4-2014

Oxidative Coupling of Methane to Ethylene

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Oxidative Coupling of Methane to Ethylene

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 C₂ hydrocarbons will offer more attractive returns.

Disciplines
Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering

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OXIDATIVE COUPLING OF METHANE TO ETHYLENE

Tyler Fini  Corey Patz
University of Pennsylvania University of Pennsylvania

Rebecca Wentzel
University of Pennsylvania
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 C₂ 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.\textsuperscript{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.\textsuperscript{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\textsubscript{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\textsubscript{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.

\[
\text{CH}_4 + \frac{1}{2} \text{O}_2 \rightarrow \frac{1}{2} \text{C}_2\text{H}_4 + \text{H}_2\text{O} \quad (1)
\]

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.

\[ \text{CH}_4 + \frac{3}{2} \text{O}_2 \rightarrow \text{CO} + 2 \text{H}_2\text{O} \]  
(2)  

\[ \text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} \]  
(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 \(\text{C}_2\) products. In order to operate the reactor section in a way that the \(\text{C}_2\) 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.

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<th>(\Delta H^\circ_{298}) (KJ/mol)</th>
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</table>
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
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 driven by customer value proposition such as 1) capitalizing on natural gas abundance, 2) environmental 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
**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 C₂ 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 CO₂ 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 CH₄ conversion, and C₂ yield and selectivity. Using the work of Matsuura et. al, our process requires that we feed our CH₄ and O₂ in a 3:1 ratio with no diluents at 700 °C. Research with these conditions gave data of 13.3% CH₄ conversion, 94.8% O₂ conversion, 49% C₂ selectivity, and a C₂H₆/C₂H₄ 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 C₂ 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 C₂ 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

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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 CO₂ and water. The final concern with MEA is that it is not effective enough for the complete removal of CO₂ 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, $\rho$ is the density of the gas stream, $\mu$ is the
dynamic viscosity, $V_s$ is the superficial velocity, and $\varepsilon$ is the void fraction.

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

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

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

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. 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. 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
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Section 300: Refrigeration Cycle

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.
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

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
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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%. 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](image)

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. 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.
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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.

![Steam Turbine](image.png)

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.
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<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>OXYGEN</td>
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<td>0.00</td>
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<td>0.00</td>
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<tr>
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<td>0.00</td>
<td>0.00</td>
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<tr>
<td>C2H6</td>
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<tr>
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<td>0.00</td>
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<td>0.00</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>PROPANE</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total Flow lb/hr</td>
<td>3.86E+06</td>
<td>3.86E+06</td>
<td>9.01E+07</td>
<td>9.01E+07</td>
<td>3.86E+06</td>
<td>9.01E+07</td>
<td>1.02E+08</td>
</tr>
</tbody>
</table>
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.
<table>
<thead>
<tr>
<th>Equipment</th>
<th>Description</th>
<th>Utility (MW/yr)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section 100</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B101</td>
<td>Blower</td>
<td>3.73</td>
<td>Steam</td>
</tr>
<tr>
<td>B102</td>
<td>Blower</td>
<td>0.60</td>
<td>Steam</td>
</tr>
<tr>
<td>P101</td>
<td>Pump</td>
<td>0.71</td>
<td>Electricity</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>5.04</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Net Section 100</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Section 200</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P201</td>
<td>Pump</td>
<td>0.02</td>
<td>Electricity</td>
</tr>
<tr>
<td>RP201</td>
<td>Reflux Pump</td>
<td>0.066</td>
<td>Electricity</td>
</tr>
<tr>
<td>RP202</td>
<td>Reflux Pump</td>
<td>2.36</td>
<td>Electricity</td>
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<tr>
<td>C201</td>
<td>Compressor</td>
<td>40.32</td>
<td>Steam</td>
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<tr>
<td>C202</td>
<td>Compressor</td>
<td>2.68</td>
<td>Steam</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>45.446</strong></td>
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<td><strong>Section 300</strong></td>
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</tr>
<tr>
<td>P301</td>
<td>Pump</td>
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<td>Electricity</td>
</tr>
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<td>P302</td>
<td>Pump</td>
<td>0.006</td>
<td>Electricity</td>
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<td>Pump</td>
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<td>Compressor</td>
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<td>Steam</td>
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<td>Compressor</td>
<td>104.80</td>
<td>Steam</td>
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<td>C303</td>
<td>Compressor</td>
<td>125.29</td>
<td>Steam</td>
</tr>
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<td><strong>309.971</strong></td>
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</tr>
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<td><strong>Net Section 300</strong></td>
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</tr>
<tr>
<td><strong>Section 400</strong></td>
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</tr>
<tr>
<td>B401</td>
<td>Blower</td>
<td>0.11</td>
<td>Steam</td>
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<td>P401</td>
<td>Pump</td>
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<td>Electricity</td>
</tr>
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<td><strong>0.21</strong></td>
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<td><strong>Net Section 400</strong></td>
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<tr>
<td><strong>Totals</strong></td>
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<tr>
<td>Total Electricity</td>
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<td><strong>3.277</strong></td>
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<tr>
<td>Total Steam</td>
<td></td>
<td><strong>356.780</strong></td>
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</tr>
<tr>
<td>Total Utilities</td>
<td></td>
<td><strong>360.007</strong></td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Purpose</th>
<th>Amount within System (lb)</th>
<th>Price ($/lb)</th>
<th>Purchased Cost</th>
<th>Amount Lost (lb/yr)</th>
<th>Replenish Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Water</td>
<td>Cooling</td>
<td>1.22E8</td>
<td>0.000628</td>
<td>$ 76,930</td>
<td>1.81E10</td>
<td>$ 11,368,650</td>
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<tr>
<td>Boiler Water</td>
<td>Steam</td>
<td>9.86E6</td>
<td>0.000215</td>
<td>$ 2,119</td>
<td>7.83E4</td>
<td>$ 17</td>
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<td>Propane</td>
<td>Refrigeration</td>
<td>5.13E6</td>
<td>0.948</td>
<td>$3,750,000</td>
<td>2.46E5</td>
<td>$234,000</td>
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<td>Ethylene</td>
<td>Refrigeration</td>
<td>2.16E6</td>
<td>-</td>
<td>-</td>
<td>1.08E5</td>
<td>-</td>
</tr>
<tr>
<td>Methane</td>
<td>Refrigeration</td>
<td>1.59E6</td>
<td>-</td>
<td>-</td>
<td>7.95E5</td>
<td>-</td>
</tr>
</tbody>
</table>
**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 preheat 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\textsubscript{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%.\textsuperscript{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 selectivity to C\textsubscript{2} hydrocarbons will increase the ROI.

<table>
<thead>
<tr>
<th>Table 8.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profitability Measures</td>
</tr>
<tr>
<td>The Internal Rate of Return (IRR) for this project is</td>
</tr>
<tr>
<td>The Net Present Value (NPV) of this project in 2015 is</td>
</tr>
</tbody>
</table>

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 allotted 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 cryogenic 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

<table>
<thead>
<tr>
<th>Percent Section</th>
<th>Cost</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 100</td>
<td>$34,973,679</td>
<td>5.82%</td>
</tr>
<tr>
<td>Section 200</td>
<td>$97,164,090</td>
<td>16.1%</td>
</tr>
<tr>
<td>Section 300</td>
<td>$369,369,353</td>
<td>61.5%</td>
</tr>
<tr>
<td>Section 400</td>
<td>$55,804,870</td>
<td>9.29%</td>
</tr>
<tr>
<td>Section 500</td>
<td>$59,558,635</td>
<td>9.92%</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>$600,360,871</td>
<td>100.00%</td>
</tr>
<tr>
<td>Description</td>
<td>Type</td>
<td>Purchase Cost</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>B-101</td>
<td>Fabricated Equipment</td>
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</tr>
<tr>
<td>BFW-01</td>
<td>Compound in System</td>
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</tr>
<tr>
<td>CW-01</td>
<td>Compound in System</td>
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<td>HX-101</td>
<td>Fabricated Equipment</td>
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<td>HX-102</td>
<td>Fabricated Equipment</td>
<td>$1,072,618</td>
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<tr>
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<td>Fabricated Equipment</td>
<td>$53,086</td>
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<td>R-101/2/3/4</td>
<td>Catalysts</td>
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<td>R-101/2/3/4 5</td>
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<td>$3,133,425</td>
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<td>RHX-101/2/3/4</td>
<td>Fabricated Equipment</td>
<td>$272,090</td>
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**Total Cost for Section 100**  $34,973,678
## Table 8.4

**Section 200 Equipment Costs**

<table>
<thead>
<tr>
<th>Equipment Description</th>
<th>Type</th>
<th>Purchase Cost</th>
<th>Bare Module Factor</th>
<th>Bare Module Cost</th>
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<tbody>
<tr>
<td>C-201</td>
<td>Process Machinery</td>
<td>$7,467,878</td>
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<td>$17,176,119</td>
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<td>C-201</td>
<td>Process Machinery</td>
<td>$6,174,762</td>
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<td>$14,201,953</td>
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<td>C-202</td>
<td>Process Machinery</td>
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<td>2.30</td>
<td>$3,148,781</td>
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<td>Fabricated Equipment</td>
<td>$1,093,303</td>
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<td>D-202</td>
<td>Fabricated Equipment</td>
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<td>DC-201</td>
<td>Fabricated Equipment</td>
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<td>Fabricated Equipment</td>
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<td>Fabricated Equipment</td>
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<td>6.98</td>
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<tr>
<td>HX-202</td>
<td>Fabricated Equipment</td>
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<td>HX-203</td>
<td>Fabricated Equipment</td>
<td>$886,891</td>
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<td>$6,793,585</td>
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<td>HX-204</td>
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<td>8.04</td>
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<td>HX-205</td>
<td>Fabricated Equipment</td>
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<td>8.04</td>
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<td>P-201</td>
<td>Process Machinery</td>
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<td>Process Machinery</td>
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<td>Process Machinery</td>
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<td>Process Machinery</td>
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<td>V-201</td>
<td>Fabricated Equipment</td>
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<td>Catalysts</td>
<td>$17,010,420</td>
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**Total Cost for Section 200**  $100,312,871
<table>
<thead>
<tr>
<th>Description</th>
<th>Type</th>
<th>Purchase Cost</th>
<th>Bare Module Factor</th>
<th>Bare Module Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-301</td>
<td>Process Machinery</td>
<td>$37,378,265</td>
<td>2.15</td>
<td>$ 80,363,270</td>
</tr>
<tr>
<td>C-302</td>
<td>Process Machinery</td>
<td>$37,378,265</td>
<td>2.15</td>
<td>$ 80,363,270</td>
</tr>
<tr>
<td>C-303</td>
<td>Process Machinery</td>
<td>$37,378,265</td>
<td>2.15</td>
<td>$ 80,363,270</td>
</tr>
<tr>
<td>F-301</td>
<td>Fabricated Equipment</td>
<td>$719,612</td>
<td>3.05</td>
<td>$ 2,194,817</td>
</tr>
<tr>
<td>F-302</td>
<td>Fabricated Equipment</td>
<td>$428,865</td>
<td>3.05</td>
<td>$ 1,308,038</td>
</tr>
<tr>
<td>F-303</td>
<td>Fabricated Equipment</td>
<td>$595,686</td>
<td>3.05</td>
<td>$ 1,816,842</td>
</tr>
<tr>
<td>HX-301/2/3</td>
<td>Fabricated Equipment</td>
<td>$14,924,202</td>
<td>6.70</td>
<td>$ 99,992,153</td>
</tr>
<tr>
<td>HX-304</td>
<td>Fabricated Equipment</td>
<td>$1,131,677</td>
<td>7.30</td>
<td>$ 8,261,242</td>
</tr>
<tr>
<td>HX-305</td>
<td>Fabricated Equipment</td>
<td>$165,595</td>
<td>7.30</td>
<td>$ 1,208,844</td>
</tr>
<tr>
<td>HX-306</td>
<td>Fabricated Equipment</td>
<td>$1,169,530</td>
<td>7.30</td>
<td>$ 8,537,569</td>
</tr>
<tr>
<td>P-301</td>
<td>Process Machinery</td>
<td>$4,833</td>
<td>6.30</td>
<td>$ 30,448</td>
</tr>
<tr>
<td>P-302</td>
<td>Process Machinery</td>
<td>$4,640</td>
<td>6.30</td>
<td>$ 29,232</td>
</tr>
<tr>
<td>P-303</td>
<td>Process Machinery</td>
<td>$4,492</td>
<td>6.30</td>
<td>$ 28,300</td>
</tr>
<tr>
<td>PR-01</td>
<td>Compound in System</td>
<td>$1,249,246</td>
<td>3.90</td>
<td>$ 4,872,059</td>
</tr>
</tbody>
</table>

**Total Cost for Section 300** $ 369,369,353
### Table 8.6

**Equipment Costs Section 400**

<table>
<thead>
<tr>
<th>Equipment Description</th>
<th>Type</th>
<th>Purchase Cost</th>
<th>Factor</th>
<th>Bare Module Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>HX-401</td>
<td>Fabricated Equipment</td>
<td>$24,563</td>
<td>7.09</td>
<td>$174,152</td>
</tr>
<tr>
<td>HX-402</td>
<td>Fabricated Equipment</td>
<td>$48,450</td>
<td>7.23</td>
<td>$350,294</td>
</tr>
<tr>
<td>K-401</td>
<td>Fabricated Equipment</td>
<td>$315,639</td>
<td>6.37</td>
<td>$2,010,620</td>
</tr>
<tr>
<td>P-401</td>
<td>Process Machinery</td>
<td>$6,917</td>
<td>6.30</td>
<td>$43,577</td>
</tr>
<tr>
<td>R-401</td>
<td>Fabricated Equipment</td>
<td>$8,921,711</td>
<td>2.58</td>
<td>$23,018,014</td>
</tr>
<tr>
<td>RHX-401</td>
<td>Fabricated Equipment</td>
<td>$22,154</td>
<td>7.06</td>
<td>$156,407</td>
</tr>
<tr>
<td>T-401/2/3/4</td>
<td>Process Machinery</td>
<td>$30,000,000</td>
<td>1.00</td>
<td>$30,000,000</td>
</tr>
</tbody>
</table>

**Total Cost of Section 400** $55,804,870
### Table 8.7

**Equipment Costs Section 500**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Description</th>
<th>Cost</th>
<th>Price</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>HX-501 AB</td>
<td>Fabricated Equipment</td>
<td>$4,350,008</td>
<td>6.56</td>
<td>$28,551,508</td>
</tr>
<tr>
<td>Pump-501 ABCD</td>
<td>Process Machinery</td>
<td>$935,480</td>
<td>6.30</td>
<td>$5,893,520</td>
</tr>
<tr>
<td>V-501/2/3/4/5/6</td>
<td>Storage</td>
<td>$9,572,136</td>
<td>1.00</td>
<td>$9,572,136</td>
</tr>
<tr>
<td>CT-501</td>
<td>Storage</td>
<td>$13,894,042</td>
<td>1.00</td>
<td>$13,894,042</td>
</tr>
<tr>
<td>V-508</td>
<td>Fabricated Equipment</td>
<td>$1,647,429</td>
<td>1.00</td>
<td>$1,647,429</td>
</tr>
</tbody>
</table>

**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:

<table>
<thead>
<tr>
<th>General Expenses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Selling / Transfer Expenses:</td>
<td>$ 18,600,000</td>
</tr>
<tr>
<td>Direct Research:</td>
<td>$ 29,760,000</td>
</tr>
<tr>
<td>Allocated Research:</td>
<td>$ 3,100,000</td>
</tr>
<tr>
<td>Administrative Expense:</td>
<td>$ 12,400,000</td>
</tr>
<tr>
<td>Management Incentive Compensation:</td>
<td>$ 7,750,000</td>
</tr>
<tr>
<td><strong>Total General Expenses</strong></td>
<td>$ 71,610,000</td>
</tr>
<tr>
<td><strong>Raw Materials</strong></td>
<td>$265,000,000</td>
</tr>
<tr>
<td><strong>Byproducts</strong></td>
<td>$(243,310,800)</td>
</tr>
<tr>
<td><strong>Utilities</strong></td>
<td>$(59,008,331)</td>
</tr>
<tr>
<td><strong>Total Variable Costs</strong></td>
<td><strong>$ 34,290,869</strong></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accounts Receivable</td>
<td>$22,931,507</td>
<td>$11,465,753</td>
<td>$11,465,753</td>
</tr>
<tr>
<td>Cash Reserves</td>
<td>$3,134,112</td>
<td>$1,567,056</td>
<td>$1,567,056</td>
</tr>
<tr>
<td>Accounts Payable</td>
<td>$(7,618,870)</td>
<td>$(3,809,435)</td>
<td>$(3,809,435)</td>
</tr>
<tr>
<td>Ethylene Inventory</td>
<td>$2,293,151</td>
<td>$1,146,575</td>
<td>$1,146,575</td>
</tr>
<tr>
<td>Raw Materials</td>
<td>$653,425</td>
<td>$326,712</td>
<td>$326,712</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$21,393,324</strong></td>
<td><strong>$10,696,662</strong></td>
<td><strong>$10,696,662</strong></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Operations</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Wages and Benefits</td>
<td>$25,480,000</td>
</tr>
<tr>
<td>Direct Salaries and Benefits</td>
<td>$3,822,000</td>
</tr>
<tr>
<td>Operating Supplies and Services</td>
<td>$1,528,800</td>
</tr>
<tr>
<td>Technical Assistance to Manufacturing</td>
<td>-</td>
</tr>
<tr>
<td>Control Laboratory</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Operations</strong></td>
<td><strong>$30,830,800</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maintenance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wages and Benefits</td>
<td>$35,067,078</td>
</tr>
<tr>
<td>Salaries and Benefits</td>
<td>$8,766,770</td>
</tr>
<tr>
<td>Materials and Services</td>
<td>$35,067,078</td>
</tr>
<tr>
<td>Maintenance Overhead</td>
<td>$1,753,354</td>
</tr>
<tr>
<td><strong>Total Maintenance</strong></td>
<td><strong>$80,654,280</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Overhead</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Plant Overhead</td>
<td>$5,192,645</td>
</tr>
<tr>
<td>Mechanical Department Services</td>
<td>$1,755,260</td>
</tr>
<tr>
<td>Employee Relations Department</td>
<td>$4,315,015</td>
</tr>
<tr>
<td>Business Services</td>
<td>$5,412,053</td>
</tr>
<tr>
<td><strong>Total Operating Overhead</strong></td>
<td><strong>$16,674,973</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property Taxes and Insurance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property Taxes and Insurance</td>
<td>$15,585,368</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other Annual Expenses</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rental Fees (Office and Laboratory Space):</td>
<td>$ -</td>
</tr>
<tr>
<td>Licensing Fees</td>
<td>$ -</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>$ -</td>
</tr>
</tbody>
</table>

| **Total Other Annual Expenses**  | **-**         |
| **Total Fixed Costs**            | **$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>
<thead>
<tr>
<th>Table 8.10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment Summary</strong></td>
</tr>
<tr>
<td><strong>Bare Module Costs</strong></td>
</tr>
<tr>
<td>Fabricated Equipment</td>
</tr>
<tr>
<td>Process Machinery</td>
</tr>
<tr>
<td>Spares</td>
</tr>
<tr>
<td>Storage</td>
</tr>
<tr>
<td>Other Equipment</td>
</tr>
<tr>
<td>Catalysts</td>
</tr>
<tr>
<td>Computers, Software, Etc.</td>
</tr>
<tr>
<td><strong>Total Bare Module Costs:</strong></td>
</tr>
<tr>
<td><strong>Direct Permanent Investment</strong></td>
</tr>
<tr>
<td>Cost of Site Preparations:</td>
</tr>
<tr>
<td>Cost of Service Facilities:</td>
</tr>
<tr>
<td>Allocated Costs for utility plants and related facilities:</td>
</tr>
<tr>
<td><strong>Direct Permanent Investment</strong></td>
</tr>
<tr>
<td><strong>Total Depreciable Capital</strong></td>
</tr>
<tr>
<td>Cost of Contingencies &amp; Contractor Fees</td>
</tr>
<tr>
<td><strong>Total Depreciable Capital</strong></td>
</tr>
<tr>
<td><strong>Total Permanent Investment</strong></td>
</tr>
<tr>
<td>Cost of Land:</td>
</tr>
<tr>
<td>Cost of Royalties:</td>
</tr>
<tr>
<td>Cost of Plant Start-Up:</td>
</tr>
<tr>
<td><strong>Total Permanent Investment - Unadjusted</strong></td>
</tr>
<tr>
<td>Site Factor</td>
</tr>
<tr>
<td><strong>Total Permanent Investment</strong></td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Year</th>
<th>Percentage of Design Capacity</th>
<th>Product Unit Price</th>
<th>Sales</th>
<th>Capital Costs</th>
<th>Working Capital</th>
<th>Var Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>0%</td>
<td>$0.62</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2016</td>
<td>0%</td>
<td>$0.62</td>
<td>-</td>
<td>(872,780,600)</td>
<td>(21,393,300)</td>
<td>-</td>
</tr>
<tr>
<td>2017</td>
<td>45%</td>
<td>$0.62</td>
<td>279,000,000</td>
<td>-</td>
<td>(10,696,700)</td>
<td>(15,430,900)</td>
</tr>
<tr>
<td>2018</td>
<td>68%</td>
<td>$0.62</td>
<td>418,500,000</td>
<td>-</td>
<td>(10,696,700)</td>
<td>(23,146,300)</td>
</tr>
<tr>
<td>2019</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2020</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2021</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2022</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2023</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2024</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2025</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2026</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2027</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2028</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2029</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2030</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2031</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2032</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2033</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2034</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2035</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>-</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>2036</td>
<td>90%</td>
<td>$0.62</td>
<td>558,000,000</td>
<td>-</td>
<td>42,786,600</td>
<td>(30,861,800)</td>
</tr>
<tr>
<td>Year</td>
<td>Fixed Costs</td>
<td>Depreciation</td>
<td>Taxable Income</td>
<td>Taxes</td>
<td>Net Earnings</td>
<td>Cash Flow</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>--------------</td>
<td>----------------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>2015</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2016</td>
<td>(143,745,400)</td>
<td>(155,853,700)</td>
<td>(36,030,000)</td>
<td>13,331,100</td>
<td>(22,698,900)</td>
<td>(894,173,900)</td>
</tr>
<tr>
<td>2017</td>
<td>(143,745,400)</td>
<td>(249,365,900)</td>
<td>2,242,400</td>
<td>(829,700)</td>
<td>1,412,700</td>
<td>(777,542,600)</td>
</tr>
<tr>
<td>2018</td>
<td>(143,745,400)</td>
<td>(149,619,500)</td>
<td>233,773,300</td>
<td>(86,496,100)</td>
<td>147,277,200</td>
<td>(684,946,600)</td>
</tr>
<tr>
<td>2019</td>
<td>(143,745,400)</td>
<td>(89,771,700)</td>
<td>293,621,100</td>
<td>(108,639,800)</td>
<td>184,981,300</td>
<td>(220,736,400)</td>
</tr>
<tr>
<td>2020</td>
<td>(143,745,400)</td>
<td>(89,771,700)</td>
<td>293,621,100</td>
<td>(108,639,800)</td>
<td>184,981,300</td>
<td>(274,753,000)</td>
</tr>
<tr>
<td>2021</td>
<td>(143,745,400)</td>
<td>(44,885,900)</td>
<td>338,506,900</td>
<td>(125,247,600)</td>
<td>213,259,400</td>
<td>(4,906,800)</td>
</tr>
<tr>
<td>2022</td>
<td>(143,745,400)</td>
<td>-</td>
<td>383,392,800</td>
<td>(141,855,300)</td>
<td>241,537,500</td>
<td>74,052,300</td>
</tr>
<tr>
<td>2023</td>
<td>(143,745,400)</td>
<td>-</td>
<td>383,392,800</td>
<td>(141,855,300)</td>
<td>241,537,500</td>
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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.
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

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<th>$120,746,154</th>
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<td>20.85%</td>
<td>20.73%</td>
<td>19.81%</td>
<td>19.39%</td>
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<td>22.02%</td>
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<td>22.13%</td>
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<td>$0.65</td>
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<td>23.45%</td>
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<tr>
<td>$0.85</td>
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<td>29.43%</td>
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<td>$1.00</td>
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<td>32.71%</td>
<td>32.34%</td>
<td>31.97%</td>
<td>31.69%</td>
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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.
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

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\(^{17}\) Data from Table 8.15 IRR Product Price vs. Total Permanent Investment
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.\(^1\) 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 autoignition 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.\(^2\) 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.\(^3\) 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-411 comes 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 C2 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).

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. 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. 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. 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

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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 ft². 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, weighs 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, weighs 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 \text{ ft}^2.\text{ The heat duty is }1,266,843\text{ MBTU/hr. The bare module cost is }$382,685\text{ 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 \text{ ft}^2.\text{ The heat duty is }1,266,843\text{ MBTU/hr. The bare module cost is }$382,685\text{ and the annual utility cost is zero because the utilities are provided from within the system.}

\textit{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 ft². 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 ft². 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 ft². 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 ft². 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 34,580,000 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 145,000 MBTU/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 145,000 MBTU/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 ft\(^2\). 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 ft\(^2\). 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 ft\(^2\). 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 ft². 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 ft². 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 ft². 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 ft². 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:

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<tr>
<th>Block Type: Blower</th>
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<tr>
<td><strong>Function:</strong> Increases pressure of methane feed</td>
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<tr>
<th>Materials:</th>
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<tr>
<td>Stream</td>
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<th>Operating Conditions:</th>
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<tr>
<td>Pressure (psi)</td>
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<td>Temperature (°F)</td>
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### B-102

**Block Type:** Blower  

**Function:** Increases pressure of oxygen feed  

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**Design Data:**

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**Bare Module Cost:** $199,139  

**Annual Operating Cost:** 0
## Block Type: Heat Exchanger

### Function: First preheater for methane feed

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<td>Stream</td>
<td>S-105</td>
<td>S-106</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>129.6</td>
<td>286</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

### 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 (ft²): 48986
- Overall Heat Transfer Coefficient (BTU/hr R ft²): 14.89
- Heat Duty (MBTU/hr): 105849

### Purchase Cost:
- $443,365

### Bare Module Cost:
- $3,241,254

### Annual Utilities Cost:
- 0
**Block Type:** Heat Exchanger

**Function:** Second preheater for methane feed

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-104</td>
<td>S-116</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>1137.6</td>
<td>482</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-106</td>
<td>S-107</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>286</td>
<td>1133.1</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

**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 (ft²)   | 106065          |
| Overall Heat Transfer Coefficient (BTU/hr R ft²) | 20.51 |
| Heat Duty (MBTU/hr)   | 801852          |

**Purchase Cost:**

| 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

<table>
<thead>
<tr>
<th>Tube</th>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
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</thead>
<tbody>
<tr>
<td>S-107</td>
<td>Temperature (°F)</td>
<td>1652.3</td>
<td>1334.6</td>
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<tr>
<td>S-109</td>
<td>Pressure (psi)</td>
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<table>
<thead>
<tr>
<th>Shell</th>
<th>Stream</th>
<th>S-108</th>
<th>S-117</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-108</td>
<td>Temperature (°F)</td>
<td>1133.2</td>
<td>1202</td>
</tr>
<tr>
<td>S-117</td>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

**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 (ft²): 1749  
- Overall Heat Transfer Coefficient (BTU/hr R ft²): 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:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-103</td>
<td>221.2</td>
<td>184.7</td>
</tr>
<tr>
<td>S-104</td>
<td>16</td>
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### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
<th>S-101B</th>
<th>S-102B</th>
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<tbody>
<tr>
<td>S-102B</td>
<td>81.1</td>
<td>205</td>
</tr>
<tr>
<td>S-101B</td>
<td>114.7</td>
<td>114.7</td>
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### Operating Conditions:

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<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>583695</td>
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<td>Shell Flow Rate (lb/hr)</td>
<td>897689</td>
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### Design Data:

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<thead>
<tr>
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<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
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<tr>
<td>Transfer Area (ft²)</td>
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<td>Overall Heat Transfer Coefficient (BTU/hr R ft²)</td>
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<td>Heat Duty (MBTU/hr)</td>
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### Purchase Cost:

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<tr>
<td></td>
<td>$48,918</td>
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### Bare Module Cost:

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<tr>
<td></td>
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### Annual Utilities Cost:

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</table>
**IDENTIFICATION:** Heat Exchanger

**FUNCTION:** Second preheater for oxygen feed

### Tube:

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<tr>
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</thead>
<tbody>
<tr>
<td>S-116</td>
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<td>1137.6</td>
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<td>Temperature (°F)</td>
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<td>87</td>
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<tr>
<td>Pressure (psi)</td>
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### Shell:

<table>
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<tr>
<th>Stream</th>
<th>S-115B</th>
<th>S-113</th>
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<tbody>
<tr>
<td>Temperature (°F)</td>
<td>205</td>
<td>1202</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>114.7</td>
<td>114.7</td>
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</table>

### Operating Conditions:

- Tube Flow Rate (lb/hr): 2042030
- Shell Flow Rate (lb/hr): 897689

### Design Data:

<table>
<thead>
<tr>
<th>Construction Material</th>
<th>Stainless Steel/Stainless Steel</th>
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</thead>
<tbody>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>4020</td>
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<tr>
<td>Overall Heat Transfer Coefficient (BTU/hr R ft²)</td>
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<td>Heat Duty (MBTU/hr)</td>
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### 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

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-115A</td>
<td>S-115B</td>
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**Operating Conditions:**

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Pressure Rise (psi)</td>
<td>203</td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>456</td>
</tr>
<tr>
<td>Flow Rate (ft³/hr)</td>
<td>51456</td>
</tr>
</tbody>
</table>

**Design Data:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>5</td>
</tr>
<tr>
<td>Pump Efficiency</td>
<td>0.86</td>
</tr>
<tr>
<td>Consumed Power (hp)</td>
<td>884</td>
</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
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**Purchase Cost:** $208,975  
**Bare Module Cost:** $208,975  
**Annual Operating Cost:** 0
**Block Type:** Fixed Bed Catalytic Reactor with internal shell and tube HX

**Function:** facilitate Oxidative coupling of methane to form ethylene/ethane

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stream</strong></td>
<td>S-109A</td>
<td>S-112A</td>
</tr>
<tr>
<td><strong>Mass Flow (lb/hr)</strong></td>
<td>514,208</td>
<td>514,208</td>
</tr>
<tr>
<td><strong>Volumetric Flow (ft³/hr)</strong></td>
<td>5.38x10⁶</td>
<td>5.42x10⁶</td>
</tr>
<tr>
<td><strong>Breakdown (Mass Frac):</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>0.563</td>
<td>0.365</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.436</td>
<td>0</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.0001</td>
<td>0.062</td>
</tr>
<tr>
<td>Ethane</td>
<td>0</td>
<td>0.033</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0</td>
<td>0.202</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>0</td>
<td>0.032</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0.306</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Operating Conditions</strong></th>
<th>Temperature (°F)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1292</td>
<td>87</td>
</tr>
</tbody>
</table>

**Interior Equipment**

**Design Data:**

<table>
<thead>
<tr>
<th></th>
<th>Stainless Steel</th>
<th>Catalyst</th>
<th>Catalyst Weight (kg)</th>
<th>LiMgO</th>
<th>Catalyst Cost</th>
<th>Catalyst Life</th>
<th>Catalyst Cost Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>304</td>
<td>4080</td>
<td>$0.003545/kg</td>
<td>4080</td>
<td>$0.003545/kg</td>
<td>90 days</td>
<td>$0.003545/kg</td>
</tr>
<tr>
<td>Vessel Weight (lb)</td>
<td>52,596</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume (ft³)</td>
<td>11.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (ft)</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall Thickness (in)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **Purchase Cost:**     |                  |          |                       |        |               |                 |                     |
| Bare Module Cost:      | $659,932         |          |                       |        |               |                 |                     |
| Annual Catalyst Cost:  | $1,555,301       |          |                       |        |               |                 |                     |
**Block Type:** Fixed Bed Catalytic Reactor with internal shell and tube HX

**Function:** facilitate Oxidative coupling of methane to form ethylene/ethane

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-109B</td>
<td>S-112B</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>514,208</td>
<td>514,208</td>
</tr>
<tr>
<td>Volumetric Flow (ft³/hr)</td>
<td>5.38x10^6</td>
<td>5.42x10^6</td>
</tr>
<tr>
<td>Breakdown (Mass Frac):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>0.563</td>
<td>0.365</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.436</td>
<td>0</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.0001</td>
<td>0.062</td>
</tr>
<tr>
<td>Ethane</td>
<td>0</td>
<td>0.033</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0</td>
<td>0.202</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>0</td>
<td>0.032</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0.306</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>1292</td>
<td></td>
</tr>
<tr>
<td>Pressure (psi)</td>
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<td>87</td>
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</table>

| Interior Equipment        |             | RHX-102     |

<table>
<thead>
<tr>
<th>Design Data:</th>
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</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
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</tr>
<tr>
<td>Vessel Weight (lb)</td>
<td>304</td>
<td>Catalyst</td>
</tr>
<tr>
<td>Volume (ft³)</td>
<td>52,596</td>
<td>Catalyst Weight (kg)</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>11.5</td>
<td>Catalyst Cost</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>34</td>
<td>Catalyst Life</td>
</tr>
<tr>
<td>Wall Thickness (in)</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Purchase Cost:</td>
<td></td>
<td>$659,932</td>
</tr>
<tr>
<td>Bare Module Cost:</td>
<td></td>
<td>$2,012,792</td>
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<tr>
<td>Annual Catalyst Cost:</td>
<td></td>
<td>$1,555,301</td>
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### R-103

**Block Type:** Fixed Bed Catalytic Reactor with internal shell and tube HX

**Function:** facilitate Oxidative coupling of methane to form ethylene/ethane

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-109C</td>
<td>S-112C</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>514,208</td>
<td>514,208</td>
</tr>
<tr>
<td>Volumetric Flow (ft$^3$/hr)</td>
<td>5.38x10$^6$</td>
<td>5.42x10$^6$</td>
</tr>
<tr>
<td>Breakdown (Mass Frac):</td>
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<td></td>
</tr>
<tr>
<td>Methane</td>
<td>0.563</td>
<td>0.365</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.436</td>
<td>0</td>
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<tr>
<td>Ethylene</td>
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<td>0.062</td>
</tr>
<tr>
<td>Ethane</td>
<td>0</td>
<td>0.033</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0</td>
<td>0.202</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>0</td>
<td>0.032</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0.306</td>
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**Operating Conditions**

<table>
<thead>
<tr>
<th>Temperature ( °F)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1292</td>
<td>87</td>
</tr>
</tbody>
</table>

**Interior Equipment**

| Design Data: | | RHX-103 |
|--------------|--------|
| Construction Material | Stainless Steel 304 | Catalyst |
| Vessel Weight (lb) | 52,596 | Catalyst Weight (kg) |
| Volume (ft$^3$) | | Catalyst Cost |
| Diameter (ft) | 11.5 | Catalyst Life |
| Length (ft) | 34 | |
| Wall Thickness (in) | 0.82 | | |

**Purchase Cost:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Purchase Cost:</td>
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<td>Bare Module Cost:</td>
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<tr>
<td>Annual Catalyst Cost:</td>
<td>$1,555,301</td>
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**Block Type:** Fixed Bed Catalytic Reactor with internal shell and tube HX

**Function:** facilitate Oxidative coupling of methane to form ethylene/ethane

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-109D</td>
<td>S-112D</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>514,208</td>
<td>514,208</td>
</tr>
<tr>
<td>Volumetric Flow (ft³/hr)</td>
<td>5.38x10⁶</td>
<td>5.42x10⁶</td>
</tr>
<tr>
<td>Breakdown (Mass Frac):</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.563</td>
<td>0.365</td>
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<tr>
<td>Oxygen</td>
<td>0.436</td>
<td>0</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.0001</td>
<td>0.062</td>
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<tr>
<td>Ethane</td>
<td>0</td>
<td>0.033</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
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<td>0.202</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
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<td>0.032</td>
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<tr>
<td>Water</td>
<td>0</td>
<td>0.306</td>
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<table>
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<tr>
<th>Operating Conditions</th>
<th>Temperature ( °F)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1292</td>
<td>87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interior Equipment</th>
<th>RHX-104</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Design Data:</th>
<th>Stainless Steel</th>
<th>Catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>304</td>
<td>Catalyst Weight (kg)</td>
</tr>
<tr>
<td>Vessel Weight (lb)</td>
<td>52,596</td>
<td>Catalyst Cost</td>
</tr>
<tr>
<td>Volume (ft³)</td>
<td></td>
<td>Catalyst Life</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Length (ft)</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>Wall Thickness (in)</td>
<td>0.82</td>
<td></td>
</tr>
</tbody>
</table>

| LiMgO                | 4080              |
| Purchase cost $      | $0.003545/kg      |
| Catalyst Life $      | 90 days           |

| Purchase Cost:       | $659,932          |
| Bare Module Cost:    | $2,012,792        |
| Annual Catalyst Cost:| $1,555,301        |
**Block Type:** Spare Fixed Bed Catalytic Reactor with internal shell and tube HX

**Function:** facilitate Oxidative coupling of methane to form ethylene/ethane

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>514,208</td>
<td>514,208</td>
</tr>
<tr>
<td>Volumetric Flow (ft³/hr)</td>
<td>5.38x10⁶</td>
<td>5.42x10⁶</td>
</tr>
<tr>
<td>Breakdown (Mass Frac):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>0.563</td>
<td>0.365</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.436</td>
<td>0</td>
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<tr>
<td>Ethylene</td>
<td>0.0001</td>
<td>0.062</td>
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<tr>
<td>Ethane</td>
<td>0</td>
<td>0.033</td>
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<tr>
<td>Carbon Dioxide</td>
<td>0</td>
<td>0.202</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>0</td>
<td>0.032</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0.306</td>
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**Operating Conditions**

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1292</td>
<td>87</td>
</tr>
</tbody>
</table>

**Interior Equipment**

<table>
<thead>
<tr>
<th>Design Data:</th>
<th>Stainless Steel</th>
<th>Catalyst</th>
<th>LiMgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>304</td>
<td>Catalyst Weight (kg)</td>
<td>4080</td>
</tr>
<tr>
<td>Vessel Weight (lb)</td>
<td>52,596</td>
<td>Catalyst Cost</td>
<td>$0.003545/kg</td>
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<tr>
<td>Volume (ft³)</td>
<td></td>
<td>Catalyst Life</td>
<td>90 days</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>11.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (ft)</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall Thickness (in)</td>
<td>0.82</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Purchase Cost:**

| Bare Module Cost:       | $2,012,792      |
| Annual Catalyst Cost:   | $1,555,301      |
## IDENTIFICATION: Heat Exchanger

## FUNCTION: Cooling in reactor to maintain isothermal temperature

<table>
<thead>
<tr>
<th>Tube:</th>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>1292</td>
<td>1292</td>
<td></td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
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</tr>
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<table>
<thead>
<tr>
<th>Shell:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>217.6</td>
<td>1265</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>217.6</td>
<td>217.6</td>
</tr>
</tbody>
</table>

### 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 (ft²): 4182
- Overall Heat Transfer Coefficient (BTU/hr R ft²): 301
- Heat Duty (MBTU/hr): 1266843

### Purchase Cost:
- $54,418

### Bare Module Cost:
- $382,685

### Annual Utilities Cost:
- 0
<table>
<thead>
<tr>
<th><strong>RHX-102</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>IDENTIFICATION:</strong> Heat Exchanger</td>
</tr>
<tr>
<td><strong>FUNCTION:</strong> Cooling in reactor to maintain isothermal temperature</td>
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### Tube:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>1292</td>
<td>1292</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
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### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
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<th>Outlet</th>
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</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>217.6</td>
<td>1265</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>217.6</td>
<td>217.6</td>
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### Operating Conditions:

<table>
<thead>
<tr>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>512659</td>
<td></td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>851222</td>
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### Design Data:

<table>
<thead>
<tr>
<th>Construction Material</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>4182</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (BTU/hr R ft²)</td>
<td>301</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>1266843</td>
</tr>
</tbody>
</table>

### Purchase Cost:

- $54,418
- Bare Module Cost: $382,685
- Annual Utilities Cost: 0
**Identification:** Heat Exchanger

**Function:** Cooling in reactor to maintain isothermal temperature

### Tube:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Temperature (°F)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>1292</td>
<td>87</td>
</tr>
<tr>
<td>Outlet</td>
<td>1292</td>
<td>87</td>
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</tbody>
</table>

### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Temperature (°F)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>217.6</td>
<td>217.6</td>
</tr>
</tbody>
</table>

**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 (ft²): 4182
- Overall Heat Transfer Coefficient (BTU/hr R ft²): 301
- Heat Duty (MBTU/hr): 1266843

**Purchase Cost:** $54,418

**Bare Module Cost:** $382,685

**Annual Utilities Cost:** $0
## IDENTIFICATION: Heat Exchanger

## FUNCTION: Cooling in reactor to maintain isothermal temperature

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>1292</td>
<td>1292</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
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<td>-</td>
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<tr>
<td>Temperature (°F)</td>
<td>217.6</td>
<td>1265</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>217.6</td>
<td>217.6</td>
</tr>
</tbody>
</table>

### 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 (ft²)**: 4182
- **Overall Heat Transfer Coefficient (BTU/hr R ft²)**: 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

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>1292</td>
<td>1292</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

| 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:**

<table>
<thead>
<tr>
<th>Construction Material</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>4182</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (BTU/hr R ft²)</td>
<td>301</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>1266843</td>
</tr>
</tbody>
</table>

**Purchase Cost:** $54,418

**Bare Module Cost:** $382,685

**Annual Utilities Cost:** 0
**Section 200:**

<table>
<thead>
<tr>
<th><strong>C-201</strong></th>
</tr>
</thead>
</table>

**Block Type:** Compressor

**Function:** Compresses gas for further separation processes

<table>
<thead>
<tr>
<th><strong>Materials:</strong></th>
<th><em>Inlet</em></th>
<th><em>Outlet</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-207A</td>
<td>S-207C</td>
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</table>

**Operating Conditions:**

<table>
<thead>
<tr>
<th></th>
<th><em>Inlet</em></th>
<th><em>Outlet</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>290</td>
</tr>
<tr>
<td>Temperature (<strong>°F</strong>)</td>
<td>81.1</td>
<td>573.8</td>
</tr>
<tr>
<td>Volumetric Flow Rate (ft(^3/)hr)</td>
<td>4,319,060</td>
<td>1,833,550</td>
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**Design Data:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Cast-Iron/Carbon Steel</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>2</td>
</tr>
<tr>
<td>Interstage Cooling</td>
<td>None</td>
</tr>
<tr>
<td>Consumed Power (BTU/hr)</td>
<td>135,572,203</td>
</tr>
<tr>
<td>Power Source</td>
<td>Steam</td>
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</table>

**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

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-211</td>
<td>S-211A</td>
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<table>
<thead>
<tr>
<th>Operating Conditions:</th>
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</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>260.2</td>
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<tr>
<td>Temperature (°F)</td>
<td>104</td>
<td>123.2</td>
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<tr>
<td>Volumetric Flow Rate (ft³/hr)</td>
<td>1,242,870</td>
<td>1,154,090</td>
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</table>

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Construction Material</td>
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<tr>
<td>Number of Stages</td>
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</tr>
<tr>
<td>Interstage Cooling</td>
<td>None</td>
</tr>
<tr>
<td>Consumed Power (BTU/hr)</td>
<td>9,146</td>
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<td>Power Source</td>
<td>Steam</td>
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<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>$1,369,035</td>
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<table>
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<td>$3,148,781</td>
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<table>
<thead>
<tr>
<th>Annual Operating Cost:</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>
**Block Type:** Sieve Tray Distillation Tower

**Function:** Separates ethane and ethylene products from rest of stream

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Feed</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-212</td>
<td>S-214</td>
<td>S-213</td>
</tr>
<tr>
<td>Phase</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Liquid</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>1,011,801</td>
<td>816,533</td>
<td>195,268</td>
</tr>
<tr>
<td>Volumetric Flow (ft³/hr)</td>
<td>637653</td>
<td>38190</td>
<td>7172</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-94</td>
<td>-170.9</td>
<td>-12.3</td>
</tr>
<tr>
<td>Breakdown (lb/hr)</td>
<td>Ethane 68165</td>
<td>11</td>
<td>68154</td>
</tr>
<tr>
<td></td>
<td>Methane 749275</td>
<td>748525</td>
<td>749</td>
</tr>
<tr>
<td></td>
<td>Ethylene 127640</td>
<td>1276</td>
<td>126364</td>
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<tr>
<td></td>
<td>Carbon Monoxide 66720</td>
<td>66720</td>
<td>0</td>
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</tbody>
</table>

**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
- Weight (lb): 98396
- Diameter (ft): 9.5
- Height (ft): 46
- Tray Efficiency: 0.39
- Number of Trays: 18
- Feed Stage: 8
- Tray Spacing (ft): 2
### Exterior Components:

<table>
<thead>
<tr>
<th>Component</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reboiler</td>
<td>DR-201</td>
</tr>
<tr>
<td>Reflux Accumulator</td>
<td>DA-201</td>
</tr>
<tr>
<td>Pump</td>
<td>RP-201</td>
</tr>
<tr>
<td>Condenser</td>
<td>RC-201</td>
</tr>
</tbody>
</table>

#### Purchase Cost:
- $1,093,303

#### Bare Module Cost:
- $4,548,140

#### Annual Operating Cost:
- 0
**Block Type:** Sieve Tray Distillation Tower

**Function:** Separates methane for recycling from carbon monoxide

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Feed</th>
<th>Distillate</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-214</td>
<td>S-215</td>
<td>S-301</td>
</tr>
<tr>
<td>Phase</td>
<td>Liquid</td>
<td>Liquid</td>
<td>Liquid</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>816,533</td>
<td>66,091</td>
<td>750,442</td>
</tr>
<tr>
<td>Volumetric Flow (ft³/hr)</td>
<td>38190</td>
<td>1868</td>
<td>37211</td>
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<tr>
<td>Temperature (°F)</td>
<td>-170.9</td>
<td>-241</td>
<td>-161.9</td>
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</table>

**Breakdown (lb/hr):**

<table>
<thead>
<tr>
<th></th>
<th>Ethane</th>
<th>Methane</th>
<th>Ethylene</th>
<th>Carbon Monoxide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>68165</td>
<td>749275</td>
<td>127640</td>
<td>66720</td>
</tr>
</tbody>
</table>

**Operating Conditions:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser Pressure (psi)</td>
<td>290</td>
</tr>
<tr>
<td>Condenser Temperature (°F)</td>
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</tr>
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<td>Reboiler Pressure (psi)</td>
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</tr>
<tr>
<td>Reboiler Temperature (°F)</td>
<td>-241</td>
</tr>
<tr>
<td>Reflux ratio</td>
<td>11.1</td>
</tr>
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</table>

**Design Data:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>257562</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>11.5</td>
</tr>
<tr>
<td>Height (ft)</td>
<td>86</td>
</tr>
<tr>
<td>Tray Efficiency</td>
<td>0.35</td>
</tr>
<tr>
<td>Number of Trays</td>
<td>37</td>
</tr>
<tr>
<td>Feed Stage</td>
<td>8</td>
</tr>
<tr>
<td>Tray Spacing (ft)</td>
<td>2</td>
</tr>
</tbody>
</table>

**Exterior Components:**
<table>
<thead>
<tr>
<th>Equipment</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reboiler</td>
<td>DR-202</td>
</tr>
<tr>
<td>Reflux Accumulator</td>
<td>DA-202</td>
</tr>
<tr>
<td>Pump</td>
<td>RP-202</td>
</tr>
<tr>
<td>Condenser</td>
<td>RC-202</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost Information</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Cost</td>
<td>$2,297,774</td>
</tr>
<tr>
<td>Bare Module Cost</td>
<td>$9,558,740</td>
</tr>
<tr>
<td>Annual Operating Cost</td>
<td>0</td>
</tr>
</tbody>
</table>

**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

**Cost Information:**

- 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:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Pressure (psi)</td>
<td>290</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-161.9</td>
</tr>
</tbody>
</table>

**Design Data:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>67795</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>10</td>
</tr>
<tr>
<td>Height (ft)</td>
<td>26</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>39</td>
<td>27.3</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-94</td>
<td>-58.5</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
<td>290</td>
</tr>
</tbody>
</table>

**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 (ft²): 1192
- Overall Heat Transfer Coefficient (BTU/hr R ft²): 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

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>68</td>
<td>39</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
</tr>
<tr>
<td>Temperature (°F)</td>
</tr>
<tr>
<td>Pressure (psi)</td>
</tr>
</tbody>
</table>

**Operating Conditions:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>4374730</td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>816533</td>
</tr>
</tbody>
</table>

**Design Data:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel/Monel</td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>1501</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (BTU/hr R ft²)</td>
<td>1139</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>49613</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Materials:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
</tr>
<tr>
<td>Phase</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
</tr>
<tr>
<td>Volumetric Flow (cuft/hr)</td>
</tr>
</tbody>
</table>

*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

**Purchasing 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

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-201</td>
<td>S-202</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>212</td>
<td>203.7</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-216B</td>
<td>S-217</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>0</td>
<td>129.6</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

**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 (ft²): 2606
- Overall Heat Transfer Coefficient (BTU/hr R ft²): 154
- Heat Duty (MBTU/hr): 522823

**Purchase Cost:** $41,200

**Bare Module Cost:** $287,576

**Annual Utilities Cost:** 0
**Block Type:** Heat Exchanger  

**Function:** Second cooler to assist with removal of water through flash vessel

<table>
<thead>
<tr>
<th>Tube: Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-202</td>
<td></td>
<td>S-205</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>203.7</td>
<td>95</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell: Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-203B</td>
<td></td>
<td>S-204</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>86</td>
<td>173.1</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>21.8</td>
<td>21.8</td>
</tr>
</tbody>
</table>

**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 (ft²)  | 119964          |

**Overall Heat Transfer Coefficient (BTU/hr R ft²)**: 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

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-207C</td>
<td>S-209</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>317.9</td>
<td>104</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
<td>209</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-206</td>
<td>S-208</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>95</td>
<td>295.8</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

**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 (ft²): 90510
- Overall Heat Transfer Coefficient (BTU/hr ft²): 7.5
- Heat Duty (MBTU/hr): 145141

**Purchase Cost:** $886,891

**Bare Module Cost:** $6,793,585

**Annual Utilities Cost:** 0
## IDENTIFICATION
Heat Exchanger

## FUNCTION
Cools inlet into column

### Tube:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°F)</td>
<td>104</td>
<td>-64</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
<td>290</td>
</tr>
</tbody>
</table>

### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°F)</td>
<td>-161.9</td>
<td>-161.4</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
<td>290</td>
</tr>
</tbody>
</table>

### Operating Conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>998432</td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>750443</td>
</tr>
</tbody>
</table>

### Design Data:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel/Monel</td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>4745</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (BTU/hr (\text{R ft}^2))</td>
<td>109</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>102776</td>
</tr>
</tbody>
</table>

### 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

<table>
<thead>
<tr>
<th><strong>Tube:</strong></th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-94</td>
<td>-113.4</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
<td>290</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Shell:</strong></th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-255.9</td>
<td>-177.55</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

**Operating Conditions:**

<table>
<thead>
<tr>
<th></th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>14778500</td>
<td></td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>1591570</td>
<td></td>
</tr>
</tbody>
</table>

**Design Data:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel/Monel</td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>9706</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (BTU/hr R ft²)</td>
<td>1042</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>196335</td>
</tr>
</tbody>
</table>

**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:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>-170.8</td>
<td>-209.7</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
<td>290</td>
</tr>
</tbody>
</table>

### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>-255.9</td>
<td>-255.9</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

### 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 (ft²):** 4721
- **Overall Heat Transfer Coefficient (BTU/hr R ft²):** 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

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**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
**Block Type:** Pump  
**Function:** Pumps cooling water

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-203A</td>
<td>S-203B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Conditions:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Rise (psi)</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.9</td>
<td></td>
</tr>
<tr>
<td>Flow Rate (ft³/hr)</td>
<td>35376</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design Data:</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td></td>
</tr>
<tr>
<td>Number of Stages</td>
<td>5</td>
</tr>
<tr>
<td>Pump Efficiency</td>
<td>0.86</td>
</tr>
<tr>
<td>Consumed Power (hp)</td>
<td>107</td>
</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
</tr>
</tbody>
</table>

<p>| Purchase Cost:        | $74,170 |
| Bare Module Cost:     | $467,270|
| Annual Operating Cost:| 0       |</p>
<table>
<thead>
<tr>
<th>Block Type: Storage Tank</th>
<th>Number of Units: 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function: Store Products</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Fraction:</td>
<td></td>
</tr>
<tr>
<td>Ethane</td>
<td>0.3491</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.6472</td>
</tr>
<tr>
<td>Methane</td>
<td>0.0038</td>
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<table>
<thead>
<tr>
<th>Operating Conditions:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>0</td>
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</table>

<table>
<thead>
<tr>
<th>Design Data:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Volume (cuft)</td>
<td>86048</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>90.7</td>
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<p>| Purchase Cost:     | $ 9,572,202 |
| Bare Module Cost:  | $ 9,572,203 |
| Annual Operating Cost: | $ - |</p>
<table>
<thead>
<tr>
<th>ST-202</th>
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</thead>
<tbody>
<tr>
<td><strong>Block Type:</strong> Storage Tank</td>
</tr>
<tr>
<td><strong>Number of Units:</strong> 1</td>
</tr>
<tr>
<td><strong>Function:</strong> Store Products</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Materials:</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Fraction:</td>
<td></td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>0.999444</td>
</tr>
<tr>
<td>Methane</td>
<td>0.000556</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Operating Conditions:</strong></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>290</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-241</td>
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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Volume (cuft)</td>
<td>89656</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>84.5</td>
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| **Purchase Cost:** | $ 1,647,316.00 |
| **Bare Module Cost:** | $ 1,647,316.00 |
| **Annual Operating Cost:** | $ 0 |
**Block Type:** Vertical Pressure Vessels  
**Number of Units:** 13  
**Function:** Separates out carbon dioxide through pressure swing adsorption

<table>
<thead>
<tr>
<th><strong>Materials:</strong></th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet 1</strong></th>
<th><strong>Outlet 2</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-209</td>
<td>S-210</td>
<td>S-211</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>1432680</td>
<td>420877</td>
<td>1011800</td>
</tr>
<tr>
<td>Volumetric Flow (ft³/hr)</td>
<td>1833550</td>
<td>266680</td>
<td>1564780</td>
</tr>
<tr>
<td>Breakdown (lb/hr):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>835739</td>
<td>0</td>
<td>835739</td>
</tr>
<tr>
<td>Ethylene</td>
<td>127640</td>
<td>0</td>
<td>127640</td>
</tr>
<tr>
<td>Ethane</td>
<td>68164</td>
<td>0</td>
<td>68164</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>415315</td>
<td>415315</td>
<td>0</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>66720.39</td>
<td>0</td>
<td>66720.39</td>
</tr>
<tr>
<td>Water</td>
<td>6020</td>
<td>6020</td>
<td>0</td>
</tr>
</tbody>
</table>

**Operating Conditions:**  
| Temperature(°F) | 96.8  
| Pressure (psi)  | 290 |

**Design Data:**

<table>
<thead>
<tr>
<th>Construction Material</th>
<th>Low-alloy Steel</th>
<th>Catalyst 13X</th>
<th>Zeolite 13X</th>
<th>Activated Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel Weight (lbs)</td>
<td>151112</td>
<td></td>
<td>3</td>
<td>1.6</td>
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<tr>
<td>Diameter (ft)</td>
<td>12.5</td>
<td>Catalyst Weight (lb)</td>
<td>1092054</td>
<td>3220</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>39</td>
<td>Catalyst Cost</td>
<td>2548562</td>
<td>3150</td>
</tr>
<tr>
<td>Wall Thickness (in)</td>
<td>1.899</td>
<td>Catalyst Life (yr)</td>
<td>3</td>
<td>3</td>
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**Purchase Cost:** $339,710  
Bare Module Cost: $1,413,195  
Annual Catalyst Cost: $850,571
Section 300:

<table>
<thead>
<tr>
<th>C-301</th>
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<tbody>
<tr>
<td><strong>Block type:</strong></td>
</tr>
<tr>
<td><strong>Function:</strong></td>
</tr>
<tr>
<td><strong>Materials:</strong></td>
</tr>
<tr>
<td>Stream</td>
</tr>
<tr>
<td>S-301</td>
</tr>
<tr>
<td><strong>Operating Conditions:</strong></td>
</tr>
<tr>
<td>Pressure (psi)</td>
</tr>
<tr>
<td>Temperature (°F)</td>
</tr>
<tr>
<td>Volumetric Flow Rate (ft³/hr)</td>
</tr>
<tr>
<td><strong>Design Data:</strong></td>
</tr>
<tr>
<td>Construction Material</td>
</tr>
<tr>
<td>Number of Stages</td>
</tr>
<tr>
<td>Interstage Cooling</td>
</tr>
<tr>
<td>Consumed Power (hp)</td>
</tr>
<tr>
<td>Power Source</td>
</tr>
<tr>
<td><strong>Purchase Cost:</strong></td>
</tr>
<tr>
<td><strong>Bare Module Cost:</strong></td>
</tr>
<tr>
<td><strong>Annual Operating Cost:</strong></td>
</tr>
</tbody>
</table>
**C-302**

**Block Type:** Compressor  

**Function:** Compress Ethylene for Refrigeration Cycle  

**Materials:**  

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S-307</td>
<td>S-308</td>
</tr>
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</table>

**Operating Conditions:**  

<table>
<thead>
<tr>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>304.5</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-31</td>
<td>382.3</td>
</tr>
<tr>
<td>Volumetric Flow Rate (ft³/hr)</td>
<td>21,900,000</td>
<td>2,240,000</td>
</tr>
</tbody>
</table>

**Design Data:**  

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Nickel Alloy</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>5</td>
</tr>
<tr>
<td>Interstage Cooling</td>
<td>None</td>
</tr>
<tr>
<td>Consumed Power (hp)</td>
<td>140551</td>
</tr>
<tr>
<td>Power Source</td>
<td>Steam</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Materials:</th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-312</td>
<td>S-313</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Conditions:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>478.6</td>
</tr>
<tr>
<td>Temperature(°F)</td>
<td>-139</td>
<td>385.4</td>
</tr>
<tr>
<td>Volumetric Flow Rate (ft³/hr)</td>
<td>21,100,000</td>
<td>1,880,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design Data:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Nickel Alloy</td>
<td></td>
</tr>
<tr>
<td>Number of Stages</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Interstage Cooling</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Consumed Power (HP)</td>
<td>180537</td>
<td></td>
</tr>
<tr>
<td>Power Source</td>
<td>Steam</td>
<td></td>
</tr>
</tbody>
</table>

| Purchase Cost: | $     | 37,378,265.00 |
| Bare Module Cost: | $     | 80,363,270.00 |
| Annual Operating Cost: | $     | -        |
### Block Type: Flash

**Function:** Separate Vapor and Liquid Phases

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream S-306</td>
<td>S-306A</td>
<td>S-306B</td>
<td></td>
</tr>
<tr>
<td>Phase MIX</td>
<td>VAP</td>
<td>LIQ</td>
<td></td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>4,374,730</td>
<td>2,053,463</td>
<td>2,316,100</td>
</tr>
<tr>
<td>Volumetric Flow (L/hr)</td>
<td>361,000,000</td>
<td>3,380,000</td>
<td>361,000,000</td>
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</table>

**Breakdown Mass Frac:**

<table>
<thead>
<tr>
<th></th>
<th>Ethylene</th>
<th>Methane</th>
<th>Propane</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Overhead</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Bottoms</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
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</tbody>
</table>

**Operating Conditions:**

<table>
<thead>
<tr>
<th></th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-39.8</td>
<td>-39.8</td>
<td>-39.8</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>Vapor-Liquid Equilibrium</td>
<td></td>
<td></td>
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**Design Data:**

<table>
<thead>
<tr>
<th></th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel-400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>126812</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume (gal)</td>
<td>113292</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (ft)</td>
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<td></td>
<td></td>
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<tr>
<td>Height (ft)</td>
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**Purchase Cost:**

<table>
<thead>
<tr>
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<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Cost:</td>
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</tr>
<tr>
<td>Bare Module Cost:</td>
<td>$ 2,194,819.00</td>
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</tr>
<tr>
<td>Annual Operating Cost:</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
**F-302**

**Block Type:** Flash  
**Function:** Separate Liquid and Vapor Phases

### Materials:

<table>
<thead>
<tr>
<th>Stream Phase</th>
<th>Feed</th>
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<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-318</td>
<td>S-318A</td>
<td>S-318B</td>
<td></td>
</tr>
<tr>
<td>MIX</td>
<td>VAP</td>
<td>LIQ</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass Flow (lb/hr)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,160,000.00</td>
<td>799,000.00</td>
<td>1,360,800.00</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Volumetric Flow (L/hr)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>164,323,000.00</td>
<td>164,323,000.00</td>
<td>1,714,000.00</td>
<td></td>
</tr>
</tbody>
</table>

*Breakdown Mass Frac:*

- **Ethylene:** 1 1 1 1
- **Methane:** 0 0 0 0
- **Propane:** 0 0 0 0
- **Water:** 0 0 0 0

### Operating Conditions:

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature(°F)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>-151.7</td>
<td>-151.7</td>
<td>-151.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equilibrium</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor-Liquid Equilibrium</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Design Data:

<table>
<thead>
<tr>
<th>Construction Material</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monel-400</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight (lb)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>63662</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume (gal)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>56298</td>
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<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter (ft)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.5</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Height (ft)</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
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<td></td>
<td></td>
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</tbody>
</table>

### Purchase Cost:

- **$ 428,865.00**

### Bare Module Cost:

- **$ 1,308,040.00**

### Annual Operating Cost:

- **0**
**Block Type:** Flash  
**Function:** Separate Vapor and Liquid Phases

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream MIX Phase</td>
<td>S-326</td>
<td>S-326A</td>
<td>S-326B</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>1,591,570</td>
<td>795,785</td>
<td>791,010</td>
</tr>
<tr>
<td>Volumetric Flow (L/hr)</td>
<td>187,650,000</td>
<td>188,000,000</td>
<td>59,714</td>
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</table>

**Breakdown Mass Frac:**

<table>
<thead>
<tr>
<th></th>
<th>Ethylene</th>
<th>Methane</th>
<th>Propane</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Methane</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Propane</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Operating Conditions:**

<table>
<thead>
<tr>
<th></th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
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<td>15.9</td>
<td>15.9</td>
</tr>
<tr>
<td>Temperature(°F)</td>
<td>-256</td>
<td>-256</td>
<td>-256</td>
</tr>
<tr>
<td>Equilibirium</td>
<td>Vapor-Liquid Equilibrium</td>
<td>Vapor-Liquid Equilibrium</td>
<td>Vapor-Liquid Equilibrium</td>
</tr>
</tbody>
</table>

**Design Data:**

<table>
<thead>
<tr>
<th></th>
<th>Feed</th>
<th>Overhead</th>
<th>Bottoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel-400</td>
<td>Monel-400</td>
<td>Monel-400</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>126812</td>
<td>126812</td>
<td>126812</td>
</tr>
<tr>
<td>Volume (gal)</td>
<td>57263</td>
<td>57263</td>
<td>57263</td>
</tr>
<tr>
<td>Diameter (ft)</td>
<td>28.5</td>
<td>28.5</td>
<td>28.5</td>
</tr>
<tr>
<td>Height (ft)</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

**Purchase Cost:**

- $719,612.00
- $2,194,819.00
- $0
## HX-301

**Block Type**: Heat Exchanger in Parallel

**Function**: Cool Stream S-302 for Expansion

### Tube:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-302</td>
<td>280.7</td>
<td>99</td>
</tr>
<tr>
<td>S-305</td>
<td>188.5</td>
<td>188.5</td>
</tr>
</tbody>
</table>

### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-303</td>
<td>81.1</td>
<td>178</td>
</tr>
<tr>
<td>S-304</td>
<td>14.5</td>
<td>14.5</td>
</tr>
</tbody>
</table>

### Operating Conditions:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>4,374,730</td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>900,764</td>
</tr>
</tbody>
</table>

### Design Data:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel/Stainless Steel</td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>982</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>6</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>2</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>144,493</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (Btu/hr-ft²-R)</td>
<td>149.6</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>145,000</td>
</tr>
</tbody>
</table>

### Purchase Cost:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ 4,974,734.00</td>
</tr>
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</table>

### Bare Module Cost:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ 33,330,717.00</td>
</tr>
</tbody>
</table>

### Annual Utilities Cost:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$ 4,464,489.04</td>
</tr>
</tbody>
</table>
### HX-302

**Block Type:** Heat Exchanger in Parallel  
**Function:** Cool Stream S-308 for Expansion

<table>
<thead>
<tr>
<th>Tube: Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-308</td>
<td>S-311</td>
<td></td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>382.3</td>
<td>87.8</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>304.56</td>
<td>304.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell: Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-309</td>
<td>S-310</td>
<td></td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>81.1</td>
<td>215.7</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>14.5</td>
<td>14.5</td>
</tr>
</tbody>
</table>

**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 (ft²): 143,493  
- Overall Heat Transfer Coefficient (Btu/hr-ft²-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

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-313</td>
<td>S-316</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>385.3</td>
<td>86</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>478.6</td>
<td>478.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th>Stream</th>
<th>S-314</th>
<th>S-315</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>81.1</td>
<td>215.7</td>
<td></td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>14.5</td>
<td>14.5</td>
<td></td>
</tr>
</tbody>
</table>

**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 (ft²) | 140,562 |
| Overall Heat Transfer Coefficient (Btu/hr-ft²-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

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-311</td>
<td>S-317</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>87.8</td>
<td>-31</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>304.5</td>
<td>304.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-306</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>-39.8</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
</tr>
</tbody>
</table>

**Operating Conditions:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>2,160,000</td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>4,370,000</td>
</tr>
</tbody>
</table>

**Design Data:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel/Monel</td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>982</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>6</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>2</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>111,249</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (Btu/hr-ft²-R)</td>
<td>149.6</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>422,000</td>
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</tbody>
</table>

**Purchase Cost:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ 1,131,677</td>
</tr>
<tr>
<td>Bare Module Cost:</td>
<td>$ 8,261,242</td>
</tr>
<tr>
<td>Annual Utilities Cost:</td>
<td>0</td>
</tr>
</tbody>
</table>
### HX-305

**Block Type:** Heat Exchanger  
**Function:** Cool Stream S-316 for Expansion

#### Tube:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>S-316</td>
<td>S-320</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>478.6</td>
<td>478.6</td>
</tr>
</tbody>
</table>

#### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>S-319</td>
<td>S-321</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

#### Operating Conditions:

<table>
<thead>
<tr>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>1,591,000</td>
<td></td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>4,370,000</td>
<td></td>
</tr>
</tbody>
</table>

#### Design Data:

<table>
<thead>
<tr>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Monel/Monel</td>
<td></td>
</tr>
<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
<td></td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>914</td>
<td></td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>23,782</td>
<td></td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (Btu/hr-ft²-R)</td>
<td>149.6</td>
<td></td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>110,600</td>
<td></td>
</tr>
</tbody>
</table>

#### Purchase Cost:

<table>
<thead>
<tr>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>165,595</td>
<td></td>
</tr>
<tr>
<td>Bare Module Cost:</td>
<td>$1,208,844</td>
<td></td>
</tr>
<tr>
<td>Annual Utilities Cost:</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
### HX-306

**Block Type:** Heat Exchanger  
**Function:** Cool Stream S-320 for Expansion

<table>
<thead>
<tr>
<th>Tube:</th>
<th><strong>Stream</strong></th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>-31</td>
<td>-148</td>
<td></td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>478.6</td>
<td>478.6</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th><strong>Stream</strong></th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>-151.7</td>
<td>-91.6</td>
<td></td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>16</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

**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 (ft²) 113,869  
- Overall Heat Transfer Coefficient (Btu/hr-ft²-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

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-303A</td>
<td>S-303B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Conditions:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Rise (psi)</td>
<td>7.25</td>
<td></td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.4</td>
<td></td>
</tr>
<tr>
<td>Flow Rate (gpm)</td>
<td>1880.2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design Data:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>1</td>
</tr>
<tr>
<td>Pump Efficiency</td>
<td>0.86</td>
</tr>
<tr>
<td>Consumed Power (BTU/hr)</td>
<td>24899.1</td>
</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-309A</td>
<td>S-309B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Conditions:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Rise (psi)</td>
<td>7.25</td>
<td></td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.4</td>
<td></td>
</tr>
<tr>
<td>Flow Rate (gpm)</td>
<td>1682.3</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Design Data:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>1</td>
</tr>
<tr>
<td>Pump Efficiency</td>
<td>0.86</td>
</tr>
<tr>
<td>Consumed Power (BTU/hr)</td>
<td>22116.1</td>
</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
</tr>
</tbody>
</table>

**Purchase Cost:** $4,640.00  
**Bare Module Cost:** $29,232.00  
**Annual Operating Cost:** 0
**Block Type:** Pump  
**Function:** Pump Cooling Water to HX-303

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S-314A</td>
<td>S-314B</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Conditions:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Rise (psi)</td>
<td>7.25</td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.4</td>
</tr>
<tr>
<td>Flow Rate (gpm)</td>
<td>1488.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design Data:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>1</td>
</tr>
<tr>
<td>Pump Efficiency</td>
<td>0.86</td>
</tr>
<tr>
<td>Consumed Power (BTU/hr)</td>
<td>20071.8</td>
</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Purchase Cost:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Cost:</td>
<td>$4,492.00</td>
</tr>
<tr>
<td>Bare Module Cost:</td>
<td>$28,300.00</td>
</tr>
<tr>
<td>Annual Operating Cost:</td>
<td>0</td>
</tr>
</tbody>
</table>
### Section 400:

**B-401**

**Block Type:** Blower

**Function:** Increases pressure of oxygen feed for purge

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-402</td>
<td>S-402A</td>
</tr>
</tbody>
</table>

**Operating Conditions:**

<table>
<thead>
<tr>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>100</td>
<td>105</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>81.1</td>
<td>91.6</td>
</tr>
<tr>
<td>Volumetric Flow Rate (ft³/hr)</td>
<td>289122</td>
<td>280741</td>
</tr>
</tbody>
</table>

**Design Data:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Cast Iron</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>1</td>
</tr>
<tr>
<td>Interstage Cooling</td>
<td>None</td>
</tr>
<tr>
<td>Consumed Power (MBTU/hr)</td>
<td>365</td>
</tr>
<tr>
<td>Power Source</td>
<td>Steam</td>
</tr>
</tbody>
</table>

**Purchase Cost:** $51,806

**Bare Module Cost:** $51,806

**Annual Operating Cost:** 0
<table>
<thead>
<tr>
<th>Block Type:</th>
<th>Combustor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function:</td>
<td>Combusts purge methane for steam generation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-404</td>
<td>S-408</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>196249</td>
<td>196249</td>
</tr>
<tr>
<td>Volumetric Flow (ft³/hr)</td>
<td>358300</td>
<td>139569</td>
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</table>

<table>
<thead>
<tr>
<th>Breakdown (lb/hr):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
</tr>
<tr>
<td>Oxygen</td>
</tr>
<tr>
<td>Ethylene</td>
</tr>
<tr>
<td>Ethane</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
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<tr>
<td>Water</td>
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<table>
<thead>
<tr>
<th>Operating Conditions:</th>
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<tbody>
<tr>
<td>Duty</td>
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<tr>
<td>Pressure (psi)</td>
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</tbody>
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<table>
<thead>
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<th>Design Data:</th>
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<tbody>
<tr>
<td>Construction Material</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Purchase Cost:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Module Cost:</td>
</tr>
<tr>
<td>Annual Operating Cost:</td>
</tr>
<tr>
<td>Purchase Cost:</td>
</tr>
</tbody>
</table>

$8,921,712
## HX-401

**Block Type:** Heat Exchanger

**Function:** Preheats the feed to the combustor

### Tube:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S-117</td>
<td>S-405</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>1334.6</td>
<td>1068.6</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>217.6</td>
<td>217.6</td>
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</tbody>
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### Shell:

<table>
<thead>
<tr>
<th>Stream</th>
<th>S-403</th>
<th>S-404</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>98.1</td>
<td>1076</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

### Operating Conditions:

- Tube Flow Rate (lb/hr): 450382
- Shell Flow Rate (lb/hr): 196848

### Internal Components:

- 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 (ft²):** 572
- **Overall Heat Transfer Coefficient (BTU/hr R ft²):** 353
- **Heat Duty (MBTU/hr):** 64817

### Purchase Cost:

- $24,563

### Bare Module Cost:

- $174,152

### Annual Utilities Cost:

- 0
**Block Type:** Heat Exchanger

**Function:** Extracts heat from flue gas to generate steam

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-408</td>
<td>S-411</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>4172</td>
<td>295</td>
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<td>Pressure (psi)</td>
<td>114.7</td>
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<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-410D</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>86.1</td>
</tr>
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<td>Pressure (psi)</td>
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**Operating Conditions:**

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Tube Flow Rate (lb/hr)</td>
<td>196848</td>
</tr>
<tr>
<td>Shell Flow Rate (lb/hr)</td>
<td>180153</td>
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**Design Data:**

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<table>
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<tr>
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<tr>
<td>Construction Material</td>
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<tr>
<td>Flow Direction</td>
<td>Countercurrent</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>934</td>
</tr>
<tr>
<td>Number of Tube Passes</td>
<td>1</td>
</tr>
<tr>
<td>Number of Shell Passes</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Area (ft²)</td>
<td>3461</td>
</tr>
<tr>
<td>Overall Heat Transfer Coefficient (BTU/hr R ft²)</td>
<td>26</td>
</tr>
<tr>
<td>Heat Duty (MBTU/hr)</td>
<td>354526</td>
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</table>

**Purchase Cost:** $48,450

**Bare Module Cost:** $350,294

**Annual Utilities Cost:** 0
<table>
<thead>
<tr>
<th>Block Type:</th>
<th>Pump</th>
</tr>
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<tbody>
<tr>
<td>Function:</td>
<td>Pumps boiler-feed water for combustor</td>
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</table>

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
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</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-410A</td>
<td>S-410B</td>
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</table>

<table>
<thead>
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<th>Operating Conditions:</th>
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</thead>
<tbody>
<tr>
<td>Pressure Rise (psi)</td>
<td>203</td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>473</td>
</tr>
<tr>
<td>Flow Rate (ft³/hr)</td>
<td>7294</td>
</tr>
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</table>

<table>
<thead>
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<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>1</td>
</tr>
<tr>
<td>Pump</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.76</td>
</tr>
<tr>
<td>Consumed Power (hp)</td>
<td>141</td>
</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
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<table>
<thead>
<tr>
<th>Purchase Cost:</th>
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<tbody>
<tr>
<td>$6,917</td>
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<tr>
<td>Bare Module Cost:</td>
<td>$43,578</td>
</tr>
<tr>
<td>Annual Operating Cost:</td>
<td>0</td>
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</table>
### Block Type: Heat Exchanger

**Function:** Extracts heat from the combustor to generate steam

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>4172</td>
<td>4172</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>114.7</td>
<td>114.7</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Shell:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>86.1</td>
<td>1583.9</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>217.6</td>
<td>217.6</td>
</tr>
</tbody>
</table>

### 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 (ft²): 690
- Overall Heat Transfer Coefficient (BTU/hr R ft²): 488
- Heat Duty (MBTU/hr): 505123

### Purchase Cost:

- $22,154

### Bare Module Cost:

- $156,407

### Annual Utilities Cost:

- 0
### CT-501

**Block Type:** Cooling Tower  
**Number of Units:** 2  
**Function:** Cool Water Prior to Outlet

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-506A</td>
<td>S-509</td>
</tr>
</tbody>
</table>

**Operating Conditions:**

<table>
<thead>
<tr>
<th></th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>121.9</td>
<td>86</td>
</tr>
<tr>
<td>Flow Rate (GPM)</td>
<td>209082</td>
<td>209082</td>
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**Design Data:**

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<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Construction Material</td>
<td>Concrete</td>
</tr>
<tr>
<td>Evaporation Losses (gpm)</td>
<td>4182</td>
</tr>
<tr>
<td>Wet Bulb (°F)</td>
<td>85</td>
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</table>

**Purchase Cost:** $13,894,042  
**Bare Module Cost:** $13,894,042  
**Annual Operating Cost:** $0
**Block Type:** Heat Exchanger

**Number of Units:** 2

**Function:** Condenser after turbine

<table>
<thead>
<tr>
<th>Tube:</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
<td>S-502</td>
<td>S-504</td>
</tr>
<tr>
<td>Temperature (°F)</td>
<td>184.7</td>
<td>95</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>7.3</td>
<td>7.3</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Shell:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream</td>
</tr>
<tr>
<td>Temperature (°F)</td>
</tr>
<tr>
<td>Pressure (psi)</td>
</tr>
</tbody>
</table>

**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 (ft²) | 185587 |
| Overall Heat Transfer Coefficient (BTU/hr R ft²) | 230 |
| Heat Duty (MBTU/hr) | 3840260 |

**Purchase Cost:** $2,175,004

**Bare Module Cost:** $14,275,754

**Annual Utilities Cost:** 0
### P-501A

**Block Type:** Pump  
**Function:** Pumps cooling water for turbine condenser

<table>
<thead>
<tr>
<th>Materials:</th>
<th></th>
<th>Stream</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Inlet</strong></td>
<td><strong>Outlet</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-503AA</td>
<td>S-503BA</td>
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**Operating Conditions:**

<table>
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<tr>
<th>Parameter</th>
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<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Rise (psi)</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.9</td>
<td></td>
</tr>
<tr>
<td>Flow Rate (cuft/hr)</td>
<td>364689</td>
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**Design Data:**

<table>
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<th>Value</th>
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<td>Construction Material</td>
<td>Stainless Steel</td>
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<tr>
<td>Number of Stages</td>
<td>10</td>
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<tr>
<td>Pump Efficiency</td>
<td>0.86</td>
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<tr>
<td>Consumed Power (hp)</td>
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</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Cost</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Purchase Cost:</strong></td>
<td>$233,870</td>
</tr>
<tr>
<td><strong>Bare Module Cost:</strong></td>
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</tr>
<tr>
<td><strong>Annual Operating Cost:</strong></td>
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</table>
### P-501B

**Block Type:** Pump  
**Function:** Pumps cooling water for turbine condenser

<table>
<thead>
<tr>
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<th>Outlet</th>
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<tbody>
<tr>
<td></td>
<td>S-503AB</td>
<td>S-503BB</td>
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#### Operating Conditions:

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<tbody>
<tr>
<td>Pressure Rise (psi)</td>
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<td></td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.9</td>
<td></td>
</tr>
<tr>
<td>Flow Rate (cuft/hr)</td>
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#### Design Data:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td>Construction Material</td>
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<td></td>
</tr>
<tr>
<td>Number of Stages</td>
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<td></td>
</tr>
<tr>
<td>Pump Efficiency (hp)</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Consumed Power (hp)</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>Power Source</td>
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<td></td>
</tr>
</tbody>
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#### Purchase Cost:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$233,870</td>
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</table>

#### Bare Module Cost:

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<table>
<thead>
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<th></th>
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</thead>
<tbody>
<tr>
<td>$1,473,380</td>
<td></td>
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#### Annual Operating Cost:

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<tbody>
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**P-501C**

**Block Type:** Pump  
**Function:** Pumps cooling water for turbine condenser

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<th>Materials:</th>
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<tbody>
<tr>
<td>Stream</td>
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<tr>
<td>Pressure Rise (psi)</td>
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<td></td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.9</td>
<td></td>
</tr>
<tr>
<td>Flow Rate (cuft/hr)</td>
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**Design Data:**

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<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Stages</td>
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<tr>
<td>Pump Efficiency</td>
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<tr>
<td>Consumed Power (hp)</td>
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**Power Source:**  
Electricity

**Purchase Cost:** $233,870  
**Bare Module Cost:** $1,473,380  
**Annual Operating Cost:** 0
<table>
<thead>
<tr>
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<th>Pump</th>
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### Materials:

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<tbody>
<tr>
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<td>S-503BD</td>
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### Operating Conditions:

<table>
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<tbody>
<tr>
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<td>7.3</td>
</tr>
<tr>
<td>Pressure Head (ft)</td>
<td>16.9</td>
</tr>
<tr>
<td>Flow Rate (cuft/hr)</td>
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### Design Data:

<table>
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<tr>
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<tbody>
<tr>
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<tr>
<td>Number of Stages</td>
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</tr>
<tr>
<td>Pump Efficiency</td>
<td>0.86</td>
</tr>
<tr>
<td>Consumed Power (hp)</td>
<td>224</td>
</tr>
<tr>
<td>Power Source</td>
<td>Electricity</td>
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</table>

<table>
<thead>
<tr>
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<th>Inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Cost:</td>
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</tr>
<tr>
<td>Bare Module Cost:</td>
<td>$1,473,380</td>
</tr>
<tr>
<td>Annual Operating Cost:</td>
<td>0</td>
</tr>
</tbody>
</table>
### T-501

**Block Type:** Turbine  
**Number of Units:** 4  
**Function:** Convert Steam to Electricity

#### Materials:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-501</td>
<td>S-502</td>
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#### Operating Conditions:

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<tr>
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<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>217.6</td>
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</tr>
<tr>
<td>Temperature (°F)</td>
<td>1252.5</td>
<td>184.7</td>
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</tbody>
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#### Design Data:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Power Range (MW)</td>
<td>26.75</td>
</tr>
<tr>
<td>Speed Range (rpm)</td>
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<tr>
<td>Turbine Efficiency</td>
<td>0.4</td>
</tr>
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<td>Power Source</td>
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#### Purchase Cost:

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<tbody>
<tr>
<td>$7,500,000</td>
<td>$30,000,000</td>
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</table>

#### Annual Operating Cost:

<p>| | |</p>
<table>
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<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
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</table>
Section 12- Conclusions and Recommendations
Recommendations

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 profitable 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 C₂ 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.
Acknowledgements

We would like to thank Mr. Gary Sawyer for proposing a project that exposed us to industrial issues and kept us on our toes. We want to acknowledge his unwavering support and thank him for his availability, resources, and good spirit about advising college students. Without his continuous urging to go the next step, we could not have created a project such as this one. We would also like to thank the other industrial consultants for meeting with us every week and not only answering our questions but also providing their insight about issues that had not yet crossed our minds.

We would also like to thank Professor Fabiano for providing the framework and environment for us and our project to grow into what it is now. We want to notice his endless support and constructive comments and thank him for his help in organizing, overseeing, and availability throughout the entire senior design timeline.

Lastly, we want to thank our advisor Dr. Vohs, for always being on our side. He asked key questions at every turn, was attentive to our needs and sacrificed his time, effort, thinking capacity, and energy every week on our behalf. We could not have come this far without his steadfast support and encouragement!
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.

\[
Q = m\Delta H_{\text{comb}}
\]

\[
Q = 104.4 \times 10^3 \frac{\text{Btu}}{\text{lb}} \times 37,430 \frac{\text{lb}}{\text{hr}}
\]

\[
Q = 3.90 \times 10^9 \frac{\text{Btu}}{\text{hr}}
\]

**ECC-002: Mass of Catalyst Needed**

\[
\text{Space Time Yield (STY)} = 4.19 \times 10^4 \frac{\text{Kg of C}_2}{\text{Kg of LiMgO \times Yr}}
\]

\[
\frac{6.94 \times 10^8 \frac{\text{Kg of C}_2}{\text{Kg of LiMgO \times Yr}}}{4.19^4} = 16320 \text{ Kg of LiMgO}
\]

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

\[
\text{Total Cost} = \frac{\$0.003545}{\text{Kg of Lithium}} \times 16320 \text{ Kg of LiMgO} = \$57.8
\]
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

\[ C_p = 0.367Q^{0.77} \] Carbon Steel P\(<20 \text{ atm}\)

\[ C_p = 0.367(3.90 \times 10^9)^{0.77} = \$8,921,711 \]

\[ C = F_m C_p C_E \]

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

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 ft³ per hour, leading to a volume need of 134,640 ft³ or 1 million gallons of storage. The maximum capacity of a spherical storage tank is 750,000 gallons.

Equations

\[ C = C_E \times 265V^{-0.51} \] (Spherical, 0-100 psig)

\[ C = \frac{570}{500} \times 265 \times (750,000)^{-0.51} = \$299,524 \]
Heat Exchanger Sizing: Sizing HX-201

\[ S = 216 \text{ Btu/hr} \]

\[ T_{min} = 50^\circ\text{F}; \text{ heuristic 26} \]

\[ Q = 582.823 \text{ MBtu/hr} \]

\[ \Delta T_{in} = \frac{T_{in} - T_{out}}{\ln \left( \frac{T_{in} - T_{out}}{T_{in} - T_{out}} \right)} = 134^\circ\text{F} \]

\[ S = \frac{T_{a, g} - T_{in}}{T_{in} - T_{out}} = 15.675 \]

\[ R = \frac{T_{in} - T_{out}}{T_{out} - T_{in}} = 0.064 \]

\[ F_r = \frac{\sqrt{\ln \left( \frac{1 - S}{S} \right) \left( R - 1 \right) \left( 2 - S^2 \right) + \sqrt{R \left( R - 1 \right)}}}{2 - S(\sqrt{R} + (R + 1))} = 10 \Rightarrow \frac{\ln U}{0.85} > 0 \]

\[ UA = \frac{Q}{F_r \Delta T_{in}} = 4013.24 \text{ Btu/hr°F} \]

\[ U_{est} = 55 \text{ LW Table 18.5} \Rightarrow U < 200 \frac{\text{Btu}}{\text{hr°F}} \text{ for water HX} \]

\[ U = 154 \frac{\text{Btu}}{\text{hr°F}} \text{ R / GUESS} \]

\[ A = 2.406 \text{ ft}^2, \text{ Approximate Size} \]

Cost:

\[ C_p = 200(11.4052 - 0.8705)(\ln(2606) + 0.09055)(\ln(2606))^2 = \$ 41,200 \]

\[ F_m = 2.70 + \frac{(2606)^{0.07}}{100} = 4.07 \]

\[ F_c = 1, 20 \text{ ft + tubes} \]

\[ F_d = 0.9803 + 0.01(\frac{0.6}{100}) + 0.0017(\frac{2}{100})^2 = 1.00 \]

\[ P = 96 \text{ PSI} \]

\[ (\text{Total Cost}) = \$ 167,684 \]

\[ (\text{Total Cost}) = \$ 107,684 \text{ (Total Cost) - $100,000) (1.10)^2} \]
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:
\[ \text{CH}_4 + \frac{1}{2} \text{O}_2 \rightarrow \frac{1}{2} \text{C}_2\text{H}_4 + \text{H}_2\text{O} \]

However, the partial or total oxidation to CO or CO2 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 CH4:O2 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 your results. 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
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 provide some 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 more recycle increases energy and equipment cost. You may consider recycling CO2 as a diluent 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 ethane/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 ***

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<th>IN</th>
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<th>RELATIVE DIFF.</th>
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<td>MASS(LB/HR  )</td>
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<tr>
<td>ENTHALPY(BTU/HR )</td>
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<td>-0.638387E+10</td>
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</table>

*** 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:

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*** OVERALL RESULTS ***

STREAMS:

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<tr>
<td>V= 1.0000D+00</td>
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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
COLDSDIE, TOTAL PSI 0.0000

*** ZONE RESULTS ***

TEMPERATURE LEAVING EACH ZONE:

HOT

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COLDOUT | VAP | COLDIN
<------|-----|<------
| 286.0|     | 129.6 |
ZONE HEAT TRANSFER AND AREA:

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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 ***

195
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
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**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 ***

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197
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 ) 0.194558E+09
NET CONDENSER DUTY (BTU/HR ) -0.194558E+09
REBOILER HEATING REQUIRED (BTU/HR ) 0.189169E+08
NET REBOILER DUTY (BTU/HR ) 0.189169E+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 -0.0587730E-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 :

<table>
<thead>
<tr>
<th>COMP</th>
<th>F(I)</th>
<th>X(I)</th>
<th>Y(I)</th>
<th>K(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>METHANE</td>
<td>0.46157</td>
<td>0.34108E-05</td>
<td>0.70578</td>
<td>0.20693E+06</td>
</tr>
<tr>
<td>C2H4</td>
<td>0.45782E-01</td>
<td>0.57342E-06</td>
<td>0.70004E-01</td>
<td>0.12208E+06</td>
</tr>
<tr>
<td>C2H6</td>
<td>0.22810E-01</td>
<td>0.19544E-06</td>
<td>0.34878E-01</td>
<td>0.17846E+06</td>
</tr>
</tbody>
</table>
**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 ***

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
<th>GENERATION</th>
<th>RELATIVE DIFF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL BALANCE</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MOLE(LBMOL/HR)</td>
<td>24967.9</td>
<td>24979.5</td>
<td>11.5980</td>
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<tr>
<td>MASS(LB/HR )</td>
<td>512659.</td>
<td>512659.</td>
<td>-0.227081E-15</td>
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<tr>
<td>ENTHALPY(BTU/HR )</td>
<td>-0.259577E+09</td>
<td>-0.818878E+08</td>
<td>-0.684534</td>
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</table>

*** 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:

<table>
<thead>
<tr>
<th>REACTION NUMBER</th>
<th>REFERENCE COMPONENT</th>
<th>HEAT OF REACTION BTU/LBMOL</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>METHANE</td>
<td>-0.12097E+06</td>
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<tr>
<td>2</td>
<td>METHANE</td>
<td>-75545.</td>
</tr>
<tr>
<td>3</td>
<td>METHANE</td>
<td>-0.34490E+06</td>
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<tr>
<td>4</td>
<td>METHANE</td>
<td>-0.22324E+06</td>
</tr>
</tbody>
</table>

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
VAPOUR FRACTION  1.0000

HEAT OF REACTIONS:

<table>
<thead>
<tr>
<th>REACTION</th>
<th>REFERENCE</th>
<th>HEAT OF</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER</td>
<td>COMPONENT</td>
<td>REACTION</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BTU/LBMOL</td>
</tr>
<tr>
<td>1</td>
<td>METHANE</td>
<td>-0.12097E+06</td>
</tr>
<tr>
<td>2</td>
<td>METHANE</td>
<td>-75545.</td>
</tr>
<tr>
<td>3</td>
<td>METHANE</td>
<td>-0.34490E+06</td>
</tr>
<tr>
<td>4</td>
<td>METHANE</td>
<td>-0.22324E+06</td>
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</table>

REACTION EXTENTS:

<table>
<thead>
<tr>
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<th>REACTION</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td>LBMOL/HR</td>
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<tr>
<td>1</td>
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<td>2</td>
<td>566.64</td>
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<tr>
<td>3</td>
<td>2359.4</td>
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<tr>
<td>4</td>
<td>589.84</td>
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</table>

206
V-L PHASE EQUILIBRIUM:

<table>
<thead>
<tr>
<th>COMP</th>
<th>F(I)</th>
<th>X(I)</th>
<th>Y(I)</th>
<th>K(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>METHANE</td>
<td>0.46446</td>
<td>0.46446</td>
<td>0.46446</td>
<td>MISSING</td>
</tr>
<tr>
<td>C2H4</td>
<td>0.45536E-01</td>
<td>0.45536E-01</td>
<td>0.45536E-01</td>
<td>MISSING</td>
</tr>
<tr>
<td>C2H6</td>
<td>0.22687E-01</td>
<td>0.22687E-01</td>
<td>0.22687E-01</td>
<td>MISSING</td>
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<tr>
<td>CO2</td>
<td>0.94452E-01</td>
<td>0.94452E-01</td>
<td>0.94452E-01</td>
<td>MISSING</td>
</tr>
<tr>
<td>CO</td>
<td>0.23839E-01</td>
<td>0.23839E-01</td>
<td>0.23839E-01</td>
<td>MISSING</td>
</tr>
<tr>
<td>WATER</td>
<td>0.34902</td>
<td>0.34902</td>
<td>0.34902</td>
<td>MISSING</td>
</tr>
</tbody>
</table>

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 ***

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
<th>RELATIVE DIFF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL BALANCE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOLE(LBMOL/HR)</td>
<td>189000</td>
<td>189000</td>
</tr>
<tr>
<td>MASS(LB/HR )</td>
<td>0.340489E+07</td>
<td>0.340489E+07</td>
</tr>
<tr>
<td>ENTHALPY(BTU/HR )</td>
<td>-0.234158E+11</td>
<td>-0.234134E+11</td>
</tr>
</tbody>
</table>

*** 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
### Section 1. Chemical product and company identification

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

### Section 2. Hazards identification

#### Physical state
Gas. **[COLORLESS GAS; MAY BE A LIQUID UNDER PRESSURE OR REFRIGERATION.]**

#### Emergency overview
**WARNING!**
- GAS: CONTENTS UNDER PRESSURE. 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

<table>
<thead>
<tr>
<th>Eyes</th>
<th>Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.</td>
</tr>
<tr>
<td>Inhalation</td>
<td>Acts as a simple asphyxiant.</td>
</tr>
<tr>
<td>Ingestion</td>
<td>Ingestion is not a normal route of exposure for gases. Contact with cryogenic liquid can cause frostbite and cryogenic burns.</td>
</tr>
</tbody>
</table>

#### 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

<table>
<thead>
<tr>
<th>Name</th>
<th>CAS number</th>
<th>% Volume</th>
<th>Exposure limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>74-82-8</td>
<td>100</td>
<td>ACGIH TLV (United States, 1/2009). TWA: 1000 ppm 8 hour(s).</td>
</tr>
</tbody>
</table>

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 wristband. 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 (-366.7°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 chemicals products if a risk assessment indicates this is necessary.

Insulated gloves suitable for low temperatures

Personal protection in case of a large spill

Product name: Methane

ACGIH TLV (United States, 1/2009).

TWA: 1000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.
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 (ft³/lb): 23.6128
Gas Density (lb/ft³): 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: 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, CO₂) 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

<table>
<thead>
<tr>
<th>Regulatory information</th>
<th>UN number</th>
<th>Proper shipping name</th>
<th>Class</th>
<th>Packing group</th>
<th>Label</th>
<th>Additional information</th>
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<tbody>
<tr>
<td>DOT Classification</td>
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<td>1</td>
<td>Not applicable (gas).</td>
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<tr>
<td></td>
<td>UN1972</td>
<td>Methane, refrigerated liquid</td>
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## Methane

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<tbody>
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<td>ERAP Index 3000</td>
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<td>Passenger Carrying Ship Index Forbidden</td>
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<tr>
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<td>Passenger Carrying Road or Rail Index Forbidden</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Mexico Classification</th>
<th>UN1971</th>
<th>(Methane) Methane, compressed or Methane or Natural gas, compressed (with high methane content)</th>
<th>2.1</th>
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<tr>
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<td>UN1972</td>
<td>Methane, refrigerated liquid</td>
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</tr>
</tbody>
</table>

"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 302/3044 emergency planning and notification: No products were found.
- SARA 302/304 hazardous chemicals: Methane.
- 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.
Methane

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 NPR: 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 PRESSURE.
  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

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

- Health: 1
- Flammability: 4
- Instability: 0
- Reactivity: 1
- Personal protection: 1
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 PRESSURE.
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

<table>
<thead>
<tr>
<th>Name</th>
<th>CAS number</th>
<th>% Volume</th>
<th>Exposure limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethane</td>
<td>74-84-0</td>
<td>100</td>
<td>ACGIH TLV (United States, 2/2010).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 1000 ppm 8 hour(s).</td>
</tr>
</tbody>
</table>

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.
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) 294.4-93.

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

Product name: ethane

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

Consult local authorities for acceptable exposure limits.
Section 9. Physical and chemical properties

Molecular weight: 30.08 g/mole
Molecular formula: C2H6
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 (ft³/lb): 12.6582
Gas Density (lb/ft³): 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, CO₂) 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

<table>
<thead>
<tr>
<th>Regulatory information</th>
<th>UN number</th>
<th>Proper shipping name</th>
<th>Class</th>
<th>Packing group</th>
<th>Label</th>
<th>Additional information</th>
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</table>
## Ethane

| DOT Classification | UN1035 | ETHANE | 2.1 | Not applicable (gas). | Limited quantity
<table>
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<td>UN1961</td>
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<td></td>
<td></td>
<td>Yes.</td>
</tr>
</tbody>
</table>
|                     |        | | | | Packaging instruction
| | | | | | Passenger aircraft
| | | | | | Quantity limitation: Forbidden.
| | | | | | Cargo aircraft
| | | | | | Quantity limitation: 150 kg

| TDG Classification | UN1035 | ETHANE | 2.1 | Not applicable (gas). | Explosive Limit and Limited Quantity Index
|---------------------|--------|--------|----|----------------------|-------------------------------|
|                     | UN1961 | Ethane, refrigerated liquid |    |                      | ERAP Index 3000
| | | | | | Passenger Carrying Ship Index
| | | | | | Forbidden
| | | | | | Passenger Carrying Road or Rail Index
| | | | | | Forbidden

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<th>ETHANE</th>
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<th>Not applicable (gas).</th>
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<td>UN1961</td>
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</tbody>
</table>

"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
### 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 PRESSURE.
  - 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.)

<table>
<thead>
<tr>
<th>Health</th>
<th>Flammability</th>
<th>Physical hazards</th>
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**Liquid:**
- Health: 3
**Ethane**

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<tr>
<th>Fire hazard</th>
<th>Reactivity</th>
<th>Personal protection</th>
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</thead>
<tbody>
<tr>
<td>4</td>
<td>0</td>
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</table>

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

<table>
<thead>
<tr>
<th>Flammability</th>
<th>Health</th>
<th>Instability</th>
<th>Special</th>
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<tr>
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</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Notice to reader**

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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 asphyxiants.
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

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

Section 3. Composition, Information on Ingredients

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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 other electrical 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 (sparks 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.

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).
OSHA PEL (United States, 6/2010).
TWA: 1800 mg/m³ 8 hour(s).
TWA: 1800 mg/m³ 8 hour(s).
**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 (-309.9°F)
- **Critical temperature**: 96.6°C (205.9°F)
- **Vapor pressure**: 109 (psig)
- **Vapor density**: 1.6 (Air = 1)
- **Specific Volume (ft³/lb)**: 8.6206
- **Gas Density (lb/ft³)**: 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**

<table>
<thead>
<tr>
<th>Ingredient name</th>
<th>Result</th>
<th>Species</th>
<th>Dose</th>
<th>Exposure</th>
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<tbody>
<tr>
<td>Propane</td>
<td>LC50 Inhalation</td>
<td>Rat</td>
<td>&gt;80000 ppm</td>
<td>15 minutes</td>
</tr>
<tr>
<td></td>
<td>Gas.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **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**: No known significant effects or critical hazards.
- **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, CO₂) 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

<table>
<thead>
<tr>
<th>Regulatory information</th>
<th>UN number</th>
<th>Proper shipping name</th>
<th>Class</th>
<th>Packing group</th>
<th>Label</th>
<th>Additional information</th>
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<tr>
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<td>PROPANE</td>
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<td>Passenger aircraft</td>
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<td>Cargo aircraft</td>
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<td><strong>Passenger Carrying Road or Rail</strong></td>
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</tr>
</tbody>
</table>

"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

### State regulations
- Clean Air Act (CAA) 112 regulated flammable substances: propane
- 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 Autely 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.)

- **Health**: 2
- **Flammability**: 0
- **Instability**: Special

### 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**

## 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 tienek; Flue gasoxide; Carbon monoxide
| MSDS #             | 001014
| Date of
| Preparation/Revision | 12/3/2012.
| In case of emergency | 1-866-734-3438

## Section 2. Hazards identification

### Physical state

| Physical state | Gas. [[COLORLESS GAS, MAY BE A LIQUID AT LOW TEMPERATURE OR HIGH PRESSURE.]]

### Emergency overview

| 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.
| Routes of entry   | cardiovascular system, central nervous system (CNS).
|                   | 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

| Medical conditions | 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

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

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 it 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).
### Section 9. Physical and chemical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<td>Melting/freezing point</td>
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<tr>
<td>Specific Volume (ft³/lb)</td>
<td>13.8889</td>
</tr>
<tr>
<td>Gas Density (lb/ft³)</td>
<td>0.072</td>
</tr>
</tbody>
</table>

### 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

<table>
<thead>
<tr>
<th>Product/ingredient name</th>
<th>Result</th>
<th>Species</th>
<th>Dose</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon monoxide</td>
<td>TDL0 Intraperitoneal</td>
<td>Rat</td>
<td>35 mL/kg</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation</td>
<td>Rat</td>
<td>13500 mg/m³</td>
<td>15 minutes</td>
</tr>
<tr>
<td></td>
<td>Vapor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation</td>
<td>Rat</td>
<td>1900 mg/m³</td>
<td>4 hours</td>
</tr>
<tr>
<td></td>
<td>Vapor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation</td>
<td>Rat</td>
<td>6600 ppm</td>
<td>30 minutes</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation</td>
<td>Rat</td>
<td>3760 ppm</td>
<td>1 hours</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation</td>
<td>Mouse</td>
<td>2444 ppm</td>
<td>4 hours</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation</td>
<td>Rat</td>
<td>1807 ppm</td>
<td>4 hours</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **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, CO₂).

**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

<table>
<thead>
<tr>
<th>Regulatory information</th>
<th>UN number</th>
<th>Proper shipping name</th>
<th>Class</th>
<th>Packing group</th>
<th>Label</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOT Classification</td>
<td>UN1016</td>
<td>CARBON MONOXIDE, COMPRESSED</td>
<td>2.3</td>
<td>Not applicable (gas)</td>
<td></td>
<td>Inhalation hazard zone D Limited quantity Yes. Packaging instruction Passenger aircraft Quantity limitation: Forbidden. Cargo aircraft Quantity limitation: 25 kg Special provisions 4</td>
</tr>
<tr>
<td>TDG Classification</td>
<td>UN1016</td>
<td>CARBON MONOXIDE, COMPRESSED</td>
<td>2.3</td>
<td>Not applicable (gas)</td>
<td></td>
<td>Explosive Limit and Limited Quantity Index 0 FRAP Index 500 Passenger Carrying Ship Index Forbidden Passenger Carrying Road or Rail</td>
</tr>
</tbody>
</table>
# Carbon Monoxide

<table>
<thead>
<tr>
<th>Mexico Classification</th>
<th>UN1016</th>
<th>CARBON MONOXIDE, COMPRESSED</th>
<th>2.3</th>
<th>Not applicable (gas).</th>
<th>Forbidden</th>
</tr>
</thead>
</table>

"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 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

**Ingredient name**

<table>
<thead>
<tr>
<th>Cancer</th>
<th>Reproductive</th>
<th>No significant risk level</th>
<th>Maximum acceptable dosage level</th>
</tr>
</thead>
</table>

### 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).
Carbon Monoxide

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

Canada
Label requirements

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

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.
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:
CONTENT'S UNDER PRESSURE.
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

<table>
<thead>
<tr>
<th>Name</th>
<th>CAS number</th>
<th>% Volume</th>
<th>Exposure limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>124-35-9</td>
<td>100</td>
<td>ACGIH TLV (United States, 2/2010):</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 54000 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 30000 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 9000 mg/m³ 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5000 ppm 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIOSH REL (United States, 6/2009):</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 54000 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 30000 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 9000 mg/m³ 10 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5000 ppm 10 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OSHA PEL (United States, 6/2010):</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 9000 mg/m³ 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5000 ppm 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OSHA PEL 1589 (United States, 3/1983):</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 54000 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 30000 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 18000 mg/m³ 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 10000 ppm 8 hour(s).</td>
</tr>
</tbody>
</table>

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 wristband. 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) Z144.4-93

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).

- 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**: C₂O₂
- **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 (ft³/lb)**: 8.7719
- **Gas Density (lb/ft³)**: 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**: Carbon dioxide
- **Result**: LC50 Inhalation Gas.
- **Species**: Rat
- **Dose**: 470000 ppm
- **Exposure**: 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**

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

"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 ATR:** 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 PRESSURE.
  - 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.)

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

Notice to reader
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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
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
GHS: Not available.
Synonym: Dihydrogen oxide
Chemical Name: Water
Chemical Formula: H2O

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:

<table>
<thead>
<tr>
<th>Name</th>
<th>CAS #</th>
<th>% by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>7732-18-5</td>
<td>100</td>
</tr>
</tbody>
</table>

Toxicological Data on Ingredients: Not applicable.

Section 3: Hazards Identification

Potential Acute Health Effects:

Potential Chronic Health Effects:
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.
**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.
- 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.
**Interactivity (in Water):** Not available.
**Dispersion Properties:** Not applicable
**Solubility:** Not Applicable

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**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.

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**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:**
**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.

<table>
<thead>
<tr>
<th>Section 12: Ecological Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecotoxicity: Not available.</td>
</tr>
<tr>
<td>BOD5 and COD: Not available.</td>
</tr>
<tr>
<td>Products of Biodegradation:</td>
</tr>
<tr>
<td>Possibly hazardous short term degradation products are not likely. However, long term degradation products may arise.</td>
</tr>
<tr>
<td>Toxicity of the Products of Biodegradation: The product itself and its products of degradation are not toxic.</td>
</tr>
<tr>
<td>Special Remarks on the Products of Biodegradation: Not available.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section 13: Disposal Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Disposal:</td>
</tr>
<tr>
<td>Waste must be disposed of in accordance with federal, state and local environmental control regulations.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section 14: Transport Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOT Classification: Not a DOT controlled material (United States).</td>
</tr>
<tr>
<td>Identification: Not applicable.</td>
</tr>
<tr>
<td>Special Provisions for Transport: Not applicable.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section 15: Other Regulatory Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal and State Regulations: TSCA 8(b) inventory: Water</td>
</tr>
<tr>
<td>Other Regulations: EINECS: This product is on the European Inventory of Existing Commercial Chemical Substances.</td>
</tr>
<tr>
<td>Other Classifications:</td>
</tr>
<tr>
<td>WHMIS (Canada): Not controlled under WHMIS (Canada).</td>
</tr>
<tr>
<td>DSCL (EEC): This product is not classified according to the EU regulations. Not applicable.</td>
</tr>
<tr>
<td>HMIS (U.S.A.):</td>
</tr>
<tr>
<td>Health Hazard: 0</td>
</tr>
<tr>
<td>Fire Hazard: 0</td>
</tr>
<tr>
<td>Reactivity: 0</td>
</tr>
<tr>
<td>Personal Protection: a</td>
</tr>
<tr>
<td>National Fire Protection Association (U.S.A.):</td>
</tr>
<tr>
<td>Health: 0</td>
</tr>
<tr>
<td>Flammability: 0</td>
</tr>
<tr>
<td>Reactivity: 0</td>
</tr>
<tr>
<td>Specific hazard:</td>
</tr>
</tbody>
</table>
### Protective Equipment:
Not applicable, Lab coat, Not applicable, Safety glasses.

### Section 16: Other Information

**References:** Not available.

**Other Special Considerations:** Not available.

**Created:** 10/10/2005 08:33 PM  
**Last Updated:** 05/21/2013 12:00 PM

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Bibliography


