream	S-503B	S-505
Temperature (°F)	86	123
Pressure (psi)	21.8	21.8
Operating Conditions:		
Tube Flow Rate (lb/hr)	2042030	
Shell Flow Rate (lb/hr)	10809200	
Design Data:		
Construction Material	Stainless Steel/Stainless Steel	
Flow Direction	Countercurrent	
Number of Tubes	886	
Number of Tube Passes	4	
Number of Shell Passes	2	
Transfer Area (ft^2)	185587	
Overall Heat Transfer Coefficient (BTU/hr R ft^2)	230	
Heat Duty (MBTU/hr)	3840260	
Purchase Cost:	$,2175,004	
Bare Module Cost:	$14,275,754	
Annual Utilities Cost:	0	

P-501A		
Block Type: Pump **Function:** Pumps cooling water for turbine condenser		
Materials:	*Inlet*	*Outlet*
Stream	S-503AA	S-503BA
Operating Conditions:		
Pressure Rise (psi)	7.3	
Pressure Head (ft)	16.9	
Flow Rate (cuft/hr)	364689	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages		10
Pump Efficiency		0.86
Consumed Power (hp)		224
Power Source	Electricity	
Purchase Cost:		$233,870
Bare Module Cost:		$1,473,380
Annual Operating Cost:		0

P-501B		
Block Type: Pump **Function:** Pumps cooling water for turbine condenser		
Materials:	*Inlet*	*Outlet*
Stream	S-503AB	S-503BB
Operating Conditions:		
Pressure Rise (psi)	7.3	
Pressure Head (ft)	16.9	
Flow Rate (cuft/hr)	364689	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages		10
Pump Efficiency		0.86
Consumed Power (hp)		224
Power Source	Electricity	
Purchase Cost:		$233,870
Bare Module Cost:		$,1473,380
Annual Operating Cost:		0

P-501C		
Block Type: Pump **Function:** Pumps cooling water for turbine condenser		
Materials:	*Inlet*	*Outlet*
Stream	S-503AC	S-503BC
Operating Conditions:		
Pressure Rise (psi)	7.3	
Pressure Head (ft)	16.9	
Flow Rate (cuft/hr)	364689	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages		10
Pump Efficiency		0.86
Consumed Power (hp)		224
Power Source	Electricity	
Purchase Cost:		$233,870
Bare Module Cost:		$1,473,380
Annual Operating Cost:		0

P-501D		
Block Type: Pump **Function**: Pumps cooling water for turbine condenser		
Materials:	*Inlet*	*Outlet*
Stream	S-503AD	S-503BD
Operating Conditions:		
Pressure Rise (psi)	7.3	
Pressure Head (ft)	16.9	
Flow Rate (cuft/hr)	364689	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages		10
Pump Efficiency		0.86
Consumed Power (hp)		224
Power Source	Electricity	
Purchase Cost:		$233,870
Bare Module Cost:		$1,473,380
Annual Operating Cost:		0

T-501		
Block Type: Turbine **Number of Units:** 4 **Function:** Convert Steam to Electricity		
Materials:		
	Inlet	*Outlet*
Stream	S-501	S-502
Operating Conditions:		
Pressure (psi)	217.6	7.3
Temperature (°F)	1252.5	184.7
Design Data:		
Construction Material	Stainless Steel	
Power Range (MW)	26.75	
Speed Range (rpm)	5100	
Turbine Efficiency	0.4	
Power Source	Electricity	
Purchase Cost:	$ 7,500,000	
Bare Module Cost:	$ 30,000,000	
Annual Operating Cost:	0	

Section 12- Conclusions and Reccomendations

Reccomendations

Several key assumptions are inherent in this process's design. First, all reactor yields and selectivity come from lab-scale experiments and examples in literature. Second, the economic analysis assumes a constant price of raw materials and that the 20 cent price spread between ethylene and ethane will hold constant. Therefore, the most critical recommendation for this plant to be profitiable is the design of a catalyst that achieves a conversion of methane while also increasing the selectively to ethylene and ethane. This catalyst would enable the oxidative coupling of methane to directly compete with the traditional production of ethylene through steam cracking. The bulk of the costs and energy within the process is spent separating the products and recycling the methane back into the system for increased conversion. If scientists in catalysis were able to isolate a catalyst that could significantly increase methane conversion and C_2 selectivity in combination, a recycle would be rendered obsolete and an OCM ethylene plant like this would save millions in capital investment.

Another recommendation concerns the development of membrane reactors and separators in the near future. The process chosen was modeled through a fixed bed reactor that had markedly smaller conversions and selectivity compared to membrane reactors used in the oxidative coupling of methane. These membranes have not yet been fully developed for mass-production, but harbor strong potential for the future. Alongside this development are membranes capable of eliminating the need for cryogenic separation to selectively remove either the products or byproducts to achieve the purity required.

Conclusions

The process of converting methane from natural gas to ethylene and ethane through OCM is currently marginally profitable with an ROI of 6.79% over a plant lifetime of twenty years. Due to the large scale of the plant, capital costs are extremely high, with permanent total investment totaling more than one billion dollars. However, by producing all of the steam and electricity requirements for the process and having minimal cooling water requirements, both a function of closely managed heat integration, operating costs are kept to a minimum. Therefore, the profitability is most sensitive to changes in the prices of ethylene, ethane, and methane.

The greatest expense by far of this design is the refrigeration process, with the compressors and heat exchangers alone costing close to $400 million and consuming the majority of the steam produced. Therefore, increasing the efficiency or reducing the size of these components is the most likely design strategy for increasing profitability. Also, small deviations to the method in which these components were priced can have a marked impact on the profitability.

This process is similar in terms of cost to current ethylene plants, but is less profitable than traditional steam cracking. This may change in the future though. Due to the growing abundance of natural gas, its price has been dropping in recent years and will likely continue to do so. Also, because the majority of ethylene is produced from steam cracking and larger hydrocarbons have been either stable or increasing in prices recently, the prices of ethylene have been going up. Therefore, in the future, this plant design may prove to be more profitable.

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Appendix

Appendix Table of Contents

- **I. Sample Calculations**
- **II. Problem Statement**
- **III. Selected Aspen Block Reports**
- **IV. MSDS Reports**
- **V. Bibliography**

I. Sample Calculations

Example Calculations

Chemistry

ECC-001: Heat of Reaction

The amount of energy available from the OCM and the combustion reaction utilizes the enthalpies of formation and combustion. The methane combusted to produce steam that enters the turbine provides a large amount of energy to the overall process. This brief calculation confirms that no outside steam will be necessary during plant operation

Equation

$$Q = m\Delta H_{comb}$$

$$Q = 104.4 * 10^3 \frac{Btu}{lb} * 37{,}430 \frac{lb}{hr}$$

$$Q = 3.90 * 10^9 \frac{Btu}{hr}$$

ECC-002: Mass of Catalyst Needed

$$Space\ Time\ Yield\ (STY) = 4.19 * 10^4 \frac{Kg\ of\ C_2}{Kg\ of\ LiMgO * Yr}$$

$$\frac{6.94*10^8\ Kg\ of C_2}{4.19^4 \left(\frac{Kg\ of\ C_2}{Kg\ of\ LiMgO*Yr}\right)} = 16320\ Kg\ of\ LiMgO$$

$$Price\ of\ Catalyst = \frac{\$0.003545}{Kg\ of\ Lithium}$$

$$Total\ Cost = \frac{\$0.003545}{Kg\ of\ Lithium} * 16320\ Kg\ of\ LiMgO = \$57.8$$

Equipment

ECE-001: Sizing Fired Heater

Fired heaters are priced using criteria set forth in SSLW and the heat duties. The equations for the combustion of methane are provided below. Prices were modified for materials and the chemical engineering index.

Equations

$C_P = 0.367Q^{.77}$ Carbon Steel P<20 atm

$C_P = 0.367(3.90 * 10^9)^{.77} = \$8{,}921{,}711$

$C = F_m C_P C_E$

$C = 2.58 * \$25{,}585 * \left(\frac{570}{500}\right) = \$23{,}018{,}014$

ECE-002: Sizing Storage Vessels

The basic requirements of storage are to hold 3 days of product. The flow rate of product is equal to 1,870 ft^3 per hour, leading to a volume need of 134,640 ft^3 or 1 million gallons of storage. The maximum capacity of a spherical storage tank is 750,000 gallons.

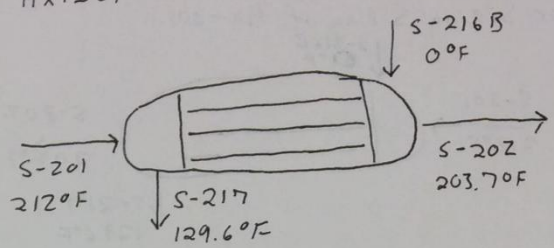
Equations

$C = C_E * 265V^{.51}$ (Spherical, 0-100 psig)

$C = \frac{570}{500} * 265 * (750{,}000)^{.51} = \$299{,}524$

Heat Exchanger Sizing: Sizing HX-201

Heat Exchanger Sizing HX-201



$T_{min} = 50°F$ = heuristic 26

$\dot{Q} = 532823$ MBTU/hr

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln \Delta T_1 / \Delta T_2} = 134°F$$

$$S = \frac{T_{out\,c} - T_{in\,c}}{T_{in\,h} - T_{out\,h}} = 15.625$$

$$R = \frac{T_{in\,h} - T_{out\,h}}{T_{out\,c} - T_{in\,c}} = 0.064$$

$$F_T = \frac{\sqrt{R^2+1}\,\ln\left(\frac{1-S}{1-RS}\right)}{(R-1)\ln\left(\frac{2-S(R+1-\sqrt{R^2+1})}{2-S(R+1+\sqrt{R^2+1})}\right)} = 10 > 0.85$$

$$UA = \frac{Q}{F_T \Delta T_{lm}} = 401324 \frac{Btu}{h°F}$$

U EST: SSLW Table 18.5 → $U < 200 \frac{Btu}{ft^2 \cdot h \cdot F}$ for water HX

$U = 154 \frac{BTU}{ft^2\,hr\,R}$, Guess

$A = \underline{2{,}606\ ft^2}$, Approximate Size

Cost:

$C_B = \exp(11.9052 - 0.8709 \ln(2606) + 0.09005 \ln(2606)^2) = \$41{,}200$

$F_M = 2.70 + \left(\frac{2606}{100}\right)^{0.07} = 4.07$

$F_L = 1$, 20 ft tubes

$F_P = 0.9803 + 0.018\left(\frac{96}{100}\right) + 0.0817\left(\frac{96}{100}\right)^2 = 1.00$

P = 96 PSIG

$\tilde{C}_P = \$41{,}200(4.07)(1)(1.00) = \$167{,}684$

$C_P = \$167{,}684\left(\frac{570}{500}\right) = \underline{\$217{,}989}$

II. Problem Statement

1. Basic Chemicals from Natural Gas: Oxidative Coupling
(recommended by Gary Sawyer, Consultant – formerly ARCO, Lyondell-Basell)

Background
The recent development of US natural gas reserves has provided an historic opportunity for natural gas as a source of basic chemicals. "The opportunity to transition from oil to natural gas as the foundation of our daily lives...echoes the wood-to-coal transition in the 19th century, and coal-to-oil in the 20th." (Dr. Alex Tkachenko) Oxidative coupling of methane (OCM) is a very active area for research and venture capital working to achieve this transition.

The basic chemistry is:
$CH_4 + ½ O_2 \rightarrow ½ C_2H_4 + H_2O$

However, the partial or total oxidation to CO or CO_2 is thermodynamically favored; thus a catalyst is needed to control the reaction kinetically such that reasonable yields to ethylene are obtained. Ethylene is the most important building block in the petrochemical industry. Over 50 billion lb/yr are produced in the US alone by steam cracking of various hydrocarbon feedstocks. (Dan Lippe, 2013). A number of catalysts have been researched under various operating conditions, as per the references below. A simplified schematic of the process with important design parameters is given in Figure 1 below.

Deliverables and Scope of Work
Your firm, Process Evaluation, Inc has been contracted by a major ethylene producer to develop a process model and economics that will guide their research on OCM catalyst. At each step below, review your findings with your stakeholders (in your case, faculty and industrial consultants).

1)Review literature and set ranges on model inputs.Determine a suitable range of parameters for the table in Figure 1 based on your review of the references below. Also, select a set of conditions that you believe are achievable targets and use these as a base case in your economic analysis. However, do not over-constrain the material balance calculations (for example, the CH_4:O_2 ratio must be at no more than 5/1 for the reaction results in the "typical" column of the table in Figure 1, or else there is insufficient oxygen.
2)Create a simplified model.Develop one or more block flow diagrams in Excel with material balances that update with changing assumptions. Determine viable separation techniques for the reaction products (that is, expand on the simple "separations" block above). Assess which streams can be recycled, or how they are disposed of. The final product will be a mixture of ethane and ethylene, free of moisture, which is sold to an ethylene producer who will produce on-spec ethylene in their existing distillation train. Perform an economic analysis and summarize yourresults. At this stage, we are only considering the raw material costs.Energy, fixed costs, and investment will come later.

3)Develop a flowsheet. Choose a design from step 2 to develop into a more detailed

flowsheet. In this flowsheet, you will:
a.Prepare a Process Flow Diagram showing major equipment such as vessels, heat exchangers, and pumps.
b.Select operating pressures for key unit operations
c.Show heating and cooling duties, and offer opportunities for heat integration.
d.Calculate compressor horsepower if gas streams are being compressed.

You may use either ASPEN PLUS or Excel to calculate heat and material balances, but the model should be able to handle reasonable changes to the Target assumptions. Again, perform an economic analysis which now includes energy and raw materials. This is essentially the variable cost of production.

4)Determine capital cost and final economics.Size the equipment, estimate the installed capital cost, and complete a cash flow analysis for your selected flowsheet.
Your analysis will consider:
•What economic environment makes the achievable targets an attractive process?
•What process parameters are needed to have an attractive process given the economic data below?

5)Additional Comments and Guidelines

•Plant Scale.
Size for 1 billion lb/yr of total ethylene plus ethane. This is roughly a 2% increase in US capacity.

•Reactor Design and Modeling. At this stage, the reactions do not need to be modeled kinetically; instead, use a stoichiometric model with conversions and yields. Be mindful of the flammable limits of methane, and that these limits widen with increased pressure. Although the reactor design is eventually very important, we are looking for the big picture, here. You can consider isothermal reactors such as packed tube-in-shell designs, or packed adiabatic reactors or fluidized beds with cooling between stages. In the latter case, assume an allowable adiabatic temperature rise of 50°C.

•Possible separation techniques. The list below is not meant to be comprehensive, and may not even be appropriate, but it can providesome insight for fitting pieces together. If using cryogenic separation techniques, be mindful that any moisture will freeze and plug equipment.

> Sample compression and condensation, to remove most water and possibly some ethylene/ethane.
>
> Selective absorption to remove ethylene/ethane from the bulk gas stream, with a solvent such as dimethylformamide. (Linde has a process to recover acetylene from ethylene with this solvent)
>
> Selective absorption to remove CO2 such as with the Benfield process.

Molecular sieve adsorption beds to remove water from gas streams.

Catalytic oxidation to convert CO to CO

•Battery Limit Conditions

Although natural gas contains some ethane and other impurities, assume pure methane as your feedstock, available at 50 psig and ambient temperature. Oxygen is available at 100 psig and ambient temperature.

An Ethane/Ethylene mixture must be supplied at 450 psig to the olefins unit with less than 100 ppm water and 50 ppm CO+CO2

•Recycles. How much of the unconverted gas gets recycled is a significant design choice you have. The tradeoff is that morerecycle increases energy and equipment cost. You may consider recycling CO2 as a diluents to limit adiabatic temperature rise and somewhat shrink the flammable envelope.

Economic Data
Your analysis will include sensitivity to pricing assumptions. Typical recent prices are:
Ethylene: 45 cent/lb (Dan Lippe, 2013)
Ethylene – Ethane price spread: 20 cent/lb (Young)
Include a "conversion cost" of 1 c/lb mixed et
hane/ethylene feed to the olefins plant that
separates these components.
Natural Gas: $3.50/MMBTU (InfoMine)

III. Selected Aspen Block Results

BLOCK: HX-101 MODEL: HEATX

HOT SIDE:

INLET STREAM: S-208

OUTLET STREAM: S-218

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

COLD SIDE:

INLET STREAM: S-105

OUTLET STREAM: S-106

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	106205.	106205.	0.00000
MASS(LB/HR)	0.177247E+07	0.177247E+07	0.00000
ENTHALPY(BTU/HR)	-0.638387E+10	-0.638387E+10	0.00000

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.287774E+08 LB/HR

PRODUCT STREAMS CO2E 0.287774E+08 LB/HR

NET STREAMS CO2E PRODUCTION 0.00000 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** 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	150.0000
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:

HOT LIQUID	COLD LIQUID	BTU/HR-SQFT-R	149.6937
HOT 2-PHASE	COLD LIQUID	BTU/HR-SQFT-R	149.6937
HOT VAPOR	COLD LIQUID	BTU/HR-SQFT-R	149.6937
HOT LIQUID	COLD 2-PHASE	BTU/HR-SQFT-R	149.6937
HOT 2-PHASE	COLD 2-PHASE	BTU/HR-SQFT-R	149.6937
HOT VAPOR	COLD 2-PHASE	BTU/HR-SQFT-R	149.6937
HOT LIQUID	COLD VAPOR	BTU/HR-SQFT-R	149.6937
HOT 2-PHASE	COLD VAPOR	BTU/HR-SQFT-R	149.6937
HOT VAPOR	COLD VAPOR	BTU/HR-SQFT-R	149.6937

```
          ***  OVERALL RESULTS  ***

STREAMS:

          --------------------------------------
          |                            |
S-208   ----->|          HOT           |-----> S-218
T=  2.9577D+02  |                       |     T=  1.5000D+02
P=  8.7023D+01  |                       |     P=  8.7023D+01
V=  0.0000D+00  |                       |     V=  0.0000D+00
          |                            |
S-106   <-----|          COLD          |<----- S-105
T=  2.8602D+02  |                       |     T=  1.2958D+02
P=  8.7023D+01  |                       |     P=  8.7023D+01
V=  1.0000D+00  |                       |     V=  1.0000D+00
          --------------------------------------

DUTY AND AREA:
 CALCULATED HEAT DUTY          BTU/HR          105848939.2158
 CALCULATED (REQUIRED) AREA    SQFT               48985.8564
 ACTUAL EXCHANGER AREA         SQFT               48985.8564
 PER CENT OVER-DESIGN                                 0.0000

HEAT TRANSFER COEFFICIENT:
 AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R        149.6937
```

UA (DIRTY) BTU/HR-R 7332871.9447

LOG-MEAN TEMPERATURE DIFFERENCE:

LMTD CORRECTION FACTOR 1.0000

LMTD (CORRECTED) F 14.4349

NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:

HOTSIDE, TOTAL PSI 0.0000

COLDSIDE, TOTAL PSI 0.0000

*** ZONE RESULTS ***

TEMPERATURE LEAVING EACH ZONE:

```
                    HOT
     ------------------------------------------------------------
      |                                       |
HOT IN  |                LIQ                  | HOT OUT
------> |                                     |------>
 295.8  |                                     |  150.0
      |                                       |
COLDOUT |                VAP                  | COLDIN
<------ |                                     |<------
 286.0  |                                     |  129.6
```

| |

COLD

ZONE HEAT TRANSFER AND AREA:

ZONE	HEAT DUTY	AREA	LMTD	AVERAGE U	UA
	BTU/HR	SQFT	F	BTU/HR-SQFT-R	BTU/HR-R
1	105848939.216	48985.8564	14.4349	149.6937	7332871.9447

BLOCK: B-101 MODEL: COMPR

INLET STREAM: FEED-A

OUTLET STREAM: FEED-B

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	28219.2	28219.2	0.00000
MASS(LB/HR)	452713.	452713.	0.00000
ENTHALPY(BTU/HR)	-0.904977E+09	-0.892251E+09	-0.140617E-01

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.113178E+08 LB/HR

PRODUCT STREAMS CO2E 0.113178E+08 LB/HR

NET STREAMS CO2E PRODUCTION 0.00000 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***

ISENTROPIC COMPRESSOR USING ASME METHOD

OUTLET PRESSURE PSIA 87.0226

ISENTROPIC EFFICIENCY 0.72000

MECHANICAL EFFICIENCY 1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP 5,001.33

BRAKE HORSEPOWER REQUIREMENT HP 5,001.33

NET WORK REQUIRED HP 5,001.33

POWER LOSSES HP 0.0

ISENTROPIC HORSEPOWER REQUIREMENT HP 3,600.96

CALCULATED OUTLET TEMP F 129.556

ISENTROPIC TEMPERATURE F 115.347

EFFICIENCY (POLYTR/ISENTR) USED 0.72000

OUTLET VAPOR FRACTION 1.00000

HEAD DEVELOPED, FT-LBF/LB 15,749.2

MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.31722
INLET VOLUMETRIC FLOW RATE , CUFT/HR	2,493,180.
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR	2,036,520.
INLET COMPRESSIBILITY FACTOR	0.99248
OUTLET COMPRESSIBILITY FACTOR	0.99320
AV. ISENT. VOL. EXPONENT	1.30311
AV. ISENT. TEMP EXPONENT	1.30343
AV. ACTUAL VOL. EXPONENT	1.46538
AV. ACTUAL TEMP EXPONENT	1.46013

BLOCK: D-201 MODEL: DSTWU

INLET STREAM: S-212

CONDENSER OUTLET: S-214

REBOILER OUTLET: S-213

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	55070.3	55070.3	0.00000
MASS(LB/HR)	998432.	998432.	0.116598E-15

ENTHALPY(BTU/HR) -0.165966E+10 -0.183530E+10 0.957018E-01

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.183977E+08 LB/HR

PRODUCT STREAMS CO2E 0.183977E+08 LB/HR

NET STREAMS CO2E PRODUCTION 0.00000 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***

HEAVY KEY COMPONENT	C2H4
RECOVERY FOR HEAVY KEY	0.0100000
LIGHT KEY COMPONENT	METHANE
RECOVERY FOR LIGHT KEY	0.99900
TOP STAGE PRESSURE (PSIA)	290.075
BOTTOM STAGE PRESSURE (PSIA)	290.075
NO. OF EQUILIBRIUM STAGES	4.00000
DISTILLATE VAPOR FRACTION	0.0

*** RESULTS ***

DISTILLATE TEMP. (F)	-171.018
BOTTOM TEMP. (F)	-12.2338
MINIMUM REFLUX RATIO	0.39074
ACTUAL REFLUX RATIO	0.59926
MINIMUM STAGES	6.94392

ACTUAL EQUILIBRIUM STAGES 13.8878

NUMBER OF ACTUAL STAGES ABOVE FEED 4.70326

DIST. VS FEED 0.87622

CONDENSER COOLING REQUIRED (BTU/HR) 0.194558+09

NET CONDENSER DUTY (BTU/HR) -0.194558+09

REBOILER HEATING REQUIRED (BTU/HR) 0.189169+08

NET REBOILER DUTY (BTU/HR) 0.189169+08

BLOCK: C-202 MODEL: COMPR

INLET STREAM: S-211

OUTLET STREAM: S-211A

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	55070.3	55070.3	0.00000
MASS(LB/HR)	998432.	998432.	0.00000
ENTHALPY(BTU/HR)	-0.155608E+10	-0.154693E+10	-0.587730E-02

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.183977E+08 LB/HR

PRODUCT STREAMS CO2E 0.183977E+08 LB/HR

NET STREAMS CO2E PRODUCTION 0.00000 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***

ISENTROPIC COMPRESSOR USING ASME METHOD

OUTLET PRESSURE PSIA 290.075

ISENTROPIC EFFICIENCY 0.72000

MECHANICAL EFFICIENCY 1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP 3,594.33

BRAKE HORSEPOWER REQUIREMENT HP 3,594.33

NET WORK REQUIRED HP 3,594.33

POWER LOSSES HP 0.0

ISENTROPIC HORSEPOWER REQUIREMENT HP 2,587.92

CALCULATED OUTLET TEMP F 123.170

ISENTROPIC TEMPERATURE F 118.279

EFFICIENCY (POLYTR/ISENTR) USED 0.72000

OUTLET VAPOR FRACTION 1.00000

HEAD DEVELOPED, FT-LBF/LB 5,132.13

MECHANICAL EFFICIENCY USED 1.00000

INLET HEAT CAPACITY RATIO 1.33872

INLET VOLUMETRIC FLOW RATE , CUFT/HR 1,242,870.

OUTLET VOLUMETRIC FLOW RATE, CUFT/HR 1,154,090.

INLET COMPRESSIBILITY FACTOR 0.97084

OUTLET COMPRESSIBILITY FACTOR 0.97192

AV. ISENT. VOL. EXPONENT 1.29955

AV. ISENT. TEMP EXPONENT 1.29912

AV. ACTUAL VOL. EXPONENT 1.46617

AV. ACTUAL TEMP EXPONENT 1.44465

BLOCK: F-201 MODEL: FLASH2

INLET STREAM: S-205

OUTLET VAPOR STREAM: S-207A

OUTLET LIQUID STREAM: S-206

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	99381.3	99381.3	0.00000
MASS(LB/HR)	0.204203E+07	0.204203E+07	0.00000
ENTHALPY(BTU/HR)	-0.746221E+10	-0.746221E+10	0.281161E-13

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.188131E+08 LB/HR

PRODUCT STREAMS CO2E 0.188131E+08 LB/HR

NET STREAMS CO2E PRODUCTION 0.00000 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***

TWO PHASE TP FLASH

SPECIFIED TEMPERATURE F 95.0000

SPECIFIED PRESSURE PSIA 87.0226

MAXIMUM NO. ITERATIONS 30

CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

OUTLET TEMPERATURE F 95.000

OUTLET PRESSURE PSIA 87.023

HEAT DUTY BTU/HR -0.26804E-03

VAPOR FRACTION 0.65398

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
METHANE	0.46157	0.34108E-05	0.70578	0.20693E+06
C2H4	0.45782E-01	0.57342E-06	0.70004E-01	0.12208E+06
C2H6	0.22810E-01	0.19544E-06	0.34878E-01	0.17846E+06

CO2	0.94962E-01	0.19261E-04	0.14519	7538.4
CO	0.23968E-01	0.15455E-07	0.36649E-01	0.23714E+07
WATER	0.35091	0.99998	0.74885E-02	0.74887E-02

BLOCK: R-101 MODEL: RSTOIC

INLET STREAM: S-110A

OUTLET STREAM: S-111A

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	24967.9	24979.5	11.5980	-0.145639E-15
MASS(LB/HR)	512659.	512659.		-0.227081E-15
ENTHALPY(BTU/HR)	-0.259577E+09	-0.818878E+08		-0.684534

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.719432E+07 LB/HR

PRODUCT STREAMS CO2E 0.475706E+07 LB/HR

NET STREAMS CO2E PRODUCTION -0.243726E+07 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION -0.243726E+07 LB/HR

*** INPUT DATA ***

STOICHIOMETRY MATRIX:

REACTION #   1:

SUBSTREAM MIXED   :

METHANE   -2.00   OXYGEN   -1.00   C2H4   1.00   WATER   2.00

REACTION #   2:

SUBSTREAM MIXED   :

METHANE   -2.00   OXYGEN   -0.500   C2H6   1.00   WATER   1.00

REACTION #   3:

SUBSTREAM MIXED   :

METHANE   -1.00   OXYGEN   -2.00   CO2   1.00   WATER   2.00

REACTION #   4:

SUBSTREAM MIXED   :

METHANE   -1.00   OXYGEN   -1.50   CO   1.00   WATER   2.00

REACTION CONVERSION SPECS: NUMBER=   4

REACTION #   1:

SUBSTREAM:MIXED   KEY COMP:METHANE CONV FRAC: 0.1360

REACTION #   2:

SUBSTREAM:MIXED   KEY COMP:METHANE CONV FRAC: 0.6840E-01

REACTION #   3:

SUBSTREAM:MIXED KEY COMP:METHANE CONV FRAC: 0.1424

REACTION # 4:

SUBSTREAM:MIXED KEY COMP:METHANE CONV FRAC: 0.3560E-01

HEAT OF REACTION SPECIFICATIONS:

REACTION NUMBER	REFERENCE COMPONENT	HEAT OF REACTION BTU/LBMOL
1	METHANE	-0.12097E+06
2	METHANE	-75545.
3	METHANE	-0.34490E+06
4	METHANE	-0.22324E+06

TWO PHASE PQ FLASH

SPECIFIED PRESSURE PSIA 87.0226

SPECIFIED HEAT DUTY BTU/HR 0.0

MAXIMUM NO. ITERATIONS 30

CONVERGENCE TOLERANCE 0.000100000

SIMULTANEOUS REACTIONS

GENERATE COMBUSTION REACTIONS FOR FEED SPECIES NO

*** RESULTS ***

OUTLET TEMPERATURE	F	4137.5
OUTLET PRESSURE	PSIA	87.023
VAPOR FRACTION		1.0000

HEAT OF REACTIONS:

REACTION NUMBER	REFERENCE COMPONENT	HEAT OF REACTION BTU/LBMOL
1	METHANE	-0.12097E+06
2	METHANE	-75545.
3	METHANE	-0.34490E+06
4	METHANE	-0.22324E+06

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT LBMOL/HR
1	1126.7
2	566.64
3	2359.4
4	589.84

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
METHANE	0.46446	0.46446	0.46446	MISSING
C2H4	0.45536E-01	0.45536E-01	0.45536E-01	MISSING
C2H6	0.22687E-01	0.22687E-01	0.22687E-01	MISSING
CO2	0.94452E-01	0.94452E-01	0.94452E-01	MISSING
CO	0.23839E-01	0.23839E-01	0.23839E-01	MISSING
WATER	0.34902	0.34902	0.34902	MISSING

BLOCK: P-101 MODEL: PUMP

INLET STREAM: S-115A

OUTLET STREAM: S-115B

PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	189000.	189000.	0.00000
MASS(LB/HR)	0.340489E+07	0.340489E+07	0.00000
ENTHALPY(BTU/HR)	-0.234158E+11	-0.234134E+11	-0.103471E-03

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.00000 LB/HR

PRODUCT STREAMS CO2E 0.00000 LB/HR

NET STREAMS CO2E PRODUCTION 0.00000 LB/HR

UTILITIES CO2E PRODUCTION 0.00000 LB/HR

TOTAL CO2E PRODUCTION 0.00000 LB/HR

*** INPUT DATA ***

OUTLET PRESSURE PSIA	217.557
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	55,413.4
PRESSURE CHANGE PSI	203.053
NPSH AVAILABLE FT-LBF/LB	32.5581
FLUID POWER HP	818.316
BRAKE POWER HP	952.220
ELECTRICITY KW	710.071
PUMP EFFICIENCY USED	0.85938
NET WORK REQUIRED HP	952.220
HEAD DEVELOPED FT-LBF/LB	475.865

IV. MSDS

Material Safety Data Sheet

Airgas

Methane

Section 1. Chemical product and company identification

Product name	:	Methane
Supplier	:	AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	:	Synthetic/Analytical chemistry.
Synonym	:	fire damp; marsh gas; methane (dot); methyl hydride
MSDS #	:	001033
Date of Preparation/Revision	:	**4/1/2013.**
In case of emergency	:	1-866-734-3438

Section 2. Hazards identification

Physical state	:	Gas. [COLORLESS GAS; MAY BE A LIQUID UNDER PRESSURE OR REFRIGERATION.]
Emergency overview	:	WARNING! GAS: CONTENTS UNDER PRESURE. Extremely flammable. May cause flash fire. Do not puncture or incinerate container. Can cause rapid suffocation. May cause severe frostbite. LIQUID: Extremely flammable. Extremely cold liquid and gas under pressure. Can cause rapid suffocation. May cause severe frostbite. Keep away from heat, sparks and flame. Do not puncture or incinerate container. Use only with adequate ventilation. Keep container closed. Contact with rapidly expanding gases or liquids can cause frostbite.
Routes of entry	:	Inhalation
Potential acute health effects		
Eyes	:	Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Skin	:	Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Inhalation	:	Acts as a simple asphyxiant.
Ingestion	:	Ingestion is not a normal route of exposure for gases. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Medical conditions aggravated by over-exposure	:	Acute or chronic respiratory conditions may be aggravated by overexposure to this gas.

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Methane	74-82-8	100	**ACGIH TLV (United States, 1/2009).** TWA: 1000 ppm 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training.If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus.It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact : Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. To avoid the risk of static discharges and gas ignition, soak contaminated clothing thoroughly with water before removing it. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Inhalation : Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion : As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 539.85°C (1003.7°F)

Flash point : Closed cup: -188.15°C (-306.7°F).

Flammable limits : Lower: 5% Upper: 15%

Products of combustion : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Fire hazards in the presence of various substances : Extremely flammable in the presence of the following materials or conditions: open flames, sparks and static discharge and oxidizing materials.

Fire-fighting media and instructions : In case of fire, use water spray (fog), foam or dry chemical.

In case of fire, allow gas to burn if flow cannot be shut off immediately. Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk.

Contains gas under pressure. Flammable gas. In a fire or if heated, a pressure increase will occur and the container may burst, with the risk of a subsequent explosion.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions : Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.

Environmental precautions : Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.

Methods for cleaning up : Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Section 7. Handling and storage

Handling : Use only with adequate ventilation. Use explosion-proof electrical (ventilating, lighting and material handling) equipment. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Keep away from heat, sparks and flame. To avoid fire, eliminate ignition sources. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
Never allow any unprotected part of the body to touch uninsulated pipes or vessels that contain cryogenic liquids. Prevent entrapment of liquid in closed systems or piping without pressure relief devices. Some materials may become brittle at low temperatures and will easily fracture.

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). Segregate from oxidizing materials. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).
For additional information concerning storage and handling refer to Compressed Gas Association pamphlets P-1 Safe Handling of Compressed Gases in Containers and P-12 Safe Handling of Cryogenic Liquids available from the Compressed Gas Association, Inc.

Section 8. Exposure controls/personal protection

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

Personal protection

Eyes : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts.

When working with cryogenic liquids, wear a full face shield.

Skin : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Respiratory : Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93

Hands : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary.

Insulated gloves suitable for low temperatures

Personal protection in case of a large spill : Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product.

Product name

methane	**ACGIH TLV (United States, 1/2009).** TWA: 1000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Methane

Section 9. Physical and chemical properties

Molecular weight	: 16.05 g/mole
Molecular formula	: C-H4
Boiling/condensation point	: -161.6°C (-258.9°F)
Melting/freezing point	: -182.6°C (-296.7°F)
Critical temperature	: -82.4°C (-116.3°F)
Vapor density	: 0.55 (Air = 1) Liquid Density@BP: 26.5 lb/ft3 (424.5 kg/m3)
Specific Volume (ft^3/lb)	: 23.6128
Gas Density (lb/ft^3)	: 0.04235

Section 10. Stability and reactivity

Stability and reactivity	: The product is stable.
Incompatibility with various substances	: Extremely reactive or incompatible with the following materials: oxidizing materials.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

Other toxic effects on humans	: No specific information is available in our database regarding the other toxic effects of this material to humans.

Specific effects

Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Products of degradation	: Products of degradation: carbon oxides (CO, CO_2) and water.
Environmental fate	: Not available.
Environmental hazards	: No known significant effects or critical hazards.
Toxicity to the environment	: Not available.

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation.Return cylinders with residual product to Airgas, Inc.Do not dispose of locally.

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1971	Methane, compressed or Methane or Natural gas, compressed (with high methane content)(Methane)	2.1	Not applicable (gas).		-
	UN1972	Methane, refrigerated liquid				

Methane						
TDG Classification	UN1971 UN1972	(Methane)Methane, compressed or Methane or Natural gas, compressed (with high methane content) Methane, refrigerated liquid	2.1	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **ERAP Index** 3000 **Passenger Carrying Ship Index** Forbidden **Passenger Carrying Road or Rail Index** Forbidden
Mexico Classification	UN1971 UN1972	(Methane)Methane, compressed or Methane or Natural gas, compressed (with high methane content) Methane, refrigerated liquid	2.1	Not applicable (gas).		-

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Section 15. Regulatory information

United States

U.S. Federal regulations : **United States inventory (TSCA 8b):** This material is listed or exempted.

SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: methane
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: methane: Fire hazard, Sudden release of pressure

Clean Water Act (CWA) 307: No products were found.

Clean Water Act (CWA) 311: No products were found.

Clean Air Act (CAA) 112 regulated flammable substances: methane

Clean Air Act (CAA) 112 regulated toxic substances: No products were found.

State regulations : **Connecticut Carcinogen Reporting:** This material is not listed.
Connecticut Hazardous Material Survey: This material is not listed.
Florida substances: This material is not listed.
Illinois Chemical Safety Act: This material is not listed.
Illinois Toxic Substances Disclosure to Employee Act: This material is not listed.
Louisiana Reporting: This material is not listed.
Louisiana Spill: This material is not listed.
Massachusetts Spill: This material is not listed.
Massachusetts Substances: This material is listed.
Michigan Critical Material: This material is not listed.
Minnesota Hazardous Substances: This material is not listed.

New Jersey Spill: This material is not listed.
New Jersey Toxic Catastrophe Prevention Act: This material is not listed.
New York Acutely Hazardous Substances: This material is not listed.
New York Toxic Chemical Release Reporting: This material is not listed.
Pennsylvania RTK Hazardous Substances: This material is listed.
Rhode Island Hazardous Substances: This material is not listed.

Canada

WHMIS (Canada) : Class A: Compressed gas.
Class B-1: Flammable gas.

CEPA Toxic substances: This material is listed.
Canadian ARET: This material is not listed.
Canadian NPRI: This material is listed.
Alberta Designated Substances: This material is not listed.
Ontario Designated Substances: This material is not listed.
Quebec Designated Substances: This material is not listed.

Section 16. Other information

United States

Label requirements : GAS:
CONTENTS UNDER PRESURE.
Extremely flammable.
May cause flash fire.
Do not puncture or incinerate container.
Can cause rapid suffocation.
May cause severe frostbite.
LIQUID:
Extremely flammable.
Extremely cold liquid and gas under pressure.
Can cause rapid suffocation.
May cause severe frostbite.

Canada

Label requirements : Class A: Compressed gas.
Class B-1: Flammable gas.

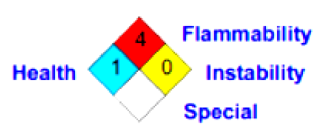
Hazardous Material Information System (U.S.A.) :

Health	1
Flammability	4
Physical hazards	0

liquid:

Health	3
Fire hazard	4
Reactivity	1
Personal protection	

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



Methane

liquid:

[Notice to reader]

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

Material Safety Data Sheet

Ethane

Section 1. Chemical product and company identification

Product name : Ethane

Supplier : AIRGAS INC., on behalf of its subsidiaries
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

Product use : Synthetic/Analytical chemistry.

Synonym : Bimethyl; Dimethyl; Ethyl hydride; Methylmethane; C2H6; UN 1035; UN 1961, R170

MSDS # : 001024

Date of Preparation/Revision : **10/23/2012.**

In case of emergency : 1-866-734-3438

Section 2. Hazards identification

Physical state : Gas. [Compressed gas.]

Emergency overview : WARNING!

GAS:
CONTENTS UNDER PRESURE.
Extremely flammable.
May cause flash fire.
Do not puncture or incinerate container.
Can cause rapid suffocation.
May cause severe frostbite.
LIQUID:
Extremely flammable.
Extremely cold liquid and gas under pressure.
Can cause rapid suffocation.
May cause severe frostbite.

Keep away from heat, sparks and flame. Do not puncture or incinerate container. May cause target organ damage, based on animal data. Use only with adequate ventilation. Keep container closed.

Contact with rapidly expanding gases or liquids can cause frostbite.

Target organs : May cause damage to the following organs: heart, central nervous system (CNS).

Routes of entry : Inhalation

Potential acute health effects

Eyes : Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.

Skin : Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.

Inhalation : Acts as a simple asphyxiant.

Ingestion : Ingestion is not a normal route of exposure for gases. Contact with cryogenic liquid can cause frostbite and cryogenic burns.

Potential chronic health effects

Chronic effects : May cause target organ damage, based on animal data.

Target organs : May cause damage to the following organs: heart, central nervous system (CNS).

Medical conditions aggravated by over-exposure : Pre-existing disorders involving any target organs mentioned in this MSDS as being at risk may be aggravated by over-exposure to this product.

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Ethane	74-84-0	100	**ACGIH TLV (United States, 2/2010).** TWA: 1000 ppm 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training.If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus.It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact : Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. To avoid the risk of static discharges and gas ignition, soak contaminated clothing thoroughly with water before removing it. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Inhalation : Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion : As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 472°C (881.6°F)

Flash point : Closed cup: -135.15°C (-211.3°F).

Flammable limits : Lower: 3% Upper: 12.5%

Products of combustion : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Fire hazards in the presence of various substances : Extremely flammable in the presence of the following materials or conditions: oxidizing materials.

Fire-fighting media and instructions : In case of fire, use water spray (fog), foam or dry chemical.

In case of fire, allow gas to burn if flow cannot be shut off immediately. Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk.

Contains gas under pressure. Flammable gas. In a fire or if heated, a pressure increase will occur and the container may burst, with the risk of a subsequent explosion.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions : Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.

Environmental precautions : Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.

Methods for cleaning up : Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Ethane

Section 7. Handling and storage

Handling : Use only with adequate ventilation. Use explosion-proof electrical (ventilating, lighting and material handling) equipment. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Keep away from heat, sparks and flame. To avoid fire, eliminate ignition sources. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
Never allow any unprotected part of the body to touch uninsulated pipes or vessels that contain cryogenic liquids. Prevent entrapment of liquid in closed systems or piping without pressure relief devices. Some materials may become brittle at low temperatures and will easily fracture.

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). Segregate from oxidizing materials. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).
For additional information concerning storage and handling refer to Compressed Gas Association pamphlets P-1 Safe Handling of Compressed Gases in Containers and P-12 Safe Handling of Cryogenic Liquids available from the Compressed Gas Association, Inc.

Section 8. Exposure controls/personal protection

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

Personal protection

Eyes : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts.

When working with cryogenic liquids, wear a full face shield.

Skin : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Respiratory : Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93

Hands : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary.

Insulated gloves suitable for low temperatures

Personal protection in case of a large spill : Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product.

Product name	
ethane	**ACGIH TLV (United States, 2/2010).** TWA: 1000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Ethane

Section 9. Physical and chemical properties

Molecular weight	: 30.08 g/mole
Molecular formula	: C2-H6
Boiling/condensation point	: -89°C (-128.2°F)
Melting/freezing point	: -183°C (-297.4°F)
Critical temperature	: 32.4°C (90.3°F)
Vapor pressure	: 543 (psig)
Vapor density	: 1.1 (Air = 1) Liquid Density: BP@34.1 lb/ft3 (546 kg/m3)
Specific Volume (ft^3/lb)	: 12.6582
Gas Density (lb/ft^3)	: 0.079

Section 10. Stability and reactivity

Stability and reactivity	: The product is stable.
Incompatibility with various substances	: Extremely reactive or incompatible with the following materials: oxidizing materials.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

Chronic effects on humans	: May cause damage to the following organs: heart, central nervous system (CNS).
Other toxic effects on humans	: No specific information is available in our database regarding the other toxic effects of this material to humans.

Specific effects

Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Products of degradation	: Products of degradation: carbon oxides (CO, CO_2) and water.
Environmental fate	: Not available.
Environmental hazards	: This product shows a low bioaccumulation potential.
Toxicity to the environment	: Not available.

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation.Return cylinders with residual product to Airgas, Inc.Do not dispose of locally.

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information

Ethane						
DOT Classification	UN1035 UN1961	ETHANE Ethane, refrigerated liquid	2.1	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: Forbidden. **Cargo aircraft** Quantity limitation: 150 kg
TDG Classification	UN1035 UN1961	ETHANE Ethane, refrigerated liquid	2.1	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **ERAP Index** 3000 **Passenger Carrying Ship Index** Forbidden **Passenger Carrying Road or Rail Index** Forbidden
Mexico Classification	UN1035 UN1961	ETHANE Ethane, refrigerated liquid	2.1	Not applicable (gas).		-

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Section 15. Regulatory information

United States

U.S. Federal regulations : **TSCA 8(a) IUR**: Not determined
United States inventory (TSCA 8b): This material is listed or exempted.

SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: ethane
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: ethane: Fire hazard, Sudden release of pressure, Immediate (acute) health hazard

Clean Air Act (CAA) 112 accidental release prevention - Flammable Substances: Ethane

Clean Air Act (CAA) 112 regulated flammable substances: ethane

State regulations : **Connecticut Carcinogen Reporting**: This material is not listed.
Connecticut Hazardous Material Survey: This material is not listed.
Florida substances: This material is not listed.
Illinois Chemical Safety Act: This material is not listed.
Illinois Toxic Substances Disclosure to Employee Act: This material is not listed.
Louisiana Reporting: This material is not listed.
Louisiana Spill: This material is not listed.
Massachusetts Spill: This material is not listed.
Massachusetts Substances: This material is listed.
Michigan Critical Material: This material is not listed.
Minnesota Hazardous Substances: This material is not listed.
New Jersey Hazardous Substances: This material is listed.
New Jersey Spill: This material is not listed.
New Jersey Toxic Catastrophe Prevention Act: This material is not listed.
New York Acutely Hazardous Substances: This material is not listed.
New York Toxic Chemical Release Reporting: This material is not listed.
Pennsylvania RTK Hazardous Substances: This material is listed.
Rhode Island Hazardous Substances: This material is not listed.

Canada

WHMIS (Canada) : Class A: Compressed gas.
Class B-1: Flammable gas.

CEPA Toxic substances: This material is listed.
Canadian ARET: This material is not listed.
Canadian NPRI: This material is listed.
Alberta Designated Substances: This material is not listed.
Ontario Designated Substances: This material is not listed.
Quebec Designated Substances: This material is not listed.

Section 16. Other information

United States

Label requirements : GAS:
CONTENTS UNDER PRESURE.
Extremely flammable.
May cause flash fire.
Do not puncture or incinerate container.
Can cause rapid suffocation.
May cause severe frostbite.
LIQUID:
Extremely flammable.
Extremely cold liquid and gas under pressure.
Can cause rapid suffocation.
May cause severe frostbite.

Canada

Label requirements : Class A: Compressed gas.
Class B-1: Flammable gas.

Hazardous Material Information System (U.S.A.) :

Health	1
Flammability	4
Physical hazards	0

liquid:

Health	3

Ethane

Fire hazard	4
Reactivity	0
Personal protection	

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

liquid:

Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

Material Safety Data Sheet

Propane

Section 1. Chemical product and company identification

Product name	:	Propane
Supplier	:	AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	:	Synthetic/Analytical chemistry.
Synonym	:	n-Propane; Dimethylmethane; Freon 290; Liquefied petroleum gas; Lpg; Propyl hydride; R 290; C3H8; UN 1075; UN 1978; A-108; Hydrocarbon propellant.
MSDS #	:	001045
Date of Preparation/Revision	:	**8/19/2013.**
In case of emergency	:	1-866-734-3438

Section 2. Hazards identification

Physical state	:	Gas. [COLORLESS LIQUEFIED COMPRESSED GAS; ODORLESS BUT MAY HAVE SKUNK ODOR ADDED.]
Emergency overview	:	WARNING! FLAMMABLE GAS. MAY CAUSE FLASH FIRE. MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA. CONTENTS UNDER PRESSURE. Keep away from heat, sparks and flame. Do not puncture or incinerate container. May cause target organ damage, based on animal data. Use only with adequate ventilation. Keep container closed. Contact with rapidly expanding gases can cause frostbite.
Target organs	:	May cause damage to the following organs: the nervous system, heart, central nervous system (CNS).
Routes of entry	:	Inhalation
Potential acute health effects		
Eyes	:	Contact with rapidly expanding gas may cause burns or frostbite.
Skin	:	Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation	:	Acts as a simple asphyxiant.
Ingestion	:	Ingestion is not a normal route of exposure for gases
Potential chronic health effects		
Chronic effects	:	May cause target organ damage, based on animal data.
Target organs	:	May cause damage to the following organs: the nervous system, heart, central nervous system (CNS).
Medical conditions aggravated by over-exposure	:	Pre-existing disorders involving any target organs mentioned in this MSDS as being at risk may be aggravated by over-exposure to this product.

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Propane	74-98-6	100	**ACGIH TLV (United States, 3/2012).** TWA: 1000 ppm 8 hour(s). **NIOSH REL (United States, 1/2013).** TWA: 1800 mg/m³ 10 hour(s). TWA: 1000 ppm 10 hour(s). **OSHA PEL (United States, 6/2010).** TWA: 1800 mg/m³ 8 hour(s). TWA: 1000 ppm 8 hour(s). **OSHA PEL 1989 (United States, 3/1989).** TWA: 1800 mg/m³ 8 hour(s). TWA: 1000 ppm 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training.If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus.It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact : Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. To avoid the risk of static discharges and gas ignition, soak contaminated clothing thoroughly with water before removing it. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Inhalation : Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion : As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 450°C (842°F)

Flash point : Closed cup: -104°C (-155.2°F). Open cup: -104°C (-155.2°F).

Flammable limits : Lower: 2.1% Upper: 9.5%

Products of combustion : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Fire hazards in the presence of various substances : Extremely flammable in the presence of the following materials or conditions: open flames, sparks and static discharge and oxidizing materials.

Fire-fighting media and instructions : In case of fire, use water spray (fog), foam or dry chemical.

In case of fire, allow gas to burn if flow cannot be shut off immediately. Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk.

Contains gas under pressure. Flammable gas. In a fire or if heated, a pressure increase will occur and the container may burst, with the risk of a subsequent explosion.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Propane	74-98-6	100	**ACGIH TLV (United States, 3/2012).** TWA: 1000 ppm 8 hour(s). **NIOSH REL (United States, 1/2013).** TWA: 1800 mg/m^3 10 hour(s). TWA: 1000 ppm 10 hour(s). **OSHA PEL (United States, 6/2010).** TWA: 1800 mg/m^3 8 hour(s). TWA: 1000 ppm 8 hour(s). **OSHA PEL 1989 (United States, 3/1989).** TWA: 1800 mg/m^3 8 hour(s). TWA: 1000 ppm 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training.If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus.It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact : Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. To avoid the risk of static discharges and gas ignition, soak contaminated clothing thoroughly with water before removing it. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Inhalation : Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion : As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 450°C (842°F)

Flash point : Closed cup: -104°C (-155.2°F). Open cup: -104°C (-155.2°F).

Flammable limits : Lower: 2.1% Upper: 9.5%

Products of combustion : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Fire hazards in the presence of various substances : Extremely flammable in the presence of the following materials or conditions: open flames, sparks and static discharge and oxidizing materials.

Fire-fighting media and instructions : In case of fire, use water spray (fog), foam or dry chemical.

In case of fire, allow gas to burn if flow cannot be shut off immediately. Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk.

Contains gas under pressure. Flammable gas. In a fire or if heated, a pressure increase will occur and the container may burst, with the risk of a subsequent explosion.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions : Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.

Environmental precautions : Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.

Methods for cleaning up : Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Section 7. Handling and storage

Handling : Use only with adequate ventilation. Use explosion-proof electrical (ventilating, lighting and material handling) equipment. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Keep away from heat, sparks and flame. To avoid fire, eliminate ignition sources. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.

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). Segregate from oxidizing materials. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Section 8. Exposure controls/personal protection

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

Personal protection

Eyes : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts.

Skin : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Respiratory : Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93

Hands : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary.

Personal protection in case of a large spill : Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product.

Product name

propane

ACGIH TLV (United States, 3/2012).
TWA: 1000 ppm 8 hour(s).
NIOSH REL (United States, 1/2013).
TWA: 1800 mg/m³ 10 hour(s).
TWA: 1000 ppm 10 hour(s).
OSHA PEL (United States, 6/2010).
TWA: 1800 mg/m³ 8 hour(s).
TWA: 1000 ppm 8 hour(s).
OSHA PEL 1989 (United States, 3/1989).
TWA: 1800 mg/m³ 8 hour(s).

TWA: 1000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 44.11 g/mole
Molecular formula	: C3-H8
Boiling/condensation point	: -42°C (-43.6°F)
Melting/freezing point	: -189.7°C (-309.5°F)
Critical temperature	: 96.6°C (205.9°F)
Vapor pressure	: 109 (psig)
Vapor density	: 1.6 (Air = 1)
Specific Volume (ft^3/lb)	: 8.6206
Gas Density (lb/ft^3)	: 0.116

Section 10. Stability and reactivity

Stability and reactivity	: The product is stable.
Incompatibility with various substances	: Extremely reactive or incompatible with the following materials: oxidizing materials.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

Product/ingredient name	Result	Species	Dose	Exposure
propane	LC50 Inhalation Gas.	Rat	>800000 ppm	15 minutes

IDLH	: 2100 ppm
Chronic effects on humans	: May cause damage to the following organs: the nervous system, heart, central nervous system (CNS).
Other toxic effects on humans	: No specific information is available in our database regarding the other toxic effects of this material to humans.

Specific effects

Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Products of degradation	: Products of degradation: carbon oxides (CO, CO_2) and water.
Environmental fate	: Not available.
Environmental hazards	: This product shows a low bioaccumulation potential.
Toxicity to the environment	: Not available.

Propane

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation.Return cylinders with residual product to Airgas, Inc.Do not dispose of locally.

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1978	PROPANE	2.1	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: Forbidden. **Cargo aircraft** Quantity limitation: 150 kg **Special provisions** 19, T50
TDG Classification	UN1978	PROPANE	2.1	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **ERAP Index** 3000 **Passenger Carrying Ship Index** 65 **Passenger Carrying Road or Rail Index** Forbidden **Special provisions** 29, 42
Mexico Classification	UN1978	PROPANE	2.1	Not applicable (gas).		-

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Section 15. Regulatory information

United States

U.S. Federal regulations	: **TSCA 8(a) IUR**: Not determined **United States inventory (TSCA 8b)**: This material is listed or exempted. **SARA 302/304/311/312 extremely hazardous substances**: No products were found. **SARA 302/304 emergency planning and notification**: No products were found. **SARA 302/304/311/312 hazardous chemicals**: propane **SARA 311/312 MSDS distribution - chemical inventory - hazard identification**: propane: Fire hazard, Sudden release of pressure **Clean Air Act (CAA) 112 accidental release prevention - Flammable Substances:** Propane **Clean Air Act (CAA) 112 regulated flammable substances**: propane
State regulations	: **Connecticut Carcinogen Reporting**: This material is not listed. **Connecticut Hazardous Material Survey**: This material is not listed. **Florida substances**: This material is not listed. **Illinois Chemical Safety Act**: This material is not listed. **Illinois Toxic Substances Disclosure to Employee Act**: This material is not listed. **Louisiana Reporting**: This material is not listed. **Louisiana Spill**: This material is not listed. **Massachusetts Spill**: This material is not listed. **Massachusetts Substances**: This material is listed. **Michigan Critical Material**: This material is not listed. **Minnesota Hazardous Substances**: This material is not listed. **New Jersey Hazardous Substances**: This material is listed. **New Jersey Spill**: This material is not listed. **New Jersey Toxic Catastrophe Prevention Act**: This material is not listed. **New York Acutely Hazardous Substances**: This material is not listed. **New York Toxic Chemical Release Reporting**: This material is not listed. **Pennsylvania RTK Hazardous Substances**: This material is listed. **Rhode Island Hazardous Substances**: This material is not listed.

Canada

WHMIS (Canada)	: Class A: Compressed gas. Class B-1: Flammable gas. **CEPA Toxic substances**: This material is not listed. **Canadian ARET**: This material is not listed. **Canadian NPRI**: This material is listed. **Alberta Designated Substances**: This material is not listed. **Ontario Designated Substances**: This material is not listed. **Quebec Designated Substances**: This material is not listed.

Section 16. Other information

United States

Label requirements	: FLAMMABLE GAS. MAY CAUSE FLASH FIRE. MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA. CONTENTS UNDER PRESSURE.

Canada

Label requirements	: Class A: Compressed gas. Class B-1: Flammable gas.

Propane

Hazardous Material Information System (U.S.A.) :

Health	*	1
Flammability		4
Physical hazards		2

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

Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

Material Safety Data Sheet

Carbon Monoxide

Airgas

Section 1. Chemical product and company identification

Product name	:	Carbon Monoxide
Supplier	:	AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	:	Synthetic/Analytical chemistry.
Synonym	:	Carbon oxide (CO); CO; Exhaust Gas; Flue gas; Carbonic oxide; Carbon oxide; Carbone; Carbonio; Kohlenmonoxid; Kohlenoxyd; Koolmonoxyde; NA 9202; Oxyde de carbone; UN 1016; Wegla tlenek; Flue gasnide; Carbon monooxide
MSDS #	:	001014
Date of Preparation/Revision	:	**12/3/2012.**
In case of emergency	:	1-866-734-3438

Section 2. Hazards identification

Physical state	:	Gas. [[COLORLESS GAS, MAY BE A LIQUID AT LOW TEMPERATURE OR HIGH PRESSURE.]]
Emergency overview	:	WARNING! FLAMMABLE GAS. MAY CAUSE FLASH FIRE. MAY BE FATAL IF INHALED. MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA. CONTENTS UNDER PRESSURE. Keep away from heat, sparks and flame. Do not puncture or incinerate container. Avoid breathing gas. May cause target organ damage, based on animal data. Use only with adequate ventilation. Keep container closed. Contact with rapidly expanding gases can cause frostbite.
Target organs	:	May cause damage to the following organs: blood, lungs, the nervous system, heart, cardiovascular system, central nervous system (CNS).
Routes of entry	:	Inhalation
Potential acute health effects		
Eyes	:	Contact with rapidly expanding gas may cause burns or frostbite.
Skin	:	Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation	:	Toxic by inhalation.
Ingestion	:	Ingestion is not a normal route of exposure for gases
Potential chronic health effects		
Chronic effects	:	May cause target organ damage, based on animal data.
Target organs	:	May cause damage to the following organs: blood, lungs, the nervous system, heart, cardiovascular system, central nervous system (CNS).
Medical conditions aggravated by over-exposure	:	Pre-existing disorders involving any target organs mentioned in this MSDS as being at risk may be aggravated by over-exposure to this product.

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Carbon Monoxide	630-08-0	100	**ACGIH TLV (United States, 2/2010).** TWA: 29 mg/m³ 8 hour(s). TWA: 25 ppm 8 hour(s). **NIOSH REL (United States, 6/2009).** CEIL: 229 mg/m³ CEIL: 200 ppm TWA: 40 mg/m³ 10 hour(s). TWA: 35 ppm 10 hour(s). **OSHA PEL (United States, 6/2010).** TWA: 55 mg/m³ 8 hour(s). TWA: 50 ppm 8 hour(s). **OSHA PEL 1989 (United States, 3/1989).** CEIL: 229 mg/m³ CEIL: 200 ppm TWA: 40 mg/m³ 8 hour(s). TWA: 35 ppm 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training.If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus.It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact : Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. To avoid the risk of static discharges and gas ignition, soak contaminated clothing thoroughly with water before removing it. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Inhalation : Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion : As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 605°C (1121°F)

Flammable limits : Lower: 12.5% Upper: 74.2%

Products of combustion : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Fire hazards in the presence of various substances : Extremely flammable in the presence of the following materials or conditions: open flames, sparks and static discharge and oxidizing materials.

Fire-fighting media and instructions : In case of fire, use water spray (fog), foam or dry chemical.

In case of fire, allow gas to burn if flow cannot be shut off immediately. Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk.

Contains gas under pressure. Flammable gas. In a fire or if heated, a pressure increase will occur and the container may burst, with the risk of a subsequent explosion.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions	: Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.
Environmental precautions	: Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.
Methods for cleaning up	: Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Section 7. Handling and storage

Handling	: Use only with adequate ventilation. Use explosion-proof electrical (ventilating, lighting and material handling) equipment. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Keep away from heat, sparks and flame. To avoid fire, eliminate ignition sources. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
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). Segregate from oxidizing materials. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Section 8. Exposure controls/personal protection

Engineering controls	: Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits. The engineering controls also need to keep gas, vapor or dust concentrations below any lower explosive limits. Use explosion-proof ventilation equipment.
Personal protection	
Eyes	: Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts.
Skin	: Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
Respiratory	: Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.
	The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93
Hands	: Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary.
Personal protection in case of a large spill	: Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product. Full chemical-resistant suit and self-contained breathing apparatus should be worn only by trained and authorized persons.

Product name	
carbon monoxide	**ACGIH TLV (United States, 2/2010).** TWA: 29 mg/m³ 8 hour(s). TWA: 25 ppm 8 hour(s). **NIOSH REL (United States, 6/2009).** CEIL: 229 mg/m³ CEIL: 200 ppm TWA: 40 mg/m³ 10 hour(s). TWA: 35 ppm 10 hour(s). **OSHA PEL (United States, 6/2010).** TWA: 55 mg/m³ 8 hour(s).

TWA: 50 ppm 8 hour(s).
OSHA PEL 1989 (United States, 3/1989).
CEIL: 229 mg/m³
CEIL: 200 ppm
TWA: 40 mg/m³ 8 hour(s).
TWA: 35 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 28.01 g/mole
Molecular formula	: C-O
Boiling/condensation point	: -191°C (-311.8°F)
Melting/freezing point	: -205°C (-337°F)
Critical temperature	: -140.1°C (-220.2°F)
Vapor density	: 0.97 (Air = 1)
Specific Volume (ft ^{3}/lb)	: 13.8889
Gas Density (lb/ft ^{3})	: 0.072

Section 10. Stability and reactivity

Stability and reactivity	: The product is stable.
Incompatibility with various substances	: Extremely reactive or incompatible with the following materials: oxidizing materials.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

Product/ingredient name	Result	Species	Dose	Exposure
carbon monoxide	TDLo Intraperitoneal	Rat	35 mL/kg	-
	LC50 Inhalation Vapor	Rat	13500 mg/m3	15 minutes
	LC50 Inhalation Vapor	Rat	1900 mg/m3	4 hours
	LC50 Inhalation Gas.	Rat	6600 ppm	30 minutes
	LC50 Inhalation Gas.	Rat	3760 ppm	1 hours
	LC50 Inhalation Gas.	Mouse	2444 ppm	4 hours
	LC50 Inhalation Gas.	Rat	1807 ppm	4 hours

IDLH	: 1200 ppm
Chronic effects on humans	: **TERATOGENIC EFFECTS**: Classified 1 by European Union. May cause damage to the following organs: blood, lungs, the nervous system, heart, cardiovascular system, central nervous system (CNS).
Other toxic effects on humans	: No specific information is available in our database regarding the other toxic effects of this material to humans.

Specific effects

Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Products of degradation : Products of degradation: carbon oxides (CO, CO_2).

Environmental fate : Not available.

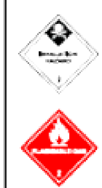
Environmental hazards : No known significant effects or critical hazards.

Toxicity to the environment : Not available.

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation.Return cylinders with residual product to Airgas, Inc.Do not dispose of locally.

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1016	CARBON MONOXIDE, COMPRESSED	2.3	Not applicable (gas).		Inhalation hazard zone D **Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: Forbidden. **Cargo aircraft** Quantity limitation: 25 kg **Special provisions** 4
TDG Classification	UN1016	CARBON MONOXIDE, COMPRESSED	2.3	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0 **ERAP Index** 500 **Passenger Carrying Ship Index** Forbidden **Passenger Carrying Road or Rail**

Carbon Monoxide						
						Forbidden
Mexico Classification	UN1016	CARBON MONOXIDE, COMPRESSED	2.3	Not applicable (gas).	 	-

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Section 15. Regulatory information

United States

U.S. Federal regulations : **TSCA 8(a) IUR**: Not determined
United States inventory (TSCA 8b): This material is listed or exempted.

SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: carbon monoxide
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: carbon monoxide: Fire hazard, Sudden release of pressure, Immediate (acute) health hazard, Delayed (chronic) health hazard

State regulations : **Connecticut Carcinogen Reporting**: This material is not listed.
Connecticut Hazardous Material Survey: This material is not listed.
Florida substances: This material is not listed.
Illinois Chemical Safety Act: This material is not listed.
Illinois Toxic Substances Disclosure to Employee Act: This material is not listed.
Louisiana Reporting: This material is not listed.
Louisiana Spill: This material is not listed.
Massachusetts Spill: This material is not listed.
Massachusetts Substances: This material is listed.
Michigan Critical Material: This material is not listed.
Minnesota Hazardous Substances: This material is not listed.
New Jersey Hazardous Substances: This material is listed.
New Jersey Spill: This material is not listed.
New Jersey Toxic Catastrophe Prevention Act: This material is listed.
New York Acutely Hazardous Substances: This material is not listed.
New York Toxic Chemical Release Reporting: This material is not listed.
Pennsylvania RTK Hazardous Substances: This material is listed.
Rhode Island Hazardous Substances: This material is not listed.

California Prop. 65 : **WARNING:** This product contains a chemical known to the State of California to cause birth defects or other reproductive harm.

Ingredient name	Cancer	Reproductive	No significant risk level	Maximum acceptable dosage level
Carbon Monoxide	No.	Yes.	No.	No.

Canada

WHMIS (Canada) : Class A: Compressed gas.
Class B-1: Flammable gas.
Class D-1A: Material causing immediate and serious toxic effects (Very toxic).
Class D-2A: Material causing other toxic effects (Very toxic).

CEPA Toxic substances: This material is not listed.
Canadian ARET: This material is not listed.
Canadian NPRI: This material is listed.
Alberta Designated Substances: This material is not listed.
Ontario Designated Substances: This material is not listed.
Quebec Designated Substances: This material is not listed.

Section 16. Other information

United States

Label requirements : FLAMMABLE GAS.
MAY CAUSE FLASH FIRE.
MAY BE FATAL IF INHALED.
MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA.
CONTENTS UNDER PRESSURE.

Canada

Label requirements : Class A: Compressed gas.
Class B-1: Flammable gas.
Class D-1A: Material causing immediate and serious toxic effects (Very toxic).
Class D-2A: Material causing other toxic effects (Very toxic).

Hazardous Material Information System (U.S.A.) :

Health	*	2
Flammability		4
Physical hazards		0

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

Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

Material Safety Data Sheet

Carbon Dioxide

Section 1. Chemical product and company identification

Product name	: Carbon Dioxide
Supplier	: AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	: Synthetic/Analytical chemistry.
Synonym	: Carbonic Acid, Carbon Dioxide Liquid, Carbon Dioxide, Refrigerated Liquid, Carbonic Anhydride
MSDS #	: 001013
Date of Preparation/Revision	: **1/20/2012.**
In case of emergency	: 1-866-734-3438

Section 2. Hazards identification

Physical state	: Gas or Liquid.
Emergency overview	: WARNING! GAS: CONTENTS UNDER PRESURE. MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION. CAN CAUSE TARGET ORGAN DAMAGE. Do not puncture or incinerate container. Can cause rapid suffocation. LIQUID: MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION. CAN CAUSE TARGET ORGAN DAMAGE. Extremely cold liquid and gas under pressure. Can cause rapid suffocation. May cause severe frostbite. Do not puncture or incinerate container. Avoid contact with eyes, skin and clothing. May cause target organ damage, based on animal data. Wash thoroughly after handling. Keep container closed. Avoid breathing gas. Use with adequate ventilation. Contact with rapidly expanding gas, liquid, or solid can cause frostbite.
Target organs	: May cause damage to the following organs: lungs.
Routes of entry	: Inhalation Dermal Eyes
Potential acute health effects	
Eyes	: Moderately irritating to eyes. Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Skin	: Moderately irritating to the skin. Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Inhalation	: Moderately irritating to the respiratory system.
Ingestion	: Ingestion is not a normal route of exposure for gases. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Potential chronic health effects	
Chronic effects	: May cause target organ damage, based on animal data.
Target organs	: May cause damage to the following organs: lungs.
Medical conditions aggravated by over-exposure	: Pre-existing disorders involving any target organs mentioned in this MSDS as being at risk may be aggravated by over-exposure to this product.

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Carbon Dioxide	124-38-9	100	**ACGIH TLV (United States, 2/2010).** STEL: 54000 mg/m³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 9000 mg/m³ 8 hour(s). TWA: 5000 ppm 8 hour(s). **NIOSH REL (United States, 6/2009).** STEL: 54000 mg/m³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 9000 mg/m³ 10 hour(s). TWA: 5000 ppm 10 hour(s). **OSHA PEL (United States, 6/2010).** TWA: 9000 mg/m³ 8 hour(s). TWA: 5000 ppm 8 hour(s). **OSHA PEL 1989 (United States, 3/1989).** STEL: 54000 mg/m³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 18000 mg/m³ 8 hour(s). TWA: 10000 ppm 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training.If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus.It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact : Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Inhalation : Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion : As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product : Non-flammable.

Products of combustion : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Fire-fighting media and instructions : Use an extinguishing agent suitable for the surrounding fire.

Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk.

Contains gas under pressure. In a fire or if heated, a pressure increase will occur and the container may burst or explode.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions	: Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.
Environmental precautions	: Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.
Methods for cleaning up	: Immediately contact emergency personnel. Stop leak if without risk. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Section 7. Handling and storage

Handling	: Wash thoroughly after handling. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Avoid contact with skin and clothing. Use with adequate ventilation. Avoid contact with eyes. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement. Never allow any unprotected part of the body to touch uninsulated pipes or vessels that contain cryogenic liquids. Prevent entrapment of liquid in closed systems or piping without pressure relief devices. Some materials may become brittle at low temperatures and will easily fracture.
Storage	: Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F). For additional information concerning storage and handling refer to Compressed Gas Association pamphlets P-1 Safe Handling of Compressed Gases in Containers and P-12 Safe Handling of Cryogenic Liquids available from the Compressed Gas Association, Inc.

Section 8. Exposure controls/personal protection

Engineering controls	: Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits.
Personal protection	
Eyes	: Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts. When working with cryogenic liquids, wear a full face shield.
Skin	: Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
Respiratory	: Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator. The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93
Hands	: Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary. Insulated gloves suitable for low temperatures
Personal protection in case of a large spill	: Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product. Full chemical-resistant suit and self-contained breathing apparatus should be worn only by trained and authorized persons.

Product name

Carbon Dioxide	
Carbon dioxide	**ACGIH TLV (United States, 2/2010).** STEL: 54000 mg/m³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 9000 mg/m³ 8 hour(s). TWA: 5000 ppm 8 hour(s). **NIOSH REL (United States, 6/2009).** STEL: 54000 mg/m³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 9000 mg/m³ 10 hour(s). TWA: 5000 ppm 10 hour(s). **OSHA PEL (United States, 6/2010).** TWA: 9000 mg/m³ 8 hour(s). TWA: 5000 ppm 8 hour(s). **OSHA PEL 1989 (United States, 3/1989).** STEL: 54000 mg/m³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 18000 mg/m³ 8 hour(s). TWA: 10000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 44.01 g/mole
Molecular formula	: C-O2
Melting/freezing point	: Sublimation temperature: -79°C (-110.2 to °F)
Critical temperature	: 30.9°C (87.6°F)
Vapor pressure	: 830 (psig)
Vapor density	: 1.53 (Air = 1) Liquid Density@BP: Solid density = 97.5 lb/ft3 (1562 kg/m3)
Specific Volume (ft^3/lb)	: 8.7719
Gas Density (lb/ft^3)	: 0.114

Section 10. Stability and reactivity

Stability and reactivity	: The product is stable.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

Product/ingredient name	Result	Species	Dose	Exposure
Carbon dioxide	LC50 Inhalation Gas.	Rat	470000 ppm	30 minutes

IDLH	: 40000 ppm
Chronic effects on humans	: May cause damage to the following organs: lungs.
Other toxic effects on humans	: No specific information is available in our database regarding the other toxic effects of this material to humans.

Specific effects

Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Toxicity of the products of biodegradation : not available

Environmental fate : Not available.

Environmental hazards : This product shows a low bioaccumulation potential.

Toxicity to the environment : Not available.

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation.Return cylinders with residual product to Airgas, Inc.Do not dispose of locally.

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1013 UN2187	CARBON DIOXIDE Carbon dioxide, refrigerated liquid	2.2	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: 75 kg **Cargo aircraft** Quantity limitation: 150 kg
TDG Classification	UN1013 UN2187	CARBON DIOXIDE Carbon dioxide, refrigerated liquid	2.2	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **Passenger Carrying Road or Rail Index** 75
Mexico Classification	UN1013 UN2187	CARBON DIOXIDE Carbon dioxide, refrigerated liquid	2.2	Not applicable (gas).		-

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Section 15. Regulatory information

United States

U.S. Federal regulations : **TSCA 8(a) IUR**: This material is listed or exempted.
United States inventory (TSCA 8b): This material is listed or exempted.
SARA 302/304/311/312 extremely hazardous substances: No products were found.
SARA 302/304 emergency planning and notification: No products were found.
SARA 302/304/311/312 hazardous chemicals: Carbon dioxide
SARA 311/312 MSDS distribution - chemical inventory - hazard identification:
Carbon dioxide: Sudden release of pressure, Immediate (acute) health hazard, Delayed (chronic) health hazard

State regulations : **Connecticut Carcinogen Reporting**: This material is not listed.
Connecticut Hazardous Material Survey: This material is not listed.
Florida substances: This material is not listed.
Illinois Chemical Safety Act: This material is not listed.
Illinois Toxic Substances Disclosure to Employee Act: This material is not listed.
Louisiana Reporting: This material is not listed.
Louisiana Spill: This material is not listed.
Massachusetts Spill: This material is not listed.
Massachusetts Substances: This material is listed.
Michigan Critical Material: This material is not listed.
Minnesota Hazardous Substances: This material is not listed.
New Jersey Hazardous Substances: This material is listed.
New Jersey Spill: This material is not listed.
New Jersey Toxic Catastrophe Prevention Act: This material is not listed.
New York Acutely Hazardous Substances: This material is not listed.
New York Toxic Chemical Release Reporting: This material is not listed.
Pennsylvania RTK Hazardous Substances: This material is listed.
Rhode Island Hazardous Substances: This material is not listed.

Canada

WHMIS (Canada) : Class A: Compressed gas.
CEPA Toxic substances: This material is listed.
Canadian ARET: This material is not listed.
Canadian NPRI: This material is not listed.
Alberta Designated Substances: This material is not listed.
Ontario Designated Substances: This material is not listed.
Quebec Designated Substances: This material is not listed.

Section 16. Other information

United States

Label requirements : GAS:
CONTENTS UNDER PRESURE.
MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION.
CAN CAUSE TARGET ORGAN DAMAGE.
Do not puncture or incinerate container.
Can cause rapid suffocation.
LIQUID:
MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION.
CAN CAUSE TARGET ORGAN DAMAGE.
Extremely cold liquid and gas under pressure.
Can cause rapid suffocation.
May cause severe frostbite.

Canada

Label requirements : Class A: Compressed gas.

Carbon Dioxide

Hazardous Material Information System (U.S.A.) :

Health	*	1
Flammability		0
Physical hazards		0

liquid:

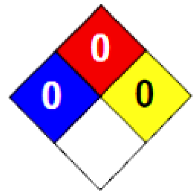
Health	3
Fire hazard	0
Reactivity	0
Personal protection	

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

liquid:

Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.



Health	0
Fire	0
Reactivity	0
Personal Protection	A

Material Safety Data Sheet
Water MSDS

Section 1: Chemical Product and Company Identification

Product Name: Water

Catalog Codes: SLW1063

CAS#: 7732-18-5

RTECS: ZC0110000

TSCA: TSCA 8(b) inventory: Water

CI#: Not available.

Synonym: Dihydrogen oxide

Chemical Name: Water

Chemical Formula: H_2O

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
Water	7732-18-5	100

Toxicological Data on Ingredients: Not applicable.

Section 3: Hazards Identification

Potential Acute Health Effects:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-irritating to the eyes. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. Non-corrosive to the eyes. Non-corrosive for lungs.

Potential Chronic Health Effects:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-irritating to the eyes. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Not available. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available.

Section 4: First Aid Measures

Eye Contact: Not applicable.

Skin Contact: Not applicable.

Serious Skin Contact: Not available.

Inhalation: Not applicable.

Serious Inhalation: Not available.

Ingestion: Not Applicable

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: Non-flammable.

Auto-Ignition Temperature: Not applicable.

Flash Points: Not applicable.

Flammable Limits: Not applicable.

Products of Combustion: Not available.

Fire Hazards in Presence of Various Substances: Not applicable.

Explosion Hazards in Presence of Various Substances: Not Applicable

Fire Fighting Media and Instructions: Not applicable.

Special Remarks on Fire Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill: Mop up, or absorb with an inert dry material and place in an appropriate waste disposal container.

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

Section 7: Handling and Storage

Precautions: No specific safety phrase has been found applicable for this product.

Storage: Not applicable.

Section 8: Exposure Controls/Personal Protection

Engineering Controls: Not Applicable

Personal Protection: Safety glasses. Lab coat.

Personal Protection in Case of a Large Spill: Not Applicable

Exposure Limits: Not available.

Section 9: Physical and Chemical Properties

Physical state and appearance: Liquid.

Odor: Odorless.

Taste: Not available.

Molecular Weight: 18.02 g/mole

Color: Colorless.

pH (1% soln/water): 7 [Neutral.]

Boiling Point: 100°C (212°F)

Melting Point: Not available.

Critical Temperature: Not available.

Specific Gravity: 1 (Water = 1)

Vapor Pressure: 2.3 kPa (@ 20°C)

Vapor Density: 0.62 (Air = 1)

Volatility: Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: Not available.

Ionicity (in Water): Not available.

Dispersion Properties: Not applicable

Solubility: Not Applicable

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: Not available.

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.

Toxicity to Animals:
LD50: [Rat] - Route: oral; Dose: > 90 ml/kg LC50: Not available.

Chronic Effects on Humans: Not available.

Other Toxic Effects on Humans:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. Non-corrosive to the eyes. Non-corrosive for lungs.

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 product itself and its products of degradation are not toxic.

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: Not a DOT controlled material (United States).

Identification: Not applicable.

Special Provisions for Transport: Not applicable.

Section 15: Other Regulatory Information

Federal and State Regulations: TSCA 8(b) inventory: Water

Other Regulations: EINECS: This product is on the European Inventory of Existing Commercial Chemical Substances.

Other Classifications:

WHMIS (Canada): Not controlled under WHMIS (Canada).

DSCL (EEC):
This product is not classified according to the EU regulations. Not applicable.

HMIS (U.S.A.):

- **Health Hazard:** 0
- **Fire Hazard:** 0
- **Reactivity:** 0
- **Personal Protection:** a

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

- **Health:** 0
- **Flammability:** 0
- **Reactivity:** 0
- **Specific hazard:**

Protective Equipment:
Not applicable. Lab coat. Not applicable. Safety glasses.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

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Last Updated: 05/21/2013 12:00 PM

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