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Process Desugb for the Photosynthesis of Ethylene

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Abstract

This project evaluates the feasibility of using cyanobacteria to produce ethylene from CO2. A recent paper published by the National Renewable Energy Lab (NREL) showed that it was possible to produce ethylene continuously in lab scale experiments. The cyanobacteria uses CO2, water, and light to photosynthesize ethylene.

We were tasked to design a plan to produce 100MM lb/year of ethylene. It was quickly determined that at the current published production rate the process would not be economically feasible. The rate would need to be significantly increased before the process becomes economically viable. Also, at the current state of technology, no commercially available or patented photobioreactor can support this process. The presence of both a gas feed and effluent pose significant obstacles for reactor design. It was also determined that due to the endothermic nature of the reaction and the inefficiency of photosynthesis, the process must rely predominantly on sunlight.

This project includes specifications and pricing for water purification, cell growth, and two separation systems. The present value of the process without the reactor section was calculated to determine the maximum reactor investment and annual operating cost to yield a return on investment of 15%. Location of the plant was also determined. Due to carbon dioxide and seawater needs, this plant will be located along the coast in Santa Rosa, CA, close to an ethanol plant. The plant will operate 340 days per year to allot for any downtime incurred in daily operation.

Cells will be initially grown in seed and growth tanks in batch-type process. Warm seawater supplemented with nitric acid, phosphorous acid, and sodium hydroxide will be used as the media for cell growth. Two separation sections were designed for purifying reactor effluent. The two separation systems investigated were pressure swing adsorption using zeolite adsorbent and cryogenic distillation with a custom nitrogen refrigeration system. These two were compared economically and it was shown that the PSA system yielded favorable economics.

Without the reactor section, the process using pressure swing adsorption yields an IRR of 67.62% with a net present value of $70MM at 15% ROI. The proposed reactor section investment and annual operating cost can have at most a net present value of -$70MM to meet project requirements.

Disciplines

Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering

Department of Chemical & Biomolecular Engineering

Senior Design Report (CBE)

University of Pennsylvania Year 2013

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PHOTOSYNTHESIS

OF

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Department of Chemical and Biomolecular Engineering

University of Pennsylvania

Spring 2013

Faculty Advisors: Leonard Fabiano and Dr. Daeyeon Lee

Project Recommendation by: Mr. Bruce Vrana

April 9, 2013
Professor Leonard Fabiano
Department of Chemical and Biomolecular Engineering
University of Pennsylvania
220 South 33rd Street
Philadelphia, PA 19104

Dear Professor Fabiano and Dr. Lee,
We would like to present our solution to the *Photosynthesis of Ethylene* design project that was conceived by Mr. Bruce Vrana. We have designed a plant, to be located in Santa Rosa, CA, which will produce 100 MM pounds of 99.5% per year by the photosynthetic reaction of a genetically modified cyanobacterium, *Synechocystis sp. PCC 6803,* with a feed of carbon dioxide provided by a nearby ethanol plant run by Pacific Ethanol in Stockton, CA. Since the technology of a reactor needed to conduct this photosynthetic reaction seems some time away from feasibility we have designed the remainder of the plant and determined an investment price of a bioreactor that would yield a 15% IRR for the project.

Seawater from the nearby Pacific Ocean will be purified and the cyanobacterium will be grown in using a specific growth media and proper conditions. After the cyanobacterium has grown to the correct production concentration they will undergo photosynthesis in the presence of carbon dioxide, air, and sunlight to yield a mixture of ethylene, carbon dioxide, nitrogen, and oxygen. Ethylene will have to be separated from the remaining stream and we have designed two possible ways to achieve the desired 99.5% ethylene purity. One separation unit design is a pressure-swing adsorption unit that utilizes a silver treated silica alumina adsorbent and the other is a cryogen distillation unit that utilizes a nitrogen refrigeration cycle.

This report contains detailed descriptions of the plant process equipment as well as overall process operating conditions. Our plant has an anticipated life of 15 years and we will assume it take three years for construction requires 6,100,000,000 cubic feet of carbon dioxide and 1,750,000,000 cubic feet of air to be fed to the process annually. We expect to operate 340 days out of the year to meet the required production capacity of our plant.

The report discusses the economic feasibility of building and operating the plant and the potential to be profitable in the ethylene market. As stated above we designed two alternative methods of separation, the pressure-swing adsorption unit and the cryogenic distillation unit, these methods are compared on economic grounds as well. The reactor technology will need time to be developed and made ready for commercial use but if and when it does our plant design can lead to profitability.

Sincerely,

Jeffrey Chien Daren Frankel Hassan Siddiqui Joseph Tuzzino

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SECTION I – ABSTRACT

Abstract

This project evaluates the feasibility of using cyanobacteria to produce ethylene from CO_2. A recent paper published by the National Renewable Energy Lab (NREL) showed that it was possible to produce ethylene continuously in lab scale experiments. The cyanobacteria uses CO_2, water, and light to photosynthesize ethylene.

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SECTION II – INTRODUCTION

Motivation

Ethylene is the most widely produced petrochemical feedstock in the world today. Currently ethylene is produced through steam cracking of fossil fuels which currently emits anywhere between 1.5 and 3 tons of carbon dioxide for every ton of ethylene that is produced.

In 2012 scientists at the US Department of Energy's National Renewable Energy Laboratory (NREL) published their findings which showed a process to produce ethylene using a genetically altered cyanobacterium – *Synechocystis sp. PCC 6803*. The organism was shown to produce ethylene at a peak rate of 171 mg/L-day through a photosynthetic process which was greater than other reported photosynthetic production rates of other chemicals by genetically manipulated microorganisms.

The process described above is unique because it consumes carbon dioxide to produce ethylene rather than emit it. This equates to saving roughly 6 tons of carbon dioxide emissions per ton ethylene produced.

The environmental advantages of this process are obvious but the economics will drive whether this process is commercially available. The cyanobacteria used in the lab were grown using seawater enriched with nitrogen and phosphorus sources which serve as nutrients for the bacteria. The use of inputs of readily available seawater as well as carbon dioxide, which could be taken from the stack gases of an ethanol plant at nearly no cost, leads to the inference that the inputs to the process may be very inexpensive and the production of ethylene via this route might be economically viable. Bruce Vrana of DuPont proposed a CBE 459 design project in 2012 that involved a design of an ethylene production facility using the photosynthetic process described above and that would suggest any necessary research and development improvements to make the process economically viable.

NREL Paper

A paper published in *Energy & Environmental Science*, 2012, 5, 8998 by researchers at the National Renewable Energy Laboratory (NREL) explores the process of producing ethylene from CO_2 using genetically engineered cyanobacterium *Synechocystis* 6803. The process of the photosynthesis of ethylene is shown in Figure 2.1. Cyanobacteria have previously been engineered to produce other products including ethanol, butyl aldehyde, and hydrogen gas.

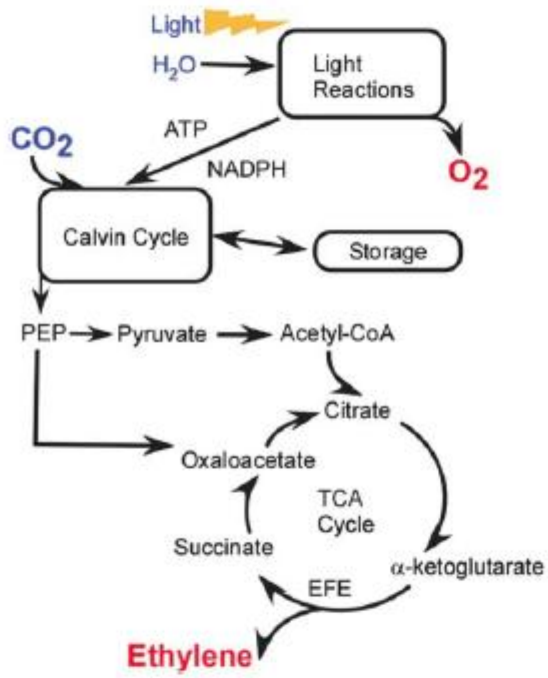

Figure 2.1 – Cellular process for the photosynthesis of ethylene.

Ethylene is a common building block for numerous polymers and chemical products. It is produced primarily through steam cracking of fossil fuels, a process which emits large amounts of CO_2. Producing ethylene via a biological route would reduce dependency on fossil fuels, consume CO_2 rather than emitting it, and create a more sustainable/renewable process.

Researchers at NREL were able to reach a peak production rate of 171 mg L^{-1} day^{-1} and a continuous production rate of 92 mg L^{-1} day^{-1}. The researchers also found that up to 5.5% of the fixed carbon was directed toward ethylene synthesis. By adding multiple copies of *Sy-efe* (the gene sequence responsible for ethylene production), researchers were able to increase production rates and percentage of fixed carbon directed toward ethylene synthesis.

Seawater supplemented with nitrogen and phosphorus sources (similar to BG-11 media) were found to support cyanobacterium growth and ethylene production. Researchers did not comment on the lifespan of engineered strains. In previous studies, engineered *Synechocystis* 6803 was found to die after as little as four generations.

Production of other molecules

Synechocystis 6803 and other cyanobacterium have been engineered to produce a variety of products. Table 2.1 includes a list of other products produced using engineered cyanobacterium.

Table 2.1 - List of other compounds produced using cyanobacterium

Product	Species	Productivity	Culture Vessel	No. of Culture Days	Production Rate	
Ethanol	Synechococcus 7942	230 mg/L	Shake Flask	28	8.2	mg/L/day
Ethanol	Synechocystis 6803	552 mg/L	Photobioreactor	6	92.0	mg/L/day
Isobutyraldehyde	Synechococcus 7942	1,100 mg/L	Roux Culture Bottle	8	137.5	mg/L/day
Isobutanol	Synechococcus 7942	18 mg/L	Shake Flask	-	-	
Isobutanol	Synechococcus 7942	450 mg/L	Shake Flask	6	75.0	mg/L/day
Fatty Alcohol	Synechocystis 6803	200 μg/L	Photobioreactor	18	11.1	μg/L/day
Alkanes	Synechocystis 6803	162 μg/L	Shake Flask	-	-	
Fatty Acids	Synechocystis 6803	197 mg/L	Bubbling CO2	17	11.6	mg/L/day
Hydrogen	Synechococcus 7942	2.8 μmol/h/mgc Chl-aa	Anaerobic Conditions	-	-	
1-Butanol	Synechococcus 7942	14.5 mg/L	Dark Roux Cuture Bottle	7	2.1	mg/L/day
Fatty Alcohol	Synechocystis 6803	20 μg/L/OD	Shake Flask	-	-	
1-Butanol	Synechococcus 7942	30 mg/L	Shake Flask	18	1.7	mg/L/Day

Most of the products produced using cyanobacterium remain in the liquid phase. Under these conditions, the reactor effluent contains a mixture of unreacted materials, cell debris, and products. These must be separated from each other and purified. On an industrial scale, processes producing liquid phase products can be done using CSTRs, batch reactors, tubular reactors, or similar equipment. One notable design for these types of products uses long, transparent, tubular bioreactors that harvest sunlight to photosynthesize liquid products.

As shown in Table 2.1, cyanobacterium *Synechococcus* 7942 has been engineered to produce hydrogen gas. In contrast to liquid phase products, hydrogen gas bubbles off the top of the solution. This makes harvesting the desired products much easier. However, hydrogen gas may not be the only gas leaving the solution. Oxygen, nitrogen, carbon dioxide and other gases may also be present. The presence of these compounds can make separations rather costly.

Energy and Feed Requirements

Figure 2.2 shows the balanced photosynthesis reaction for the production of ethylene. Table 2.2 summarizes this reaction on a per-pound of ethylene basis. For each pound of ethylene produced, the reaction consumes 1.1 pounds of carbon dioxide, 1.3 pounds of water, and produces 3.422 pounds of oxygen. It should be noted that under certain conditions, this reaction may produce flammable gas streams.

$$2CO_2 + 2H_2O \rightarrow C_2H_4 + 3O_2$$

Figure 2.2 – Photosynthesis reaction for the production of ethylene

Table 2.2 – Photosynthesis reaction to produce ethylene on a per mole and per pound ethylene basis.

Species	Reaction Coefficient (mol/mol Ethylene)	MM (g/mol)	MM (lb/mol)	Ratio (lb/lb Ethylene Produced)
CO_2	-2	44.010	0.097	-3.138
H_2O	-2	18.015	0.040	-1.285
C_2H_4	1	28.050	0.062	1.000
O_2	3	31.998	0.072	3.422

Table 2.3 shows the individual enthalpies of formation for each reactant and product and the overall reaction enthalpy. The reaction is highly endothermic, requiring 2.28 x 10^4 kj/lb C_2H_4.

Table 2.3 – Standard enthalpies of formation for reactants and products for the photosynthesis of ethylene

Species	Reaction Coefficient	Standard Enthalpy of Formation (kj/mol)
CO2 (g)	-2	-393.5
H2O (l)	-2	-285.8
C2H4 (g)	1	52.3
O2 (g)	3	0
Total Reaction	**-**	**1,410.9 kj/mol C_2H_4 (2.28 x 10^4 kj/lb C_2H_4)**

Reactor Feeds

The reactor(s) will require both liquid and gas feeds. The liquid feed will include fresh cells, nutrients, and water. This stream also includes a base to maintain the pH of the reactor at optimal pH.

A gas stream containing a mixture of CO_2 and air will be fed to the bottom of the reactor. The optimum mixture needs to be determined through further study of the bacteria. It is unclear whether or not the bacteria can process higher CO_2 concentrations. The ratio of air to CO_2 feed is also a factor in determining the concentration of oxygen and ethylene in the outlet stream. It is important to adjust this ratio so that the reactor effluent is kept well clear of the flammability limits. Light energy would be supplied to the system via LED lamps.

Reactor Effluent

The reactor(s) will produce both liquid and gas effluent. The liquid effluent will contain leftover water, salts, cell debris, and sludge. This stream must be appropriately treated prior to disposal into local water bodies.

The gas stream leaving the reactor will contain a mixture of oxygen, nitrogen, carbon dioxide, ethylene, and trace elements from the air. It is crucial that this stream is kept well outside the flammability limits for ethylene. This can be altered by changing the ratio of CO_2 and air fed to the reactor, or decreasing the amount of time the gas and liquid streams are in contact with each other (longer contact means higher conversion of carbon dioxide into ethylene and oxygen).

Optimal Growth Conditions

Cyanobacterium grow well at temperatures at or above 25°C with the optimal temperature at 33°C with an optimal pH of 11. This high pH value also helps to inhibit the growth of unwanted microorganisms. Low light intensities can support bacterial growth, around 20-40 $\mu E\text{-}m^{-2}\text{-}s^{-1}$. The cells need at least 5 minutes of exposure per day to grow but will otherwise grow in complete darkness.

Synechocystis 6803 are typically grown using BG-11 media for lab scale experiments. As the NREL paper noted, the bacteria may be grown in seawater supplemented with phosphorus and nitrogen sources. These nutrients are essential for growth, although it remains unclear which nutrient is limiting.

Size of Reactor vs. Rate

Using 100MM lb/year as a basis, the required reactor size is dependent on production rate. Figure 2.3 shows how the volume of broth required to produce 100MM lb/year changes as the production rate increases. The required volume varies inversely with production rate.

At the current state of research, the cyanobacterium are only able to produce 92mg/L-day of ethylene. Based on this rate, 1.45 billion liters of broth would need to be undergoing production at all times. Increasing the reaction rate to around 8.5g/L-day would require about 15.6 million liters of broth. Figure 2.3 shows how the required volume varies with production rate. The rate 8.5g/L-day was selected for the purposes of feasibility analysis for the project.

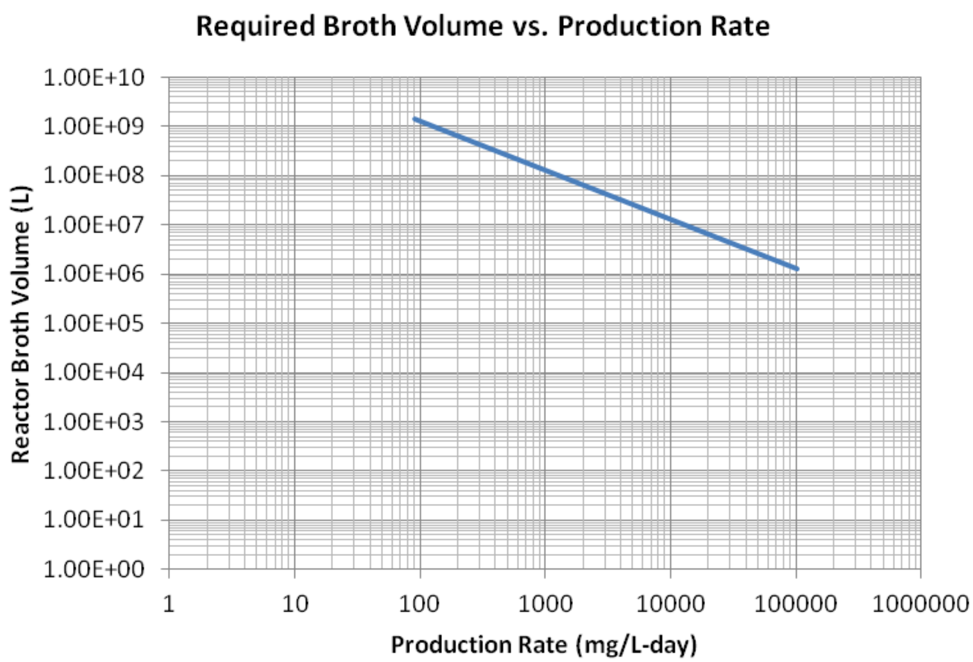

Figure 2.3 – Using 100MM lb/year as a basis for production, the above plot shows how the required broth volume (the amount of volume in the production stage at any given point in time) varies with the production rate. This plot assumes 340 operating days/year. At the current stage of research, the bacteria can only produce 92mg/L-day. This would require 1.45 billion liters of broth to be in the production phase of the process at all times.

CSTR Production Reactor Design

Using large CSTRs is one option for the production stage of this process. The liquid feed would be introduced at the top of the reactor and would be removed from the bottom. The gas feed would be introduced at the bottom of the reactor using a sparger and the gas effluent could be easily collected off the top of the reactor as it bubbles out of the liquid.

This design would include lamps to provide light energy for photosynthesis spaced throughout the reactor. Because of the size of the reactor and the lamps within the reactor, using a motor driven stirrer does not seem feasible. Instead, it would be suggested that a pump be used to take liquid from various points throughout the tank and reintroduce them to the top of the reactor. This combined with the bubbling up of gases should provide sufficient mixing.

These reactors have a few major issues. The most prevalent issue is cleaning and removal of wastes. The reactors will produce a lot of sludge and cell debris that will settle on the bottom. The reactors would require continuous or frequent removal of solids. Cell debris and sludge may also clog the sparger if not properly monitored. If reactor sterilization is necessary, a lot of production time will be wasted for draining, cleaning, and refilling the reactor.

Energy and Design Issues

Photosynthesis has a maximum efficiency in the range of 10%-15%. Only a fraction of the light energy absorbed by the organism is diverted to the final product (in this case ethylene). In the case of photosynthesis in bacteria, the efficiency is much lower, on the order of 3%-6%.

The energy required to produce 100 MM lb/year of ethylene at 2.28×10^4 kj/lb comes out to 6.34×10^8 kWh/year. If 100% of the energy that was supplied to the reactor via LED bulbs was converted to ethylene, at $0.06/kWh, the electricity would cost $31.6MM/year. In reality only a fraction of the light supplied would be converted to ethylene. At 63.3% efficiency, the electricity cost would equal the value of the ethylene produced. Photosynthesis for bacteria is only 3%-6% efficient, which would require from $500MM to over $1BB in yearly electricity.

As the electricity cost far surpasses the value of the products, the light energy for production must be supplied via sunlight in order for this process to be industrially feasible. Large CSTR tanks may then not be viable options for this process. Currently, there are bioreactor concepts that make use of long transparent tubes through which algae and raw materials are pumped. As the algae move through the tube, they absorb sunlight and covert glucose or other aqueous materials into product. Unfortunately, this concept may not be applicable for the production of ethylene. As the process uses CO_2 gas to produce a gaseous product, distribution of CO_2 throughout the reactor becomes problematic. This may be the most difficult problem to solve. Likewise, collection of product gases becomes an issue.

One possible reactor design could make use of a large bank of vertically oriented translucent tubes filled with production broth. CO_2 would be bubbled in through the bottom and product gases would be collected off the top. The design of this type of system is beyond the scope of this project.

The process may be viable in a horizontal tubular reactor if the CO_2 feed is replaced with a bicarbonate source, glucose, or another aqueous carbon source. This would eliminate the need to distribute gas throughout the reactor. However, as there is no CO_2 or N_2 being supplied to the reactor, it is possible that this route will produce combustible reactor effluent. If that is the case, sufficient amounts of N_2 or other inert/easily separable gases could be supplied to blanket the system. Investigation of this alternate route is beyond the scope of this project. See table 2.4 for a summary of the advantages and disadvantages of these reactor types.

Table 2.4– Reactor type advantages and disadvantages

Reactor Type	Advantage(s)	Disadvantage(s)
CSTR	• Efficient for holding large amounts of liquid	• Difficult to clean • Difficult to stir
Horizontal Tube	• Allows for sunlight penetration	• Gas distribution/collection difficult
Vertical Tube	• Allows for sunlight penetration • Easy gas distribution and collection	• Technology not currently developed • Smaller reactors

Project Scope

In light of the findings that the commercialization of the reactor is years away, we have decided to pursue a slightly different project scope. We have decided to design the rest of the plant as if a reactor existed and then determine the capital investment that one could spend on a reactor given a 15% IRR for the project. This plant design also includes 2 different separation trains which will be compared economically to determine which one is preferable. We believe this will add value to a company who is pursuing this technology in the future when a proper photobioreactor becomes commercially available.

SECTION III – CUSTOMER REQUIREMENTS

Innovation Map

To optimize the value of engaging in a venture of designing a plant to produce ethylene via photosynthesis it is important to understand the new processes and material technologies that are being used to improve the process. The innovation map for our process is displayed below (Figure 3.1).

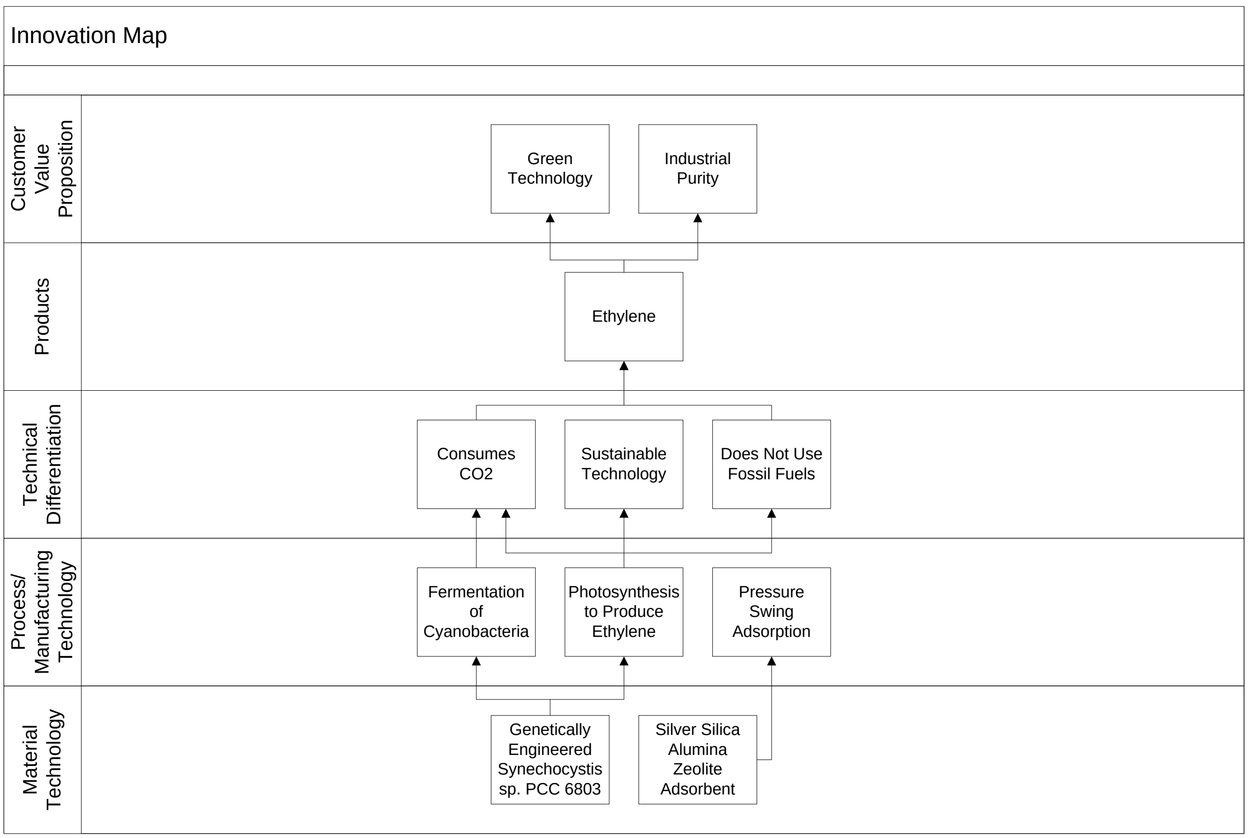

Figure 3.1 – Innovation Map

Ethylene Industrial Specifications

Under ambient temperature ethylene is a colorless, inflammable, and explosive gas. In order to be a viable business venture the ethylene produced via photosynthesis must meet industrial standards of purity which is mainly concerned with the trace molecules that are contained in the ethylene being sold. Industrial specifications are broken down into Premium-grade and 1st-grade ethylene each of which is presented in the table below, for purposes of this project 1st-grade will suffice as a target for the ethylene produced.

Table 3.1 – Ethylene Purity Standards

Ethylene Purity Standards		
Chemical Component	**Quality Criteria**	
	Premium-grade	1st-grade
Ethylene (%)	99.95	99.5
Methane and Ethane (%)	.05	.1
C_3-fraction and above (ppm)	10	50
Carbon monoxide (ppm)	1	5
Carbon dioxide (ppm)	5	20
Oxygen (ppm)	1	5
Acetylene (ppm)	5	10
Sulfur (ppm)	1	2
Water (ppm)	1	20
Hydrogen (ppm)	5	10
Methanol (ppm)	5	10
Chlorine (ppm)	1	2

Voice of the Customer

While ethylene is mass produced over the world, this plant's design differentiates itself from other ethylene plants because it is "green". Not only does this plant not produce carbon dioxide, it consumes the greenhouse gas. Also, this plant does not consume any fossil fuels, unlike other ethylene plants. Customers of this plant will mainly be plastic companies, since ethylene is used in polymerization. Target customers will be producing products like polyvinyl chloride, polyethylene, and ethylene glycol. Ethylene demand is classified as fitness-to-standard. The ethylene demand is growing as more countries industrialize and consume more plastic. Locating this plant in the United States is advantageous in this regard because it is projected by 2030 that the demand for ethylene will be around 5MM tonnes per year. Having an environmentally friendly product that has a negative carbon footprint will add value to the ethylene produced by this plant.

SECTION IV – PROCESS FLOW DIAGRAMS AND MATERIAL BALANCES

Process Flow Diagrams and Material Balances – Overall Process

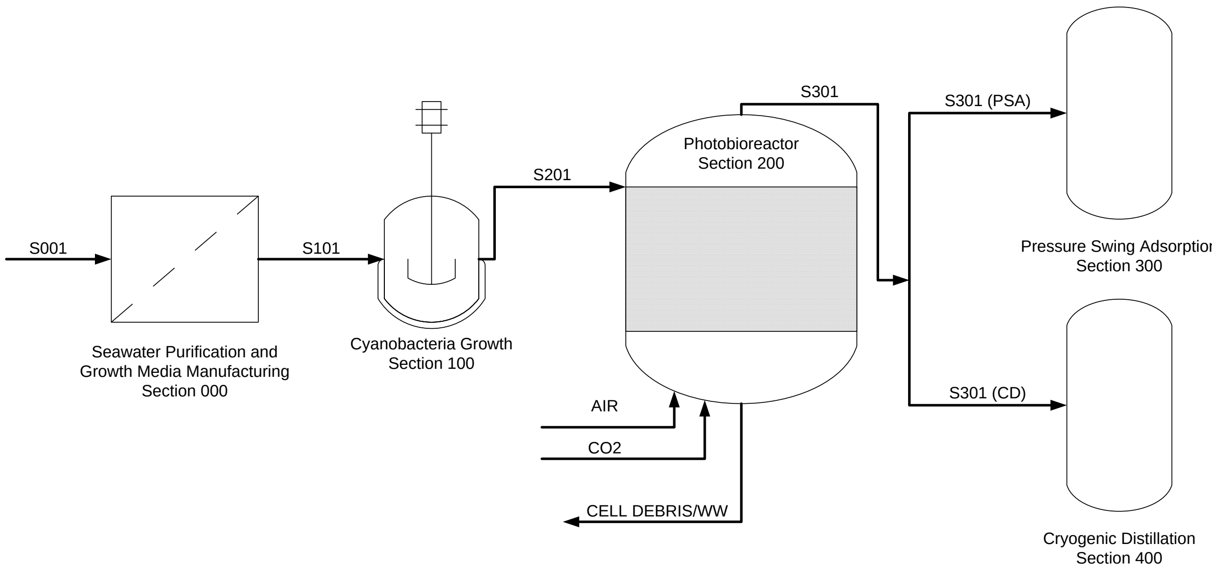

Figure 4.1 – Overall process diagram

Process Flow Diagrams and Material Balances – Seawater Purification and Growth Media Manufacturing, Section 000

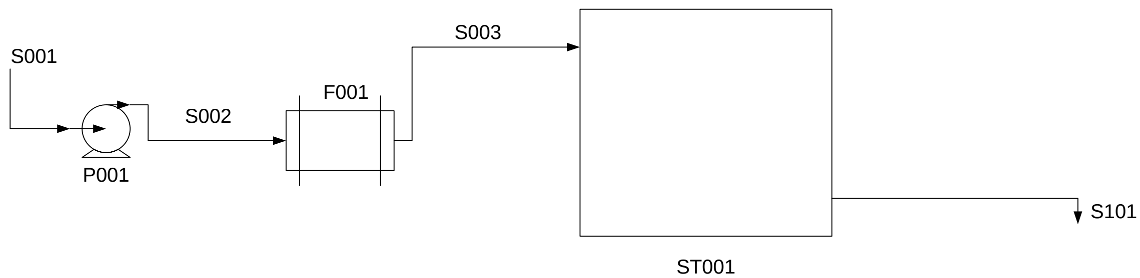

Figure 4.2 – Flow diagram for section 000

Table 4.1 – Stream Table for Section 000

Stream Table for Section 000			
Stream ID	S-001	S-002	S-003
Destination	P001	F001	ST001
Source		P001	F001
Phase	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)			
Seawater	216417	216417	216417
Mass Fraction			
Seawater	1	1	1
Total Flow (lb/hr)	216417	216417	216417
Volume Flow(cuft/hr)	3384	3384	3384
Temperature(F)	75.2	75.2	75.2
Pressure(psi)	14.7	14.7	14.7
Vapor Fraction	0	0	0
Enthalpy (BTU/hr)	9304273	9304273	9304273

Process Flow Diagrams and Material Balances – Cyanobacteria Growth, Section 100

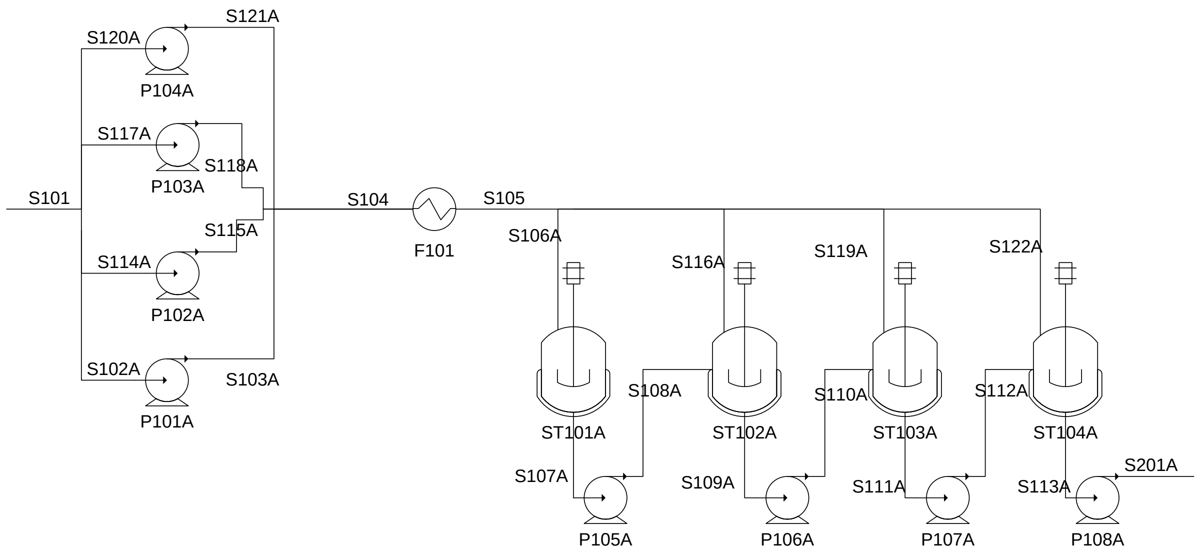

Figure 4.3 – Flow Diagram for Section 100

Table 4.2a – Stream Table for Section 100

Stream Table for Section 100						
Stream ID	S-101	S-102A	S-103A	S-104	S-105	S-106A
Destination	M1	P101A	M2	F101	M3	ST101A
Source	ST001	M1	P101A	M2	F101	M3
Phase	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID
Mass Flow(lb/hr)						
NO3	Varies	0.418	0.418	Varies	Varies	0.418
PO4	Varies	15.266	15.266	Varies	Varies	15.266
NaOH	Varies	10.214	10.214	Varies	Varies	10.214
H2O	Varies	101974	101974	Varies	Varies	101974
Total Flow (lb/hr)	Varies	101999	101999	Varies	Varies	101999
Total Flow (cuft/hr)	Varies	1604	1604	Varies	Varies	1604
Cell Conc. (cells/mL)	0	0	0	0	0	0.00
Temperature(F)	75.2	75.2	75.2	75.2	91.4	91.4
Pressure(psi)	14.7	14.7	46.8	46.8	31.8	31.8
Vapor Fraction	0	0	0	0	0	0

Table 4.2b – Stream Table for Section 100

Stream Table for Section 100 (Cont.)						
Stream ID	S-107A	S-108A	S-109A	S-110A	S-111A	S-112A
Destination	P105A	ST102A	P106A	ST103A	P107A	ST104A
Source	ST101A	P105A	ST102A	P106A	ST103A	P107A
Phase	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID
Mass Flow(lb/hr)						
NO3	0	0	0	0	0	0
PO4	0	0	0	0	0	0
NaOH	10	10	25	25	127	127
H2O	101989	101989	254974	254974	1274871	1274871
Total Flow (lb/hr)	101999	101999	254999	254999	1274999	1274999
Total Flow (cuft/hr)	1604	1604	4010	4010	20051	20051
Cell Conc. (cells/mL)	1.13E+07	1.13E+07	1.07E+07	1.07E+07	1.01E+07	1.01E+07
Temperature(F)	91.4	91.4	91.4	91.4	91.4	91.4
Pressure(psi)	14.7	35.0	14.7	39.4	14.7	48.7
Vapor Fraction	0	0	0	0	0	0

Table 4.2c – Stream Table for Section 100

Stream Table for Section 100 (Cont.)						
Stream ID	S-113A	S-114A	S-115A	S-116A	S-117A	S-118A
Destination	P108A	P102A	M2	ST102A	P103A	M2
Source	ST104A	M1	P102A	M3	M1	P103A
Phase	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID
Mass Flow (lb/hr)						
NO3	0	1.044	1.044	1.044	5.220	5.220
PO4	0	38.166	38.166	38.166	190.829	190.829
NaOH	255.346	25.535	25.535	25.535	127.673	127.673
H2O	2549743.50	254935.14	254935.14	254935.14	1274675.70	1274675.70
Total Flow (lb/hr)	2549998.85	254999.88	254999.88	254999.88	1274999.42	1274999.42
Total Flow (cuft/hr)	40103.91	4010.39	4010.39	4010.39	20051.96	20051.96
Cell Conc. (cells/mL)	1.51E+07	0	0	0	0	0
Temperature(F)	91.4	75.2	75.2	91.4	75.2	75.2
Pressure(psi)	14.7	14.7	48.986	33.986	14.7	53.326
Vapor Fraction	0	0	0	0	0	0

Table 4.2d – Stream Table for Section 100

Stream Table for Section 100 (Cont.)					
Stream ID	S-119A	S-120A	S-121A	S-122A	S-201A
Destination	ST103A	P104A	M2	ST104A	Reactor
Source	M3	M1	P104A	M3	P108A
Phase	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID
			Mass Flow (lb/hr)		
NO3	5.220	10.440	10.440	10.440	0
PO4	190.829	381.658	381.658	381.658	0
NaOH	127.673	255.346	255.346	255.346	255.346
H2O	1274675.70	2549351.41	2549351.41	2549351.41	2549743.50
Total Flow (lb/hr)	1274999.42	2549998.85	2549998.85	2549998.85	2549998.85
Total Flow (cuft/hr)	20051.96	40103.91	40103.91	40103.91	40103.91
Cell Conc. (cells/mL)	0	0	0	0	1.51E+07
Temperature(F)	91.4	75.2	75.2	91.4	91.4
Pressure(psi)	38.326	14.7	62.44	47.44	58.904
Vapor Fraction	0	0	0	0	0

Process Flow Diagrams and Material Balances – Photobioreactor, Section 200

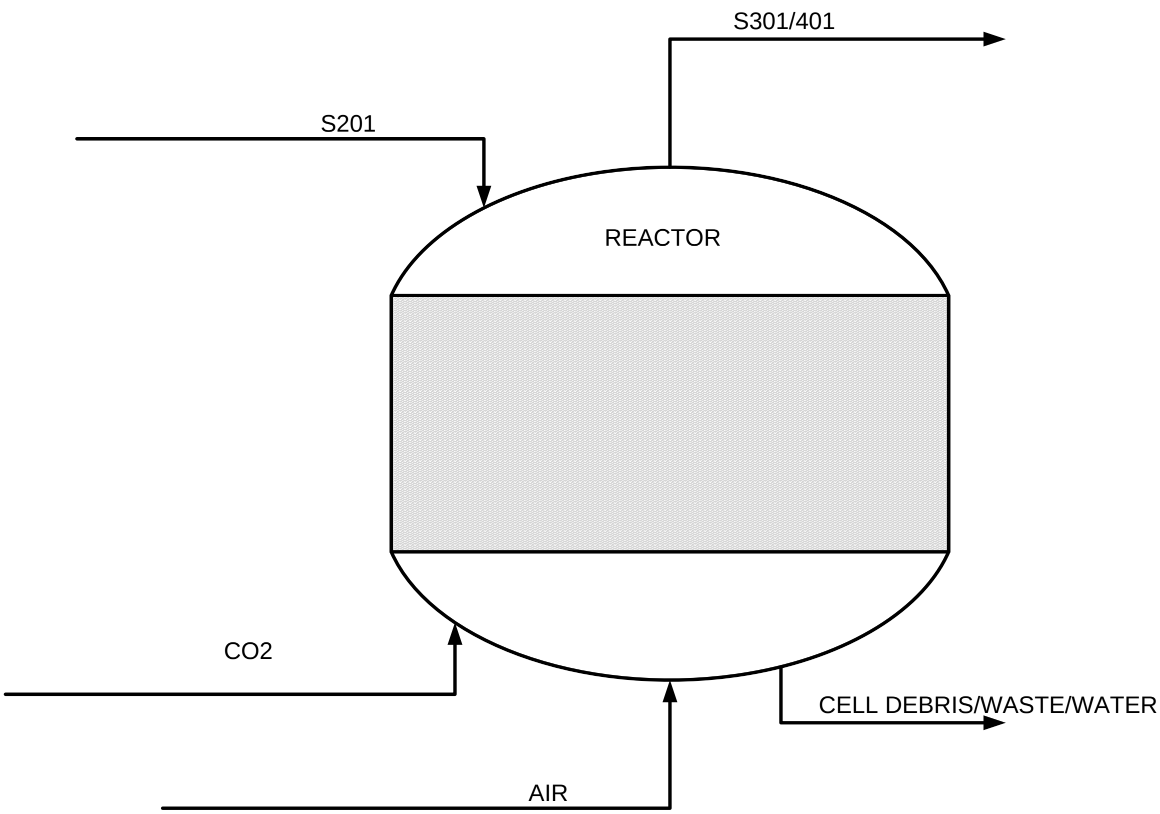

Figure 4.4 – Flow diagram for section 200

Table 4.2d – Stream Table for Section 200

Stream Table for Section 200					
Stream ID	S-201A	CO2	AIR	CELL DEBRIS/WW	S-301
Destination	Reactor	Reactor	Reactor	-	C301
Source	P108A	-	-	Reactor	-
Phase	LIQUID	VAPOR	VAPOR	LIQUID	VAPOR
Mass Flow (lb/hr)					
N2	0	0	0	0	
CO2	0	76902	0	0	
O2	0	0	0	0	16120
C2H4	0	0	0	0	42730
H2O	2549743	0	0	2549743	51560
NO3	0	0	0	0	13620
PO4	0	0	0	0	0
NaOH	255	0	0	255	
Air	0	0	19225	0	
Cell Conc. (cells/mL)	1.51E+07	0	0	1.51E+07	
Total Flow (lb/hr)	2549998.85	76902	19225	2549998.85	124030
Total Flow (cuft/hr)	40103.91	747549		40103.91	1045900
Temperature (F)	91.4	65	65	91.4	70
Pressure (psia)	58.904	14.7	14.7	58.904	14.7
Vapor Frac	0	1	1	0	1

Process Flow Diagrams and Material Balances – Pressure Swing Adsorption, Section 300

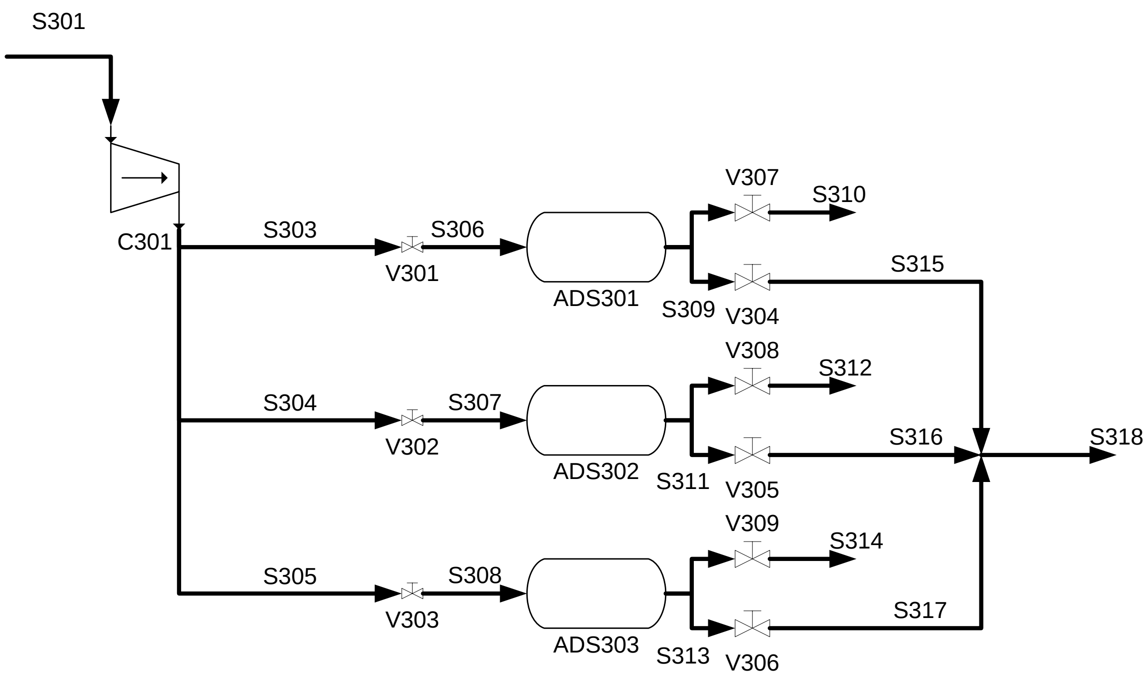

Figure 4.5 – Flow diagram for section 300

C301 is a multistage compressor comprising of three stages and cooling units between each stage. Below is a more detailed diagram of the multistage compressor block C301. The interstage cooling is designed to keep the reactor effluent stream at lower temperatures throughout the compression to reduce the risk of combustion between the steam, which consists of ethylene and oxygen.

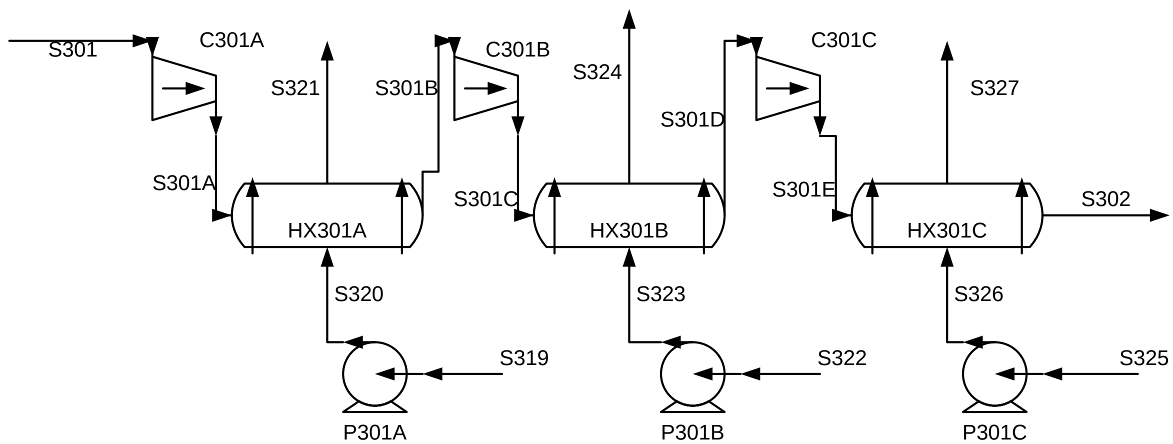

Figure 4.6 – Flow diagram for C301

Table 4.3a– Stream Table for Section 300

Stream Tables for Section 300						
Stream ID	S-301	S-302	S-303	S-304	S-305	S-306
Destination	C301	SPLITTER	V301	V302	V303	ADS301
Source	-	C301	SPLITTER	SPLITTER	SPLITTER	V301
Phase	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)						
N2	16120	16120	5373.3	5373.3	5373.3	5373.3
CO2	42730	42730	14243.3	14243.3	14243.3	14243.3
O2	51560	51560	17186.7	17186.7	17186.7	17186.7
C2H4	13620	13620	4540	4540	4540	4540
H2O	0	0	0	0	0	0
Mass Frac						
N2	0.129969	0.129969	0.129969	0.129969	0.129969	0.129969
CO2	0.344513	0.344513	0.344513	0.344513	0.344513	0.344513
O2	0.415706	0.415706	0.415706	0.415706	0.415706	0.415706
C2H4	0.109812	0.109812	0.109812	0.109812	0.109812	0.109812
H2O	0	0	0	0	0	0
Total Flow (lb/hr)	124030	124030	41343.33	41343.3	41343.3	41343.3
Total Flow (cuft/hr)	1045900	67815	22604	22604	22604	22986
Temperature (F)	70	80	80	80	80	79.7
Pressure (psia)	14.7	299.6	299.6	299.6	299.6	294.6
Vapor Frac	1	1	1	1	1	1

Table 4.3b– Stream Table for Section 300

Stream Tables for Section 300						
Stream ID	S-307	S-301A	S-301B	S-301C	S-301D	S-301E
Destination	ADS302	HX301A	C301B	HX301B	C301C	HX301C
Source	V302	C301A	HX301A	C301B	HX301B	C301C
Phase	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)						
N2	5373.3	16120	16120	16120	16120	16120
CO2	14243.3	42730	42730	42730	42730	42730
O2	17186.7	51560	51560	51560	51560	51560
C2H4	4540	13620	13620	13620	13620	13620
H2O	0	0	0	0	0	0
Mass Frac						
N2	0.129969	0.129969	0.129969	0.129969	0.129969	0.129969
CO2	0.344513	0.344513	0.344513	0.344513	0.344513	0.344513
O2	0.415706	0.415706	0.415706	0.415706	0.415706	0.415706
C2H4	0.109812	0.109812	0.109812	0.109812	0.109812	0.109812
H2O	0	0	0	0	0	0
Total Flow (lb/hr)	41343.3	124030	124030	124030	124030	124030
Total Flow (cuft/hr)	22986	707430	621320	283940	206180	100677
Temperature (F)	79.7	272.1	105	346.5	105	327.3
Pressure (psia)	294.6	40.4	35.4	110.9	109.5	304.6
Vapor Frac	1	1	1	1	1	1

Table 4.3c– Stream Table for Section 300

Stream Tables for Section 300 (Cont.)						
Stream ID	S-308	S-309	S-310	S-311	S-312	S-313
Destination	ADS303	V304	-	V305	-	V306
Source	V303	ADS301	ADS301	ADS302	ADS302	ADS303
Phase	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)						
N2	5373.3	3.00	5370.3	3.00	5370.3	3
CO2	14243.3	7.94	14235.4	7.94	14235.4	7.94
O2	17186.7	9.58	17177.1	9.58	17177.1	9.58
C2H4	4540	4085	455	4085	455	4085
H2O	0	0	0	0	0	0
Mass Frac						
N2	0.129969	0.00073	0.144217	0.00073	0.144217	0.000731
CO2	0.344513	0.001934	0.382283	0.001934	0.382283	0.001934
O2	0.415706	0.002334	0.461281	0.002334	0.461281	0.002333
C2H4	0.109812	0.995002	0.012219	0.995002	0.012219	0.995002
H2O	0	0	0	0	0	0
Total Flow (lb/hr)	41343.3	4105.52	37237.8	4105.52	37237.8	4105.52
Total Flow (cuft/hr)	22986	2521.1	22350	2521.1	22350	2521.1
Temperature (F)	79.7	79.7	98.6	79.7	98.6	79.7
Pressure (psia)	294.6	294.6	279.6	294.6	279.6	294.6
Vapor Frac	1	1	1	1	1	1

Table 4.3d– Stream Table for Section 300

Stream Tables for Section 300 (Cont.)					
Stream ID	S-314	S-315	S-316	S-317	S-318
Destination	-	MIX	MIX	MIX	-
Source	ADS303	V304	V305	V306	MIX
Phase	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)					
N2	5370.3	3.00	3	3	9.00
CO2	14235.4	7.942	7.94	7.94	23.82
O2	17177.1	9.58	9.58	9.58	28.74
C2H4	455	4085	4085	4085	12255
H2O	0	0	0	0	0
Mass Frac					
N2	0.144217	0.00073	0.000731	0.000731	0.00073
CO2	0.382283	0.001934	0.001934	0.001934	0.001934
O2	0.461281	0.002334	0.002333	0.002333	0.002334
C2H4	0.012219	0.995002	0.995002	0.995002	0.995002
H2O	0	0	0	0	0
Total Flow (lb/hr)	37237.8	4105.52	4105.52	4105.52	12316.56
Total Flow (cuft/hr)	22350	52930	52930	52930	158790
Temperature (F)	98.6	39.9	39.9	39.9	39.9
Pressure (psia)	279.6	14.7	14.7	14.7	14.7
Vapor Frac	1	1	1	1	1

Table 4.3e– Stream Table for Section 300

Stream Tables for Section 300 (Cont.)						
Stream ID	S-319	S-320	S-321	S-322	S-323	S-324
Destination	P301A	HX301A	-	P301B	HX301B	-
Source	-	P301A	HX301A	-	P301B	HX301B
Phase	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)						
N2	0	0	0	0	0	0
CO2	0	0	0	0	0	0
O2	0	0	0	0	0	0
C2H4	0	0	0	0	0	0
H2O	171000	171000	171000	253000	253000	253000
Mass Frac						
N2	0	0	0	0	0	0
CO2	0	0	0	0	0	0
O2	0	0	0	0	0	0
C2H4	0	0	0	0	0	0
H2O	1	1	1	1	1	1
Total Flow (lb/hr)	171000	171000	171000	253000	253000	253000
Total Flow (cuft/hr)	2742.8	2742.8	2755.3	4058.1	4058.1	4076.6
Temperature (F)	65	65	95	65	65	95
Pressure (psia)	14.7	20	15	14.7	20	15
Vapor Frac	0	0	0	0	0	0

Table 4.3f– Stream Table for Section 300

Stream Tables for Section 300 (Cont.)			
Stream ID	S-325	S-326	S-327
Destination	P301C	HX301C	-
Source	-	P301C	HX301C
Phase	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)			
N2	0	0	0
CO2	0	0	0
O2	0	0	0
C2H4	0	0	0
H2O	795000	795000	795000
Mass Frac			
N2	0	0	0
CO2	0	0	0
O2	0	0	0
C2H4	0	0	0
H2O	1	1	1
Total Flow (lb/hr)	795000	795000	795000
Total Flow (cuft/hr)	12752	12752	12767
Temperature (F)	65	65	75
Pressure (psia)	14.7	20	15
Vapor Frac	0	0	0

Process Flow Diagrams and Material Balances – Cryogenic Distillation, Section 400

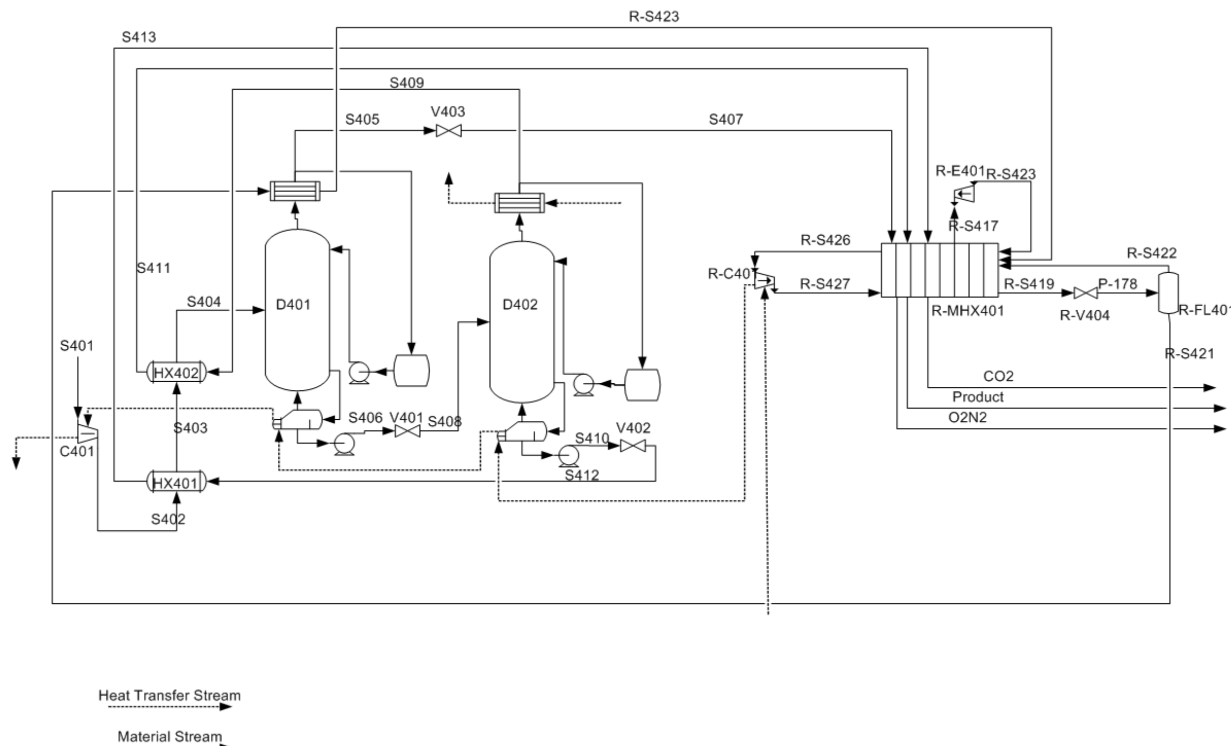

Figure 4.7 – Process Flow Diagram for Section 400

Table 4.4a – Stream Table for Section 400

Stream Table for Section 400							
Stream ID	401	402	403	404	405	406	407
Destination	B1	HX1	HX2	TOW1	VALVE2	VALVE	MHX
Source		B1	HX1	HX2	TOW1	TOW1	VALVE2
Phase	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	VAPOR
Mass Flow (lb/hr)							
N2	16122.82	16122.82	16122.82	16122.82	16122.78	0.039752	16122.78
CO2	42663.46	42663.46	42663.46	42663.46	1.973633	42661.48	1.973633
O2	51593.02	51593.02	51593.02	51593.02	51585.94	7.076665	51585.94
C2H4	13642.38	13642.38	13642.38	13642.38	5.142786	13637.24	5.142786
Mass Frac							
N2	0.13	0.13	0.13	0.13	0.238095	7.06E-07	0.238095
CO2	0.344	0.344	0.344	0.344	2.91E-05	0.757674	2.91E-05
O2	0.416	0.416	0.416	0.416	0.7618	1.26E-04	0.7618
C2H4	0.11	0.11	0.11	0.11	7.59E-05	0.242199	7.59E-05
Total Flow (lb/hr)	1.24E+05	1.24E+05	1.24E+05	1.24E+05	67715.84	56305.84	67715.84
Total Flow (cuft/hr)	1.46E+06	70621.61	53433.82	52887.03	13086.88	1222.851	2.08E+05
Temperature (F)	91.4	100	-15	-18.4	-226.9	-8.4	-277.0
Pressure (psia)	14.7	300	300	300	300	303.7	20
Vapor Frac	1	1	1	1	1	0	1
Enthalpy (BTU/hr)	-1.53E+08	-1.53E+08	-1.56E+08	-1.57E+08	-5.45E+06	-1.62E+08	-5.45E+06

Table 4.4b – Stream Table for Section 400

Stream Tables for Section 400 (Cont.)							
Stream ID	408	409	410	411	412	413	CO2
Destination	TOW2	HX2	HX1	MHX	VALVE4	MHX	
Source	VALVE	TOW2	TOW2	HX2	HX1	VALVE4	MHX
Phase	MIXED	VAPOR	LIQUID	VAPOR	MIXED	MIXED	VAPOR
				Mass Flow (lb/hr)			
N2	0.039752	0.039752	2.66E-47	0.039752	2.66E-47	2.66E-47	2.66E-47
CO2	42661.48	102.8358	42558.66	102.8358	42558.66	42558.66	42558.66
O2	7.076665	7.076663	6.96E-36	7.076663	6.96E-36	6.96E-36	6.96E-36
C2H4	13637.24	13532.43	104.8056	13532.43	104.8056	104.8056	104.8056
				Mass Frac			
N2	7.06E-07	2.91E-06	6.24E-52	2.91E-06	6.24E-52	6.24E-52	6.24E-52
CO2	0.757674	7.54E-03	0.997543	7.54E-03	0.997543	0.997543	0.997543
O2	1.26E-04	5.19E-04	1.63E-40	5.19E-04	1.63E-40	1.63E-40	1.63E-40
C2H4	0.242199	0.99194	2.46E-03	0.99194	2.46E-03	2.46E-03	2.46E-03
Total Flow (lb/hr)	56305.84	13642.38	42663.46	13642.38	42663.46	42663.46	42663.46
Total Flow (cuft/hr)	3932.717	8690.381	656.0492	9452.248	11879.72	1.33E+05	2.74E+05
Temperature (F)	-32.7	-43.5	-21.2	-23.4	-21.19	-117.2	70
Pressure (psia)	200	200	210.96	200	210.96	20	20
Vapor Frac	0.105293	1	0	1	0.634574	0.764846	1
Enthalpy (BTU/hr)	-1.62E+08	9.71E+06	-1.70E+08	9.82E+06	-1.67E+08	-1.67E+08	-1.64E+08

Table 4.4c – Stream Table for Section 400

Stream Tables for tion 400 (Cont.)				
Stream ID	R-S414	R-S417	R-S419	R-S420
Destination	R-MHX401	R-E401	R-V404	R-FL401
Source		R-MHX401	R-MHX401	R-V404
Phase	VAPOR	VAPOR	VAPOR	MIXED
Mass Flow (lb/hr)				
N2	1.13E+06	5.67E+05	5.67E+05	5.67E+05
Mass Frac				
N2	1	1	1	1
Total Flow (lb/hr)	1.13E+06	5.67E+05	5.67E+05	5.67E+05
Total Flow (cuft/hr)	2.04E+05	61712.75	20112.86	49884.15
Temperature (F)	100	-80	-213	-250.753
Pressure (psia)	1215	1215	1210	300
Vapor Frac	1	1	1	0.42433
Enthalpy (BTU/hr)	-4.62E+05	-3.12E+07	-7.08E+07	-7.08E+07

Table 4.4d – Stream Table for Section 400

Stream Tables for Section 400 (Cont.)		
Stream ID	O2N2	PRODUCT
Destination		
Source	R-MHX401	R-MHX401
Phase	VAPOR	VAPOR
Mass Flow (lb/hr)		
N2	16122.78	0.0397515
CO2	1.973633	102.8358
O2	51585.94	7.076663
C2H4	5.142786	13532.43
Mass Frac		
N2	0.2380947	2.91E-06
CO2	2.91E-05	7.54E-03
O2	0.7618003	5.19E-04
C2H4	7.59E-05	0.9919404
Total Flow (lb/hr)	67715.84	13642.38
Total Flow (cu.ft/hr)	6.21E+05	12591.45
Temperature (F)	70	70
Pressure (psia)	20	200
Vapor Frac	1	1
Enthalpy (BTU/hr)	-1.21E+05	1.03E+07

Table 4.4e – Stream Table for Section 400

Stream Tables for Section 400 (Cont.)						
Stream ID	R-S421	R-S422	R-S423	R-S426	R-S427	RS418
Destination	D401	R-MHX401	R-MHX401	R-C402		R-MHX401
Source	R-FL401	R-FL401	D401	R-MHX401	R-C402	R-E401
Phase	LIQUID	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
Mass Flow (lb/hr)						
N2	3.24E+05	2.43E+05	3.24E+05	1.13E+06	1.13E+06	5.67E+05
Mass Frac						
N2	1	1	1	1	1	1
Total Flow (lb/hr)	3.24E+05	2.43E+05	3.24E+05	1.13E+06	1.13E+06	5.67E+05
Total Flow (cu.ft/hr)	9032.99	42081.58	57292.14	8.29E+05	2.04E+05	1.61E+05
Temperature (F)	-251.322	-251.322	-251.898	92.23019	100	-199.167
Pressure (psia)	295	295	290	290	1215	300
Vapor Frac	0	1	1	1	1	1
Enthalpy (BTU/hr)	-4.71E+07	-2.37E+07	-3.16E+07	2.36E+06	-4.62E+05	-4.40E+07

Note: Sections 300 and 400 are not both included in one process rather they are alternative separation processes to extract the ethylene from the reactor effluent stream. Streams 301 and 401 are the same stream, they are the reactor effluent that feeds the back end alternative separation units sections 300 and 400.

SECTION V – PROCESS DESCRIPTION

Overall Process

As seen in Figure 5.1 below, the process begins with Seawater Purification and Growth Media Manufacturing. Seawater is pumped in through a filter, and then is treated with the proper additives for cell growth. The growth media is then sent to the Cyanobacteria Growth section where production broth is created. The cell broth is then pumped to the Photobioreactor section where it is fed a mixture of CO_2 and air and produces ethylene. The cell debris and wastewater is harvested off the bottom of the reactor and then properly disposed of. The gas stream coming off the top of the reactor is then sent to separations. In this diagram, stream S301 is split between pressure swing adsorption and cryogenic distillation. Only one of these two systems would be used.

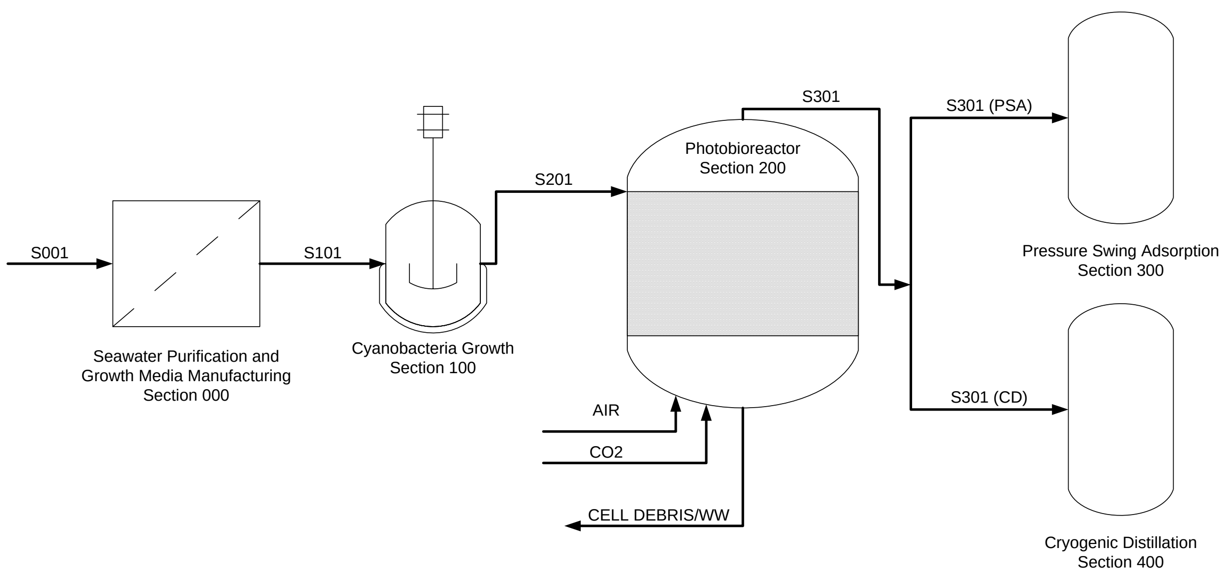

Figure 5.1 – Overall process flow diagram

Seawater Purification and Growth Media Manufacturing, Section 000

Recent research has found that this certain strain of bacteria can grow and produce ethylene at the same rate in both freshwater and saltwater. To save on utilities cost, this design utilizes seawater to cultivate cyanobacteria and produce ethylene. Using a 27.18 sq. ft. steel grate with one inch bar spacing to keep out large debris, a pump will be used to extract water from the nearby Pacific Ocean. As seen in Figure 4.1, the pump will be pumping 421.67 gpm of seawater and will have a pressure head of 133.14 feet. The pump feeds a 4 pod sand bed filter. The sand filter's are modeled as 1100 gallon storage tanks filled with a sand a gravel mixture that uses gravity to filter the seawater. The filter will get rid of any organic and inorganic debris that are larger than 50 microns in diameter. From the sand filter, the purified seawater will be fed into a large 580,500 gallon storage tank that is 96.18 feet tall. This tank will hold the seawater and add in necessary salts for cell growth and photosynthesis until the water is required by the seed growth tanks. The tank has bins that hold nitric acid, phosphoric acid, and sodium hydroxide above that dispense directly into the tank. An agitator provides mixing for this media. An alternative to using seawater would have been to buy process water, which would not require a sand filter. But the annual cost of the process water would be 3 times the bare module cost of the filters.

Cyanobacteria Growth, Section 100

The growth section of the process is shown in Figure 4.2 It is important to reiterate that the section shown only contains 1 of each unit. This section of the process will take place under batch conditions. As a result, there will be multiple storage tanks that are staggered to minimize the downtime between each batch. The diagram shown in Figure 4.2 is a simplified case that contains only one of each process unit, shown by the letter A after each unit. Factors like growth rate, ethylene production rate, and production tank size all impact the timing of each batch unit and subsequently how many of each unit is required for maximum staggering.

While only one of each process equipment is shown, there are multiple process units of the same tank, named B,C,D,E, etc. The numbers of production tanks, given different conditions, are shown in Table 5.1. In any scenario, the setup of the process is unchanged and as follows. Pumps P101A, P102A, P103A, and P104A transport the balance water through heater F101 to their respective seed/growth tank. Storage tanks ST101A, ST102A, ST103A, and ST104A are vessels in which cells are grown to concentrations of around $1x10^7$cells/mL. Upon reaching that concentration, rounded to the nearest quarter day, the contents of the vessel are transferred to the next vessel via pumps P105A, P106A, P107A, and P108A. The specific timing of each transfer at various conditions are shown in Table 5.2.

Table 5.1 - Number of production tanks needed given desired size of tank and ethylene production rate, rounded to the nearest higher integer. * indicates the cases that have been investigated with economics calculated.

Number of Prod Tanks Needed						
		Production Rate(mg/L/day)				
Prod Tank Size (L)	**Prod Tank Size (Usable, L)**	**171(1x)**	**1710 (10x)**	**4275 (25x)**	**8550 (50x)**	**17100 (100x)**
2,000,000	1,400,000	557	56	22	11	6
4,000,000	2,800,000	279	28	11	6*	3
6,000,000	4,200,000	186	19	7	4*	2*
8,000,000	5,600,000	139	14	6*	3*	2*

Table 5.2 - Number of days cells are allowed to growth in each seed and growth tanks given ethylene production rate, production tank size, and cell growth. Each of these cases are investigated economically and are the starred cases from Table 5.1. The bolded case is the scenario considered in detail in this project.

Growth Rate (day^{-1})	Volume of Seed and Growth Tanks (L)			
4, 6, and 8 million L tank w/ 8550 mg/L/day	1,000	10,000	100,000	1,000,000
0.9	5	2.5	2.5	2.75
1.8	**2.5**	**1.25**	**1.25**	**1.5**
3.6	1.25	0.75	0.5	0.75
8 million L tank w/ 4275 mg/L/day	2,000	20,000	200,000	2,000,000
0.9	5	2.5	2.5	2.75
1.8	2.5	1.25	1.25	1.5
3.6	1.25	0.75	0.5	0.75
6 million L tank w/ 17100 mg/L/day	500	5,000	50,000	500,000
0.9	3.5	2.5	2.5	2.75
1.8	1.75	1.25	1.25	1.5
3.6	1	0.5	0.5	0.75
8 million tank w/ 17100 mg/L/day	500	5,000	50,000	500,000
0.9	4.25	2.5	2.5	2.75
1.8	2	1.5	1.25	1.25
3.6	1	0.75	0.5	0.75

Cells are initially transferred from inoculums of 1 μL to 250mL flasks to grow to a concentration of $1x10^7$cells/mL. Since the time taken to prepare and grow these flasks are small and can be done in the time when seed/growth tanks are growing. Fifty flasks are then transported to ST101A where it is then combined with the appropriate amount of water to grow until the proper cell concentration is achieved. Transport times between flasks and ST101A have also been ignored due to ease of transport. While ST101A is filled, ST101B, ST101C, ST101D are being filled at later times that coincide with downstream tank emptying.

Each seed/growth tank will be operated at 33C, maintained by insulation, under atmospheric pressure of 14.7 psi. Each tank is provided 5 mins of blue light per day for the duration of growth in each respective tank. The pumps transporting fluid are designed given the desired flow rate and pressure head needed between source and destination. The length of piping between each storage tank is at most assumed to be 100 feet of which 1 psi is allotted. Each pump is allotted 15 psi across the unit. As a result the pressure head was the summation of 16 psi and the pressure equivalent of the height difference between storage tanks for pumps transporting fluid between storage tanks. For pumps transporting water to storage tanks, an additional 15 psi is needed to account for the pressure drop associated with the heater, F101.

Upon reaching the appropriate concentration in the final growth tank, the cells are then sent to the reactor where continuous ethylene production is done. Assuming cells survive 2 weeks, production tanks need to be filled with new cells before reaching that time to ensure continuous ethylene production. As a result, a time of around 8 days is set as the time in which a new tank is needed. Since the growth section of this process is batch, the way a tank with new media is achieved is either by refilling the completely tank every 8 days or refilling a certain percentage every day or so with a “new” tank in 8 days.

The first approach of providing a completely new tank every 8 days would be easier in terms of timing and work, however would require millions of liter of media of which is already considered unfeasible. This approach would also result in work being concentrated on certain days. The second approach which is investigated in this design involves replacing appropriately 11% of a production tank every day for 8 days, resulting in a “new” tank. This approach incorporates smaller volumes with work being spread out more evenly across operation days.

As a summary, Pumps 101A(6 units), 102A(3), 103A(3), and 104A(4) feed into the heater F101A at different times shown in the Gantt chart below. These pumps then fed into ST101A(6), ST102A (3), ST103A(3), and ST104A(4) respectively. Pumps P105A (6), P106A (3), P107A (3), P108A(24) transport grown cell media from ST101A through each subsequent seed/growth tank up to the production tanks (Section 200).

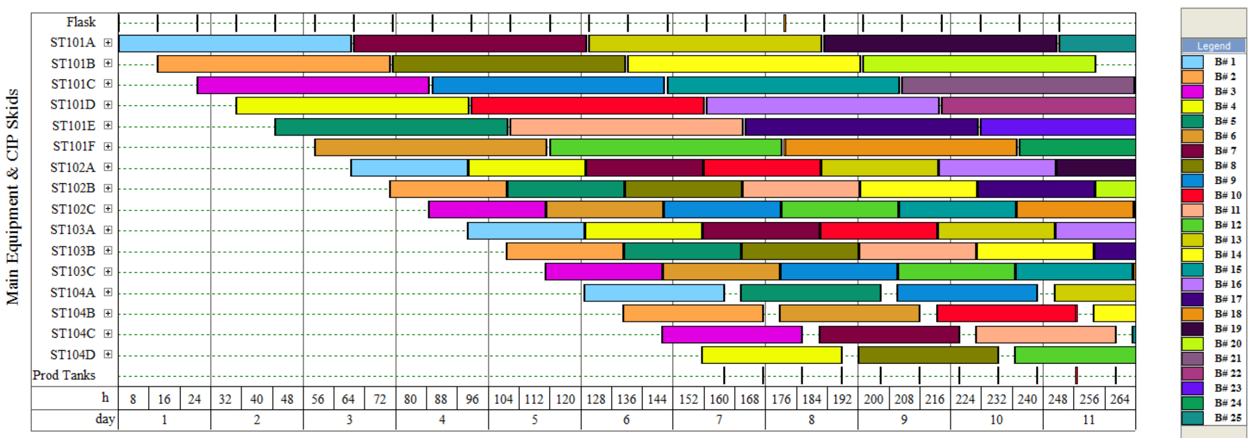

Figure 5.2 - Gantt chart depicting the duration and timing each process unit holds and transport fluid.

Table 5.3 - Details how final growth tanks are divided among production tanks and the time for a "new" tank given the conditions specified. The bolded case is the scenario considered in detail in this project.

Production Tank Size (mil L)	Ethylene Production Rate (mg/L/day)	Growth Rate (day^{-1})	Number of Production Tanks Served by 1 ST104A	Total Number of Production Tanks	Time per ST104A (days)	Time per "New" Tank (days)
4	**8550**	0.9	**3**	**6**	0.63	10.584
		1.8			**0.42**	**7.056**
		3.6			0.42	7.056
6		0.9	2	4	0.63	10.584
		1.8			0.42	7.056
		3.6			0.42	7.056
8		0.9	3	3	0.63	10.584
		1.8			0.42	7.056
		3.6			0.42	7.056
8	4275	0.9	3	6	0.63	10.584
		1.8			0.42	7.056
		3.6			0.42	7.056
6	17100	0.9	1	2	0.50	8.4
		1.8			0.44	7.392
		3.6			0.52	8.736
8		0.9	1	2	0.50	11.2
		1.8			0.44	9.408
		3.6			0.52	11.648

Photobioreactor, Section 200

As we have said the reactor that would be required to produce ethylene through this photosynthetic reaction is not yet commercially available but to design the back end of the system the basic mass balance of the system should be understood. Section 200 takes the outlet from Section 100, the concentrated stream of cyanobacteria and growth media, as its liquid feed. In addition to this 76,902 lb/hr of carbon dioxide and 19,225 lb/hr of air both of which are at atmospheric pressure and ambient temperature. The addition of air is intended to dilute and provide some nitrogen to reduce the risk of combustion of the product ethylene with oxygen. In the presence of light the photosynthetic reaction will proceed with 50% conversion of carbon dioxide to produce a stream of carbon dioxide, oxygen, nitrogen, and ethylene which is sent to the separation sections designed for this process.

Alternative Separation Sections

Sections 300 and 400 are alternative separation sections that were designed for the process. Section 300 is a Pressure Swing Adsorption Section and Section 400 is a Cryogenic Distillation Section with a nitrogen refrigeration cycle. Both sections will be analyzed for economic profitability in the proceeding sections. Originally three separation processes were chosen to be investigated as a means of removing ethylene from the reactor effluent. These three included pressure swing adsorption using a zeolite adsorbent, cryogenic distillation, and liquid adsorption of ethylene. The latter was investigated using a number of solvents including: trichloroethylene, hydrocarbons, and amines. We ran into trouble using this liquid solvents because our simulation engine, ASPEN, was giving results that showed that any solvent that was selective for ethylene also adsorbed carbon dioxide as well yielding the separation ineffective. Thus, adsorbing ethylene in a solvent was abandoned and the other two separation methods which were effective were compared on economic grounds.

Pressure Swing Adsorption, Section 300

Section 300 takes the reactor effluent and separates the ethylene from the stream by adsorbing the ethylene on a silver treated silica alumina zeolite adsorbent. The reactor effluent, S-301, is first compressed in a 3-stage compressor with interstage cooling, C301, to a pressure of 299.6 psia and a temperature of 80 °F. It is necessary to compress the gas because ethylene selectively adsorbs on the silica alumina adsorbent at high pressures. Figure 5.3 below shows the adsorption isotherm for ethylene on this adsorbent and it should be noted at the pressure and temperature it is compressed to ethylene adsorbs at a rate of approximately 4 mol/kg of adsorbent.

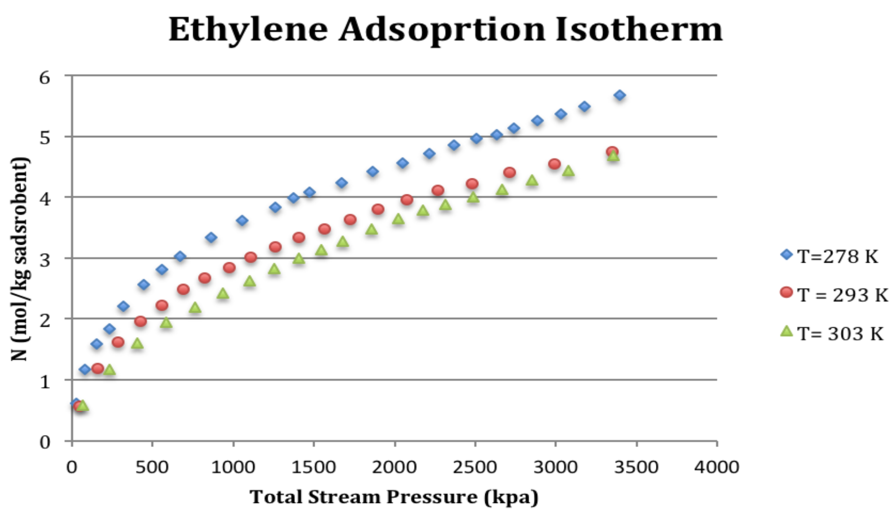

Figure 5.3– Ethylene Adsorption Isotherm

After the effluent is compressed it is sent through one of the three adsorption towers, ADS301/302/303, for 5 minutes at a time. To accomplish this there are three control valves V301/302/303 which are opened for 5 minutes at a time. There is a 5 psi pressure drop through these valves. The reason the effluent stream is only passed through each tower for 5 minutes is that in pressure swing adsorption systems it is uncommon to fully saturate the packed bed so they are run in shorter cycles. During the adsorption time 90% of the ethylene is adsorbed on the adsorbent with trace amounts of oxygen, nitrogen, and carbon dioxide. The balance gas is passed through the adsorption column and sent out of there process. There is a 15 psi pressure drop through the tower and the adsorption is an exothermic process which releases 163,810 BTU/hr of heat which is absorbed by the balance gas stream that is removed from the process.

After the ethylene is adsorbed on the adsorbent for 5 minutes the pressure in the column must be dropped to atmospheric pressure to allow it to desorb. Valves V304/305/306 are responsible for releasing the pressure in the vessel to facilitate the desorption. Research into the area of hydrocarbon adsorption processes has also yielded information about the rates of adsorption and desorption on zeolite adsorbents. It is generally accepted that desorption is a slower process than adsorption by about 2 fold. This results in the design decision to include three towers each of which are absorbing ethylene a third of the time and desorbing two thirds of this time. This allows the separation process to run continuously. Each adsorption tower will adsorb ethylene for 5 minutes at a time so 10 minutes is allotted to desorb the ethylene. Figure 5.4 is provided to show the scheduling of the adsorption towers in the separation section.

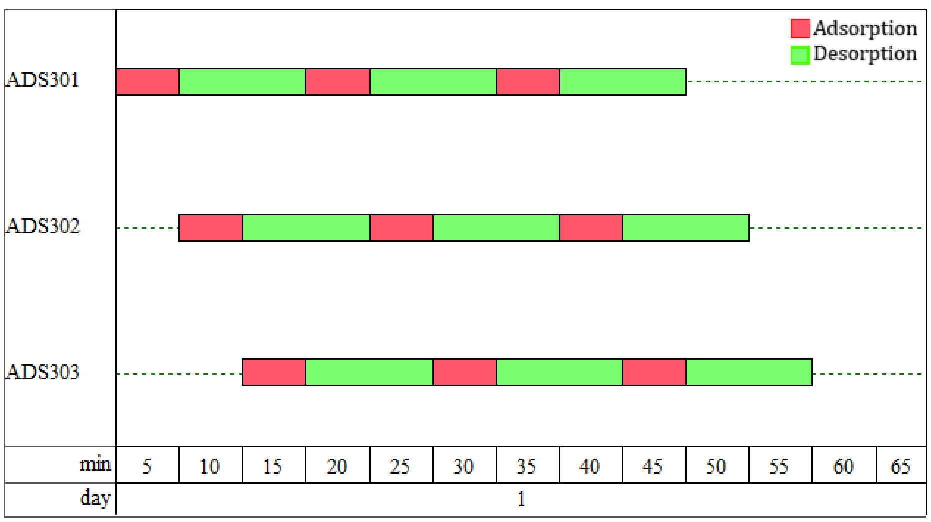

Figure 5.4 – Gant chart for adsorption towers

The process run continuously and results in a product stream of 12316.56 lb/hr of ethylene at 99.5 wt% purity.

Cryogenic Distillation, Section 400

An alternative separation of the gas products is cryogenic distillation, and this process is displayed in Figure 4.4 and Tables 4.4a-e. This utilizes distillation at very cold temperature. The feed gas stream, coming in at 124922 lb/hr, is first compressed by C401 from atmospheric pressure to 300 psi. This stream(S-402) is then fed to a shell and tube exchanger, HX401, and is cooled by S-410, which is the bottoms product of D402. The temperature of S-402 drops from 100 °F to -15 °F. To drop the temperature even more before the feed gas enters the first distillation tower, S-403 goes through a second exchanger HX402. The temperature is dropped another 3.48 °F by using the distillate of D402.

D401 separates oxygen and nitrogen from ethylene and carbon dioxide. This separation is done to avoid any flammability from the combination of oxygen and ethylene. The distillation temperature ranges from -227 °F at the condenser to -8.44 °F at the reboiler. A nitrogen refrigeration system will be used to operate this condenser. The distillate contains oxygen and nitrogen, and the stream, S-405, is fed to the multistage heat exchanger complex, MHX401, at a rate of 67715.84 lb/hr. The bottoms, ethylene and carbon dioxide, is fed to the second distillation tower, D402. D402 operates in a temperature range from -43.5°F to -21.23 °F. 13532 lb/hr of ethylene comes off the top, while 42558.24 lb/hr of carbon dioxide is the bottoms product. The distillate is used in the tube side of HX402, while the bottoms is used in the tube side of HX401. All of the streams from the distillation towers, S-407, 411, 413, are all fed into MHX401 to be cooled by the nitrogen recycle system.

SECTION VI – ENERGY BALANCES AND UTILITY REQUIREMENTS

Energy Balances and Utility Requirements

Before an analysis of the energy requirements of the process, it is important to note that Section 400 is presented as an alternative to Section 300, not in addition to.

The major energy requirements for this process are heater F101, compressor pump in C401, condenser in D402, and the compressor pump in R-C-402. These units alone combine to consume 202,201,715.7 BTU/hr. The energy usages of other units are around the order of hundreds of thousands of BTU/hr and shown in Table 6.1. The compressors in section 300 are the next highest energy users with approximately 6-7 million BTU/hr. Along with the compressors, the heat exchangers present in section 300 also contribute similar magnitudes of usage but in the negative direction. Cooling water in heat exchangers HX301A, HX301B, HX301C extract energy present in hot streams and as a result, the overall energy requirement for section 300 is shown to be negative.

It is important to note that while some of these units have high energy usage, they are not run constantly. Of the previously mentioned highest energy consumers, heater F101 is the only unit to run on demand. Likewise, most of the next highest energy consuming units are run continuously like the compressors from section 300. As a result, for better comparison of energy usage, annual utility cost would be a better indicator for total usage. From Table 6.2 it can be seen that since C401, D402, and R-C-402 are run continuously and are the highest energy consuming units, they are indeed the most expensive units to run, with a total of $29,969,429.34 per year. The next highest utility is around $1 million per year. From this energy and cost analysis it can be seen that Section 400-Cyrogenic Distillation is much more expensive and energy intensive than Section 300- Pressure Swing Adsorption.

Table 6.1 - Energy balance

ENERGY REQUIREMENTS OF PROCESS				
Equipment	Description	Duty (BTU/hr)	Source	
Section 000				
P001	Pump	190,832.25	Electricity	
F001	Filter	2,047.29	Electricity	
ST001	Agitator	147,789.70	Electricity	
		340,660.20		*Net Section 000*
Section 100				
F101	Electric Heater	32,977,418.80	Electricity	
P101A (6)	Pump	190,832.52	Electricity	
P102A (3)	Pump	190,832.52	Electricity	
P103A (3)	Pump	508,886.72	Electricity	
P104A (4)	Pump	636,108.40	Electricity	
P105A (6)	Pump	190,832.52	Electricity	
P106A (3)	Pump	190,832.52	Electricity	
P107A (3)	Pump	508,886.72	Electricity	
P108A (24)	Pump	636,108.40	Electricity	
ST101A (6)	Agitator	2,544.434	Electricity	
ST102A (3)	Agitator	2,544.434	Electricity	
ST103A (3)	Agitator	10,177.734	Electricity	
ST104A (4)	Agitator	96,668.476	Electricity	
		36,142,674.20		*Net Section 100*
Section 300				
C301A	Compressor	6,093,920	Electricity	
C301B	Compressor	7,442,470	Electricity	
C301C	Compressor	6,775,830	Electricity	
HX301A	Heat Exchanger	-5,110,000	Cooling Water	
HX301B	Heat Exchanger	-7,570,000	Cooling Water	
HX301C	Heat Exchanger	-7,904,000	Cooling Water	
P301A	Pump	3,969	Electricity	
P301B	Pump	5,572	Electricity	
P301C	Pump	15,572	Electricity	
		-246,667		*Net Section 300*
	Section 400- Alternative to Section 300			
C401	Compressor Pump	20,439,434.95	Electricity	
	Compressor	-20,710,000	Cooling Water	
D401	Reboiler	4,698,760	Cooling Water	
D402	Condenser	64,685,200	Electricity	
	Reboiler	-66,016,800	Cooling Water	
R-C-402	Compressor Pump	84,099,661.90	Electricity	
	Compressor	-99,634,600	Cooling Water	
		-12,438,343		*Net Section 400*
Net Energy	w/ Section 300	36,236,667.40	BTU/hr	
	w/ Section 400	24,044,991.40	BTU/hr	

Note: Parentheses next to units indicate the number of those units included in the full scale process design

Table 6.2 - Utility requirements

Electricity

Equipment List	Description	Usage (kWh)	Cost ($)
P001		55.927	27,382.06
F001		0.6	73.44
F101		9,664.727	480,696.16
ST001		43.31	21,204.67
P101A (6)		55.927	9.92 (per unit)
P102A (3)		55.927	72.34 (per unit)
P103A (3)		149.140	385.79 (per unit)
P104A (4)		186.425	2,009.33 (per unit)
P105A (6)		55.927	10.05(per unit)
P106A (3)		55.927	80.37 (per unit)
P107A (3)		149.140	428.66 (per unit)
P108A (24)		186.425	744.20 (per unit)
ST101A (6)		587.611	2,114.40 (per unit)
ST102A (3)		587.611	1,057.70 (per unit)
ST103A (3)		2,350.446	4,230.80 (per unit)
ST104A (4)		22,329.237	48,231.15 (per unit)
C301A		1,785.952	874,399
C301B		2,181.173	1,067,898
C301C		1,985.80	972,244
P301A		1.163	570
P301B		1.633	800
P301C		4.564	2,234
C401		6,305.482	3,026,631.46
D402		30,186.427	14,489,484.80
R-C-402		25,944.402	12,453,313.08

Cooling Water

Equipment List	Description	Usage (lb/hr)	Cost ($)
HX301A		171,000	12,557
HX301B		253,000	18,578
HX301C		795,000	58,378
C401		3,321,153	
D401	CW from C401	3,321,153	
D402	CW from D401	3,321,153	239,218.69
R-C-402	CW from D402	3,321,153	

Note: Parentheses next to units indicate the number of those units included in the full scale process design

SECTION VII – MARKET AND ECONOMIC ANALYSIS

Market Analysis

From the project prompt, the cost of ethylene produced will be sold for $0.50/lb. Since 2006, ethylene prices have varied between $0.30/lb to $0.80/lb as seen in Figure 7.1. Using this revenue, a process can be feasibly designed (incorporating pressure swing adsorption) with increasingly positive Net Present Value over time. Based on the global trend, ethylene consumption is expected to grow at approximately 3.4% per year. This increase in demand will further help improve our Net Present Value over time, increasing profits over time. Especially in a world ever increasingly concerned with fossil fuel use and global warming, a green alternative in the production of ethylene may be seen as a perfect solution.

While consumption is expected to rise annually, so is the number of producers. It is projected that from 2010 to 2016, the Middle East and China will account for 81% of the world market of ethylene. These regions are expected to make up roughly 80% of new ethylene production plants. With these projected plants that use the traditional steam crackers, competition over price may ensue with the green solution possibly being forced to infeasibility. As a result, as cheaper, more fossil fuel dependent methods of producing ethylene are brought online, green plants like this design project may be forced out of the market until improved technology becomes available.

Nevertheless the following section details the various costs of the proposed plant both to show the major energy consuming units and determine future research and development potential for improvements. As a result, a sensitivity analysis is also conducted to see how the plant will be affected under different conditions.

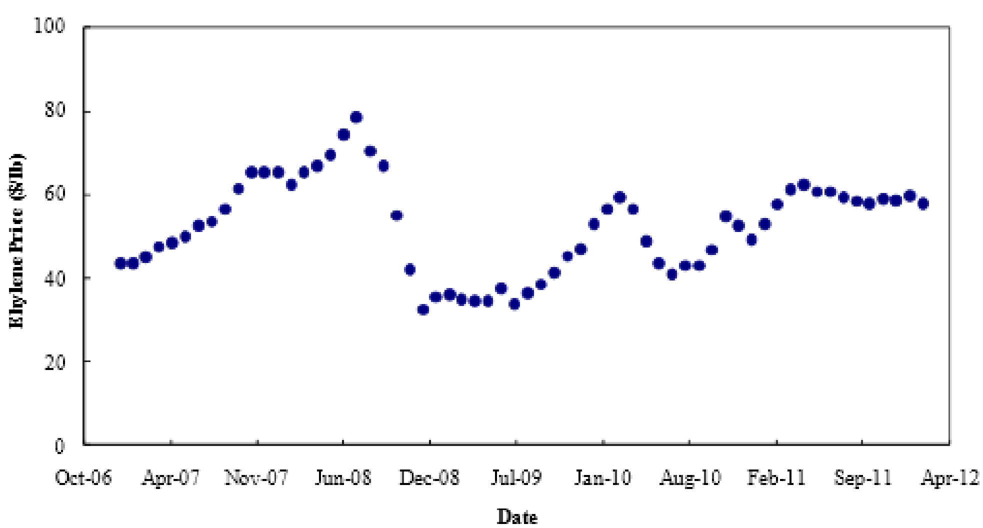

Figure 7.1 – Historic ethylene prices

Economic Analysis

Both pressure swing adsorption and cryogenic distillation were evaluated for economic feasibility. As hypothesized, cryogenic distillation is not economically feasible for separating our products. The COGS exceeds the value of the ethylene produced even without the reactor. When dealing with such a low valued product in small concentrations, cryogenic distillation is not an option due to incredibly high utility costs for the nitrogen refrigeration cycle that keeps the system at the necessary low temperatures.

PSA has shown promising economics. Without the reactor section, the process yields an IRR of 67.62% with a net present value of $70MM at 15% ROI.

Figure 7.1 plots how annual operating cost varies with the initial reactor section investment to achieve a 15% IRR. Anything above the 15% line yields a lower IRR for the process, and anything below the 15% line yields a process with an IRR exceeding 15%.

Tables 7.11 and 7.12 show how the IRR and NPV (at 15% ROI) vary with ethylene prices. As shown in these tables, PSA still has a positive NPV even at $0.30/lb, while distillation does not yield positive NPV until the ethylene price reaches just over $0.70/lb. This again reinforces the fact that cryogenic distillation is not an option for separations. If the ethylene price is less than $0.58/lb, the process costs more to run than the value of the ethylene produced even without the reactor section.

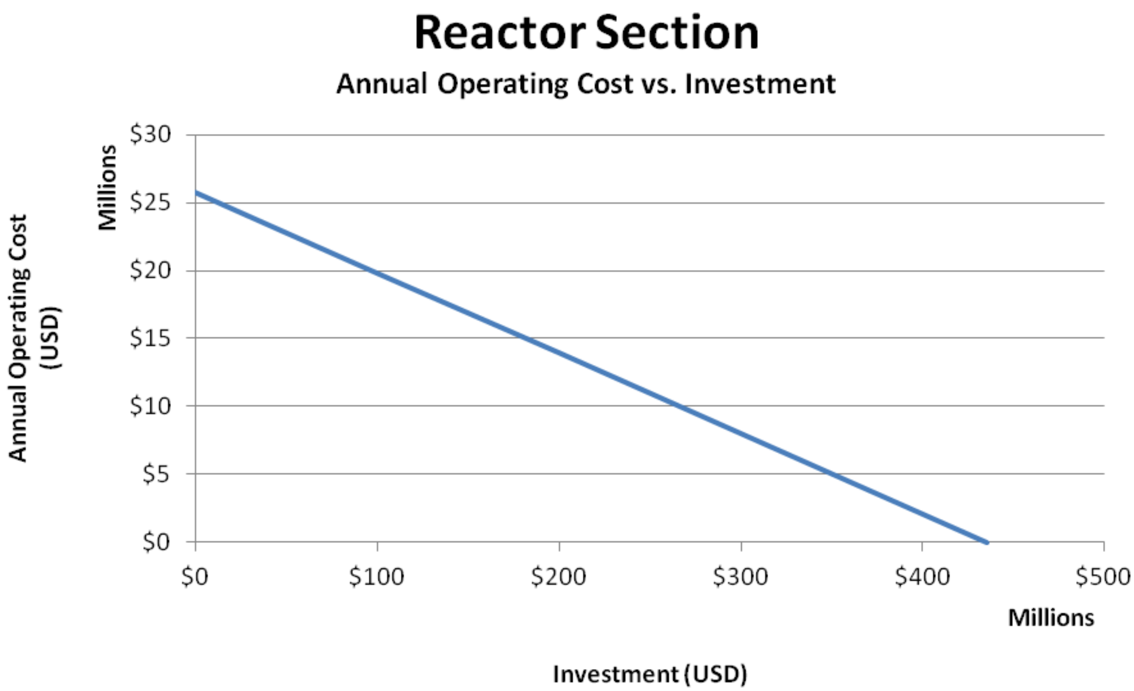

Figure 7.2 – Reactor section annual operating cost vs. investment to achieve 15% IRR

Table 7.1 - Equipment Description PSA Separations, w/o Reactor)

Section	Unit	Bare Module Cost	Annual Operating Cost
0	ST001	$282,106	$91,651
0	P001	$33,728	$27,382
0	F001	$53,908	$73
1	P101A	$186,461	$60
1	P102A	$121,698	$217
1	P103A	$316,946	$1,157
1	P104A	$828,304	$8,304
1	P105A	$175,056	$60
1	P106A	$112,277	$241
1	P107A	$296,738	$1,286
1	P108A	$4,722,586	$17,861
1	ST101A	$70,456	$12,692
1	ST102A	$82,021	$3,173
1	ST103A	$250,655	$12,692
1	ST104A	$1,097,118	$192,925
1	F101	$50	$480,696
3	HX301A	$75,365	$12,557
3	HX301B	$78,736	$18,578
3	HX301C	$87,904	$58,378
3	ADS301/302/303	$1,146,906	$3,081,783
3	P301A	$41,353	$570
3	P301B	$44,946	$800
3	P301C	$62,725	$2,234
WWT	-	$4,846,887	$0
TOTAL:		**$15,014,929**	**$4,025,103**

Table 7.2 - Investment Summary (PSA Separations, w/o Reactor)

Bare Module Costs	
Process Equipment:	$14,458,618
Spares:	$0
Storage:	$0
Other:	$0
Catalysts:	$515,880
Computers, Software, Etc.:	$0
Total Bare Module Cost:	**$15,014,929**
Direct Permanent Investment	
Cost of Site Prep:	$2,246,175
Cost of Service Facilities:	$748,725
Direct Permanent Investment:	**$17,969,398**
Total Depreciable Capital	
Cost of Contingencies & Contractor Fees:	$2,695,410
Total Depreciable Capital:	**$20,664,807**
Total Permanent Investment	
Cost of Land:	$413,296
Cost of Plant Startup:	$1,497,450
Total Permanent Investment – Unadjusted:	$22,575,553
Site Factor:	1.25
Total Permanent Investment:	**$28,219,442**

Table 7.3 - Fixed Cost Summary (PSA Separations, w/o Reactor)

Operations	
Direct Wages and Benefits:	$4,368,000
Direct Salaries and Benefits:	$655,200
Operating Supplies and Services:	$262,080
Technical Assistance to Manufacturing:	$720,000
Control Laboratory:	$780,000
Total Operations:	**$6,785,280**
Maintenance	
Wages and Benefits:	$723,268
Salaries and Benefits:	$180,817
Materials and Services:	$723,268
Maintenance Overhead:	$36,163
Total Maintenance:	**$1,663,517**
Operating Overhead	
General Plant Overhead:	$420,837
Mechanical Dept. Services:	$142,255
Employee Relations Dept.:	$349,710
Business Services:	$438,619
Total Operating Overhead:	**$1,351,421**
Property Taxes and Insurance	
Property Taxes and Insurance	$413,296
Total Fixed Costs	
Total Fixed Costs:	**$10,213,514**

Table 7.4 - Variable Cost Summary (PSA Separations, w/o Reactor)

Variable Costs at 100% Capacity		
General Expenses		
	Selling/Transfer Expenses:	$1,500,000
	Direct Research:	$2,400,000
	Allocated Research:	$250,000
	Administrative Expense:	$1,000,000
	Management Incentive Compensation:	$625,000
	Total General Expenses:	**$5,775,000**
Raw Materials		
	Raw Materials:	$70,446
Utilities		
	Utilities:	$4,025,103
Total Variable Costs		
	Total Variable Costs:	**$9,820,549**

Table 7.5 - Cash Flow Summary (PSA Separations, w/o Reactor)

Year	Total Dep. Capital	Working Capital	Depreciation	COGS	Sales	Net Earnings	Discounted Cash Flow	ROI	Cash Flow (PV)	Cumulative PV
2013	$9,406,481						($9,406,481)	15%	($9,406,481)	($9,406,481)
2014	$9,406,481						($9,406,481)	15%	($8,179,548)	($8,179,548)
2015	$9,406,481						($9,406,481)	15%	($7,112,651)	($7,112,651)
2016		$5,463,899	$4,032,558	$17,983,385	$25,000,000	$1,790,434	$359,093	15%	$312,255	($9,094,225)
2017			$6,910,941	$17,635,404	$37,500,000	$7,772,193	$14,683,134	15%	$9,654,399	$560,174
2018			$4,935,580	$20,109,367	$50,000,000	$14,973,031	$19,908,612	15%	$11,382,813	$11,942,987
2019			$3,524,608	$20,109,367	$50,000,000	$15,819,615	$19,344,223	15%	$9,617,498	$21,560,485
2020			$2,519,996	$20,109,367	$50,000,000	$16,422,382	$18,942,378	15%	$8,189,313	$29,749,797
2021			$2,517,174	$20,109,367	$50,000,000	$16,424,075	$18,941,249	15%	$7,120,717	$36,870,515
2022			$2,519,996	$20,109,367	$50,000,000	$16,422,382	$18,942,378	15%	$6,192,297	$43,062,812
2023			$1,258,587	$20,109,367	$50,000,000	$17,179,227	$18,437,814	15%	$5,241,178	$48,303,989
2024				$20,109,367	$50,000,000	$17,934,380	$17,934,380	15%	$4,433,104	$52,737,093
2025				$20,109,367	$50,000,000	$17,934,380	$17,934,380	15%	$3,854,873	$56,591,967
2026				$20,109,367	$50,000,000	$17,934,380	$17,934,380	15%	$3,352,064	$59,944,031
2027				$20,109,367	$50,000,000	$17,934,380	$17,934,380	15%	$2,914,838	$62,858,869
2028				$20,109,367	$50,000,000	$17,934,380	$17,934,380	15%	$2,534,642	$65,393,510
2029				$20,109,367	$50,000,000	$17,934,380	$17,934,380	15%	$2,204,036	$67,597,547
2030		($5,463,899)		$20,109,367	$50,000,000	$17,934,380	$23,398,279	15%	$2,500,452	$70,097,998

Table 7.6 - Equipment Description (Distillation Separations, w/o Reactor)

Section	Unit	Bare Module Cost	Annual Operating Cost
0	ST001	$282,106	$91,651
0	P001	$33,728	$27,382
0	F001	$53,908	$73
1	P101A	$186,461	$60
1	P102A	$121,698	$217
1	P103A	$316,946	$1,157
1	P104A	$828,304	$8,037
1	P105A	$175,056	$60
1	P106A	$112,277	$241
1	P107A	$296,738	$1,286
1	P108A	$4,722,586	$17,861
1	ST101A	$70,456	$12,692
1	ST102A	$82,021	$3,173
1	ST103A	$250,655	$12,692
1	ST104A	$1,097,118	$192,925
1	F101	$50	$480,696
4	D401	$1,542,164	$0
4	D402	$12,891,718	$14,489,485
4	HX401	$41,327	$0
4	HX402	$31,571	$0
4	C401	$26,486,459	$3,026,631
4	R-C402	$26,669,816	$12,453,313
4	R-E401	$1,441,858	$0
4	R-FL401	$355,394	$0
4	MHX401	$2,853,000	$0
WWT	-	$4,846,887	$0
TOTAL:		**$85,790,300**	**$30,819,632**

Table 7.7 - Investment Summary (Distillation Separations, w/o Reactor)

Bare Module Costs	
Process Equipment:	$85,790,300
Spares:	$0
Storage:	$0
Other:	$0
Catalysts:	$0
Computers, Software, Etc.:	$0
Total Bare Module Cost:	**$85,790,300**
Direct Permanent Investment	
Cost of Site Prep:	$12,862,480
Cost of Service Facilities:	$4,287,493
Direct Permanent Investment:	**$102,899,843**
Total Depreciable Capital	
Cost of Contingencies & Contractor Fees:	$15,434,976
Total Depreciable Capital:	**$118,334,820**
Total Permanent Investment	
Cost of Land:	$2,366,696
Cost of Plant Startup:	$8,574,987
Total Permanent Investment – Unadjusted:	$129,276,503
Site Factor:	1.25
Total Permanent Investment:	**$161,595,629**

Table 7.8 - Fixed Cost Summary (Distillation Separations, w/o Reactor)

Operations	
Direct Wages and Benefits:	$4,004,000
Direct Salaries and Benefits:	$600,600
Operating Supplies and Services:	$240,240
Technical Assistance to Manufacturing:	$660,000
Control Laboratory:	$715,000
Total Operations:	**$6,219,840**
Maintenance	
Wages and Benefits:	$4,141,719
Salaries and Benefits:	$1,035,430
Materials and Services:	$4,141,719
Maintenance Overhead:	$207,086
Total Maintenance:	**$9,525,953**
Operating Overhead	
General Plant Overhead:	$694,504
Mechanical Dept. Services:	$234,762
Employee Relations Dept.:	$577,123
Business Services:	$723,849
Total Operating Overhead:	**$2,230,239**
Property Taxes and Insurance	
Property Taxes and Insurance:	$2,366,696
Total Fixed Costs	
Total Fixed Costs:	**$20,342,728**

Table 7.9 - Variable Cost Summary (Distillation Separation, w/o Reactor)

Variable Costs at 100% Capacity

General Expenses

	Selling/Transfer Expenses:	$1,500,000
	Direct Research:	$2,400,000
	Allocated Research:	$250,000
	Administrative Expense:	$1,000,000
	Management Incentive Compensation:	$625,000
	Total General Expenses:	**$5,775,000**

Raw Materials

	Raw Materials:	$70,446

Utilities

	Utilities:	$30,819,632

Total Variable Costs

	Total Variable Costs:	**$36,665,078**

Table 7.10 - Cash Flow Summary (Distillation Separations, w/o Reactor)

Year	Total Dep. Capital	Working Capital	Depreciation	COGS	Sales	Net Earnings	Discounted Cash Flow	ROI	Cash Flow (PV)	Cumulative PV
2013	$53,865,210						($53,865,210)	15%	($53,865,210)	($53,865,210)
2014	$53,865,210						($53,865,210)	15%	($46,839,313)	($46,839,313)
2015	$53,865,210						($53,865,210)	15%	($40,729,837)	($40,729,837)
2016		$5,463,899	$23,092,015	$54,847,482	$25,000,000	($31,763,698)	($14,135,582)	15%	($12,291,810)	($66,157,020)
2017			$39,574,769	$47,860,515	$37,500,000	($29,961,171)	$9,613,599	15%	$6,321,097	($59,835,923)
2018			$28,263,075	$57,033,110	$50,000,000	($21,177,712)	$7,085,364	15%	$4,051,080	($55,784,843)
2019			$20,183,294	$57,033,110	$50,000,000	($16,329,843)	$3,853,451	15%	$1,915,846	($53,868,996)
2020			$14,430,490	$57,033,110	$50,000,000	($12,878,160)	$1,552,330	15%	$671,115	($53,197,882)
2021			$14,414,330	$57,033,110	$50,000,000	($12,868,464)	$1,545,866	15%	$581,148	($52,616,733)
2022			$14,430,490	$57,033,110	$50,000,000	($12,878,160)	$1,552,330	15%	$507,459	($52,109,274)
2023			$7,207,165	$57,033,110	$50,000,000	($8,544,165)	($1,337,000)	15%	($380,059)	($52,489,333)
2024				$57,033,110	$50,000,000	($4,219,866)	($4,219,866)	15%	($1,043,086)	($53,532,419)
2025				$57,033,110	$50,000,000	($4,219,866)	($4,219,866)	15%	($907,032)	($54,439,451)
2026				$57,033,110	$50,000,000	($4,219,866)	($4,219,866)	15%	($788,723)	($55,228,174)
2027				$57,033,110	$50,000,000	($4,219,866)	($4,219,866)	15%	($685,846)	($55,914,020)
2028				$57,033,110	$50,000,000	($4,219,866)	($4,219,866)	15%	($596,388)	($56,510,408)
2029				$57,033,110	$50,000,000	($4,219,866)	($4,219,866)	15%	($518,598)	($57,029,007)
2030		($5,463,899)		$57,033,110	$50,000,000	($4,219,866)	$1,244,033	15%	$132,943	($56,896,064)

Table 7.11 – NPV/IRR of PSA separation vs. ethylene price

Ethylene Price	NPV (MM)	IRR
$0.60	($29.9)	3%
$0.70	($3.0)	14%
$0.80	$24.0	21%

Table 7.12 – NPV/IRR of PSA separation vs. ethylene price

Ethylene Price	NPV (MM)	IRR
$0.30	$16.1	31%
$0.40	$43.1	51%
$0.50	$70.0	68%
$0.60	$97.0	84%
$0.70	$124.0	99%
$0.80	$151.0	114%

Growth Section Analysis

While previous attention was focused on one specific combination of ethylene production rate, production tank size, and cell growth rate, others were invested and are present in Figures 7.3, 7.4, 7.5, 7.6 with the data supporting these graphs below in Tables 7.13 and 7.14.

Table 7.13. The initial capital cost for the growth section given various conditions. The bolded case is the scenario investigated in this project.

Ethylene Production Rate (mg/L/day)	Production Tank Size (million L)	Cell Growth Rate (day^{-1})		
		0.9	1.8	3.6
8,550	4	$10,459,802.38	$8,260,364.73	$4,326,929.58
	6	$8,492,058.08	$6,686,169.29	$3,539,831.86
	8	$7,508,185.93	$5,899,071.57	$3,146,283.00
4,275	8	$11,391,453.39	$8,991,753.03	$4,724,287.71
17,100	6	$7,032,538.15	$4,520,385.92	$2,078,078.30
	8	$7,032,538.15	$4,520,385.92	$2,078,078.30

Table 7.14. The annual operating cost for the growth section given various conditions. The bolded case is the scenario investigated in this project.

Ethylene Production Rate (mg/L/day)	Production Tank Size (million L)	Cell Growth Rate (day^{-1})		
		0.9	1.8	3.6
8,550	4	$1,018,641.60	$731,098.08	$567,353.37
	6	$1,018,641.50	$731,097.92	$567,353.41
	8	$1,012,552.65	$722,167.68	$549,952.77
4,275	8	2102238.61	$1,553,862.00	1237885.34
17,100	6	$596,783.35	$393,591.44	$308,481.59
	8	$596,783.35	$393,591.44	$308,481.59

From this analysis it can be seen that in general as the growth rate increases, both capital costs and operating costs for specific production tank sizes decreases. Annual operating costs, however, decrease at a slower, almost constant, rate than capital costs as shown in Figures 7.3 and 7.4. These decreased costs would immediately suggest the use of the largest possible tank size with the highest cell growth rate possible. This would ultimately result in tradeoffs, increasing cell growth rate would like require increased costs for the research needed to achieve those rate while increasing production tank size would likely increase costs due to the currently unavailable sizes for our production tanks. As a result, the specific combination of factors in this report was chosen as a middle ground of both growth and production sections.

Likewise, while holding production tank size constant in Figures 7.5 and 7.6, we can see decreased costs associated with both increased growth and ethylene production rates. Unlike before, increasing theses two factors will substantially reduce both capital and operating costs. This is most likely due to the combination of decreased volume necessary for ethylene production and faster cell growth rates. In the prior analysis, the growth rate of cells were varied while the ethylene production rate was held constant. The constant ethylene production rate contraints the processs to large volumes of media, only by decreasing both volume and time, can the growth section see decreases in both capital and annual operating costs.

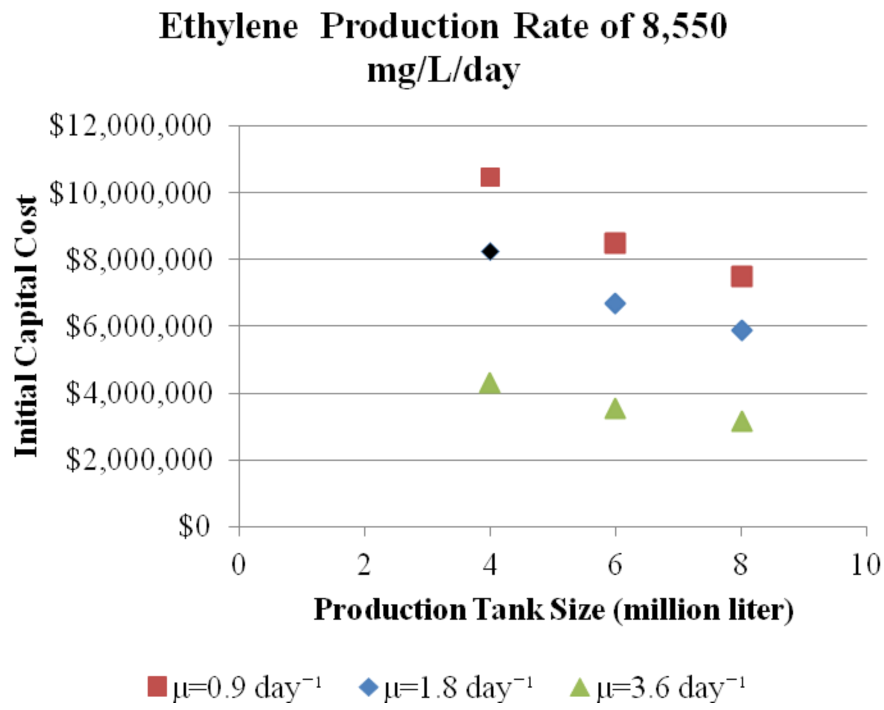

Figure 7.3. Initial capital cost for an ethylene production rate of 8,550 mg/L/day. The black data point is the scenario studied in this project.

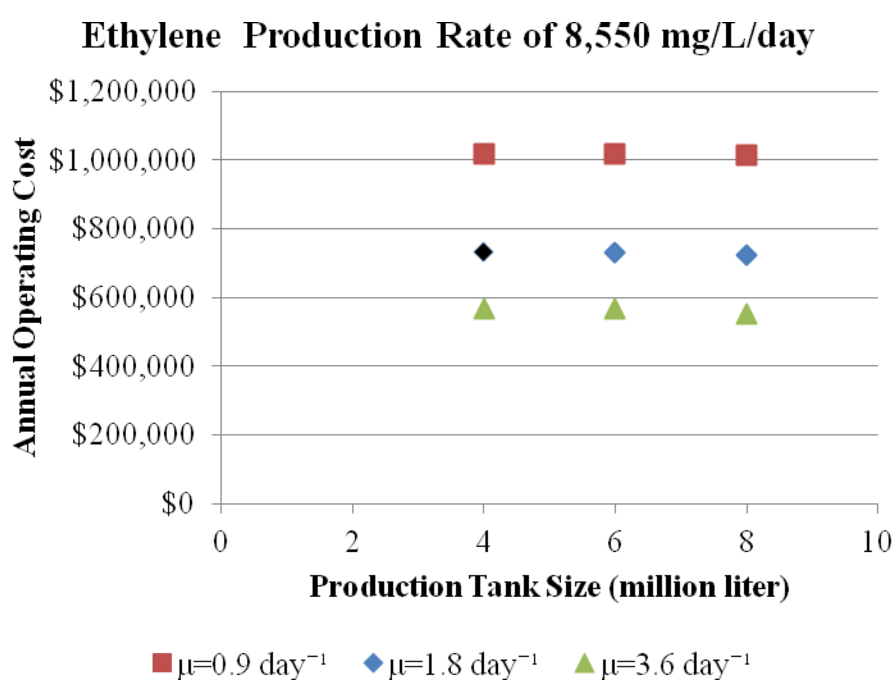

Figure 7.4. Annual operating cost for an ethylene production rate of 8,550 mg/L/day. The black data point is the scenario studied in this project.

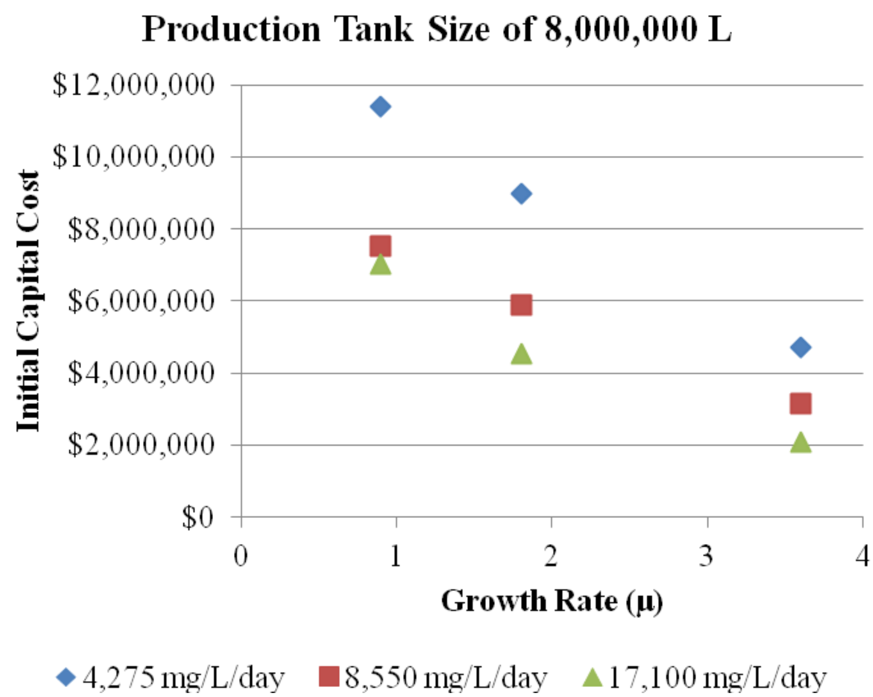

Figure 7.5. Initial capital cost for an production tank size of 8,000,000 L.

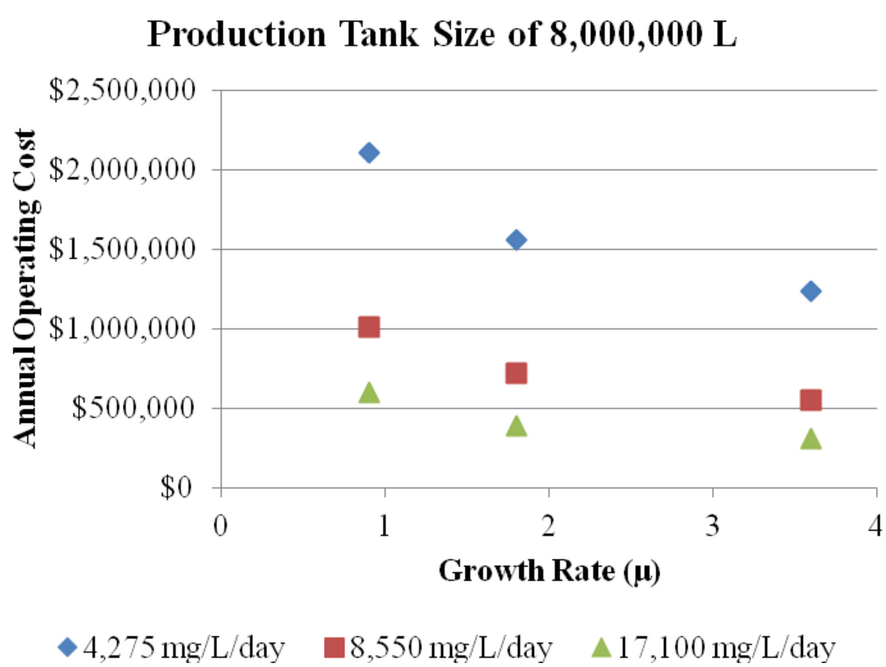

Figure 7.6. Annual operating cost for an production tank size of 8,000,000 L.

SECTION VIII – LOCATION

Plant Location

Plant location is a major factor when determining the success of a plant venture. Based on some process requirements and other considerations our green technology ethylene plant was chosen to be located in Santa Rosa, CA which is located along California's northern Pacific Coast. The location is shown on a map in Figure 8.1.

Figure 8.1: Map of Plant Location in Northern California

Site Factor

Site factors help companies compare the cost of building a plant in different locations based on certain factors such as the availability of labor, efficiency of the workforce, local rules and customs, and union status as well as other issues. The Pacific Coast where we will chose to locate has a site factor of 1.25 which is larger than the 1.00 of the United States Gulf Coast, so this factor makes the plant a little more expensive. California has been a very progressive liberal political climate which may bode well for this project since it is a green technological application. This could result in tax credits and other community support that could make this project a more profitable endeavor. Real estate prices are more expensive which is an underlying cause in the site factor but as we will see in the following sections the choice to locate in Santa Rosa, CA was one of necessity.

Carbon Dioxide Source

The true value of our technology is that it offers a green solution to producing the largest commodity chemical feedstock in the world, ethylene. The process uses a feed of carbon dioxide so our group proposed a solution to obtain carbon dioxide for free by engaging in a partnership with another company to reduce the carbon tax burden on a plant that gives off carbon dioxide as a byproduct. We would pipe the partnering plants carbon dioxide outlet to our plant to use as an input. Since our process requires relatively pure carbon dioxide an ethanol plant is a good candidate to engage with in this process and there is an ethanol plant operated by Pacific Ethanol in Stockton, CA which is close in proximity to Santa Rosa, CA. This is a major reason in locating along the Pacific Coast was chosen for this ethylene plant.

Seawater Source

Our process uses a large amount of seawater to grow the bacteria needed for the photosynthetic reaction to ethylene. The two main specifications we needed for location were close to the coast and close to an ethanol plant so Santa Rosa, CA solves both these issues. Santa Rosa is in close proximity to the Pacific Ocean where we can extract seawater to use in our process. Most ethanol plants are located in the Midwest where water is scarce so the opportunity to have an ethanol plant near a seawater source was very fortunate for this plant and truly dictated out choice in location.

Ethylene Price

Since our plant is located in the United States and there are many ethylene plants in the United States, the market is well defined and our location does not really affect the price at which we can sell ethylene. We will use a price of $.50/lb of ethylene that is a fair market price that has been consistent in the United States over the recent years.

Transportation

For a plant to be operable there must be a means of transportation to and from it. This is necessary for the plant to be constructed and materials to be shipped to and from the site. Additionally raw materials, products, and employees must be brought to and from the site. Good transportation infrastructure must be present in the region to allow for ease of transportation and this is present in Santa Rosa, CA. The nearby Pacific Ocean also allows materials to be shipped in by sea if it is necessary to ship materials or good to or from overseas.

SECTION IX – SAFETY AND OTHER CONSIDERATIONS

Ethylene Safety

Ethylene is a very flammable gas so its transportation and storage must be done with extraordinary care and attention to avoid serious hazards. The plant is not at a risk for ethylene auto ignition as ethylene's ignition temperature is 914 °F and in the process the highest temperature it reaches is approximately 400 °F.

The major safety concern in our plant is the possible combustion of ethylene and oxygen. An unavoidable consequence of the photosynthetic reaction is that oxygen is a product and it can make a combustive mixture with ethylene. Ethylene is highly volatile and flammable but it is relatively low concentration in the reactor effluent which is compressed to high pressures in the separation sections described in the process description section. Ethylene is about 10 wt% of the reactor effluent so when it is compressed in the presence of oxygen, combustion is a risk. The interstage cooling in the multistage compressors is designed to keep the mixture at a lower temperature to reduce the risk of combustion. The balance nitrogen and carbon dioxide will provide some leeway as well to reduce the risk of combustion of the ethylene and oxygen.

Measures should be taken to ensure that leaks can be easily detected and plugged. Also we advise that much is invested in piping and transport equipment to lower leakage risks. If leaks occur with the oxygen present it is possible that the mixture will combust which exposes the workers and the plant at serious risk.

Another concern is the possibility of the free radical polymerization of ethylene. These reactions are used to generate polyethylene on industrial scales. Since free radical polymerization occurs at high pressures and the ethylene stream is pressurized in the separation sections described in this process pipes with periodic pinches should be used. Pinches in the pipes prevent polymerization from spreading through the plant and causing clogging issues as well as wasting the ethylene gas being produced.

Bioreactor and Growth of Bacteria Considerations

Since the process uses seawater to grow the cyanobacteria to concentrations for production it is important that the water be purified at least for other microbes. Contamination in plants that use bacteria is a major issue and can result in major shutdown times as well a major sanitization costs. Processing the seawater through a filter is thoroughly addressed in Section 000 and should be a main concern.

As we have stated the bioreactor to produce ethylene in this fashion is not readily available but when it is and the bacteria undergo photosynthesis sludge-like material (biomass) will be created. This sludge cannot be simply dumped back into the environment, it must be processed in some way (possibly with UV radiation) to kill the excess bacteria to avoid pollution and environmental sanctions or fines. This could be done on site or outsourced to another company. Since there will be a cost associated with this and there is not a feasible design for a reactor we can consider this cost an annual operating cost for the reactor. We provide an economic sensitivity between the annual cost of the reactor and the capital investment on the reactor in Section VII and this bacteria handling would be included in the annual costs when a reactor is proposed.

Additional Safety Considerations and Material Handling

All of the chemicals in the process are well understood. Ethylene's safety concerns have been discussed above and oxygen, nitrogen, and carbon dioxide are common entities in industrial processes so they present no major issues. Nitric acid, sodium hydroxide, and phosphoric acid are also used in the sections preceding the reactor and our also thoroughly understood. The MSDS's for each component are contained in the Appendix and can be reviewed.

The silica-alumina adsorbent used in the Pressure-Swing adsorption section (Section 300) is also common but our adsorbent is treated with silver nitrate which may change its handling protocol and should be adhered to properly.

SECTION X – EQUIPMENT LIST AND UNIT DESCRIPTIONS

Table 10.1 – Equipment List

PUMPS	
Equipment ID	Type
P001	Centrifugal Pump
P101A (6)	Centrifugal Pump
P102A (3)	Centrifugal Pump
P103A (3)	Centrifugal Pump
P104A (4)	Centrifugal Pump
P105A (6)	Centrifugal Pump
P106A (3)	Centrifugal Pump
P107A (3)	
P108A(24)	Centrifugal Pump
P301A	Centrifugal Pump
P301B	Centrifugal Pump
P301C	Centrifugal Pump
HEAT EXCHANGERS	
Equipment ID	Type
F101	Electric Heater
HX301A	Shell and Tube Heat Exchanger
HX301B	Shell and Tube Heat Exchanger
HX301C	Shell and Tube Heat Exchanger
HX401	Shell and Tube Heat Exchanger
HX402	Shell and Tube Heat Exchanger
MHX401	Multistream Heat Exchanger
COMPRESSORS and EXPANDERS	
Equipment ID	Type
C301A	Compressor
C301B	Compressor
C301C	Compressor
C401	Multistage Compressor
R-C-402	Multistage Compressor
R-E-401	Expander Turbine

TOWERS and VESSELS	
Equipment ID	Type
ADS301/302/303	Adsorption Column
D401	Distillation Column
D402	Distillation Column
R-FL401	Flash Drum
TANKS	
Equipment ID	Type
ST001	Storage Tank
ST101A (6)	Seed Tank
ST102A (3)	Seed Tank
ST103A (3)	Growth Tank
ST104A (4)	Growth Tank
FILTERS	
Equipment ID	Type
F001	Sand Filter Tank
VALVES	
Equipment ID	
V301	
V302	
V303	
V304	
V305	
V306	
V307	
V308	
V309	
V401	
V402	
V403	
R-V404	

Note: Parentheses next to units indicate the number of those units included in the full scale process design

Unit Descriptions – Seawater Purification and Growth Media Manufacturing, Section 000

Pump

P001 is a stainless steel centrifugal pump that pumps up water from the sea for our process. The pump is protected from large debris by a 27.18 sq. ft steel grate at the mouth of the pipe in the sea. The pump provides a pressure increase of only 57.64 psi. The seawater is pumped into F001, the sand filter. The pump is pumping a high volume of seawater, 421.66 gpm because of the high water requirement for the growth of the cyanobacteria. To keep the volumetric flow rate at a reasonable amount, the pump will be running all day, every day. This will require a large power requirement, 190,835.25 Btu/hr, but this is not unreasonable for providing seawater for this entire biological process.

Filter

F001 is a sand bed filter used to separate seawater from any inorganic and organic debris that may have gone through P001. Influent seawater will enter from the top of the tanks and will flow through the hard media and be collected at the bottom and sent to ST001.

The sand filter will consist of 4 polyurethane tanks that are filled 54% with a sand and gravel mixture. The tanks are internally lined with 3M Skotchkote 134, which is resistant to abrasion from the seawater. Each tank has a volume of 1100 gallons, a height of 8.90 feet, and a diameter of 5.25 feet. The entire process can filter a peak flow of 1000 gpm and can operate at pressures as high as 80 psi. It operates at ambient temperature. This filter is modeled from the Yardney 4-Pod sand filter, attached in the Appendix.

The sand filtration removes particulates that are larger than 50 microns. This unit uses 2,047.29 Btu/hr only. An automatic backwash to clear the debris from the filter occurs at a rate of 240 gpm.

Since this product is a biotechnological and not pharmaceutical, the purity of the water does not have to be high. This simple, cheap filtration unit should keep the rest of the process relatively clean and filter out most organic matter that would disrupt cyanobacteria growth. 4 tanks are necessary to allow for a continuous flow rate even when a tank backwash, which is estimated to take 6 hours per tank. Staggering the flow into the tanks so that 3 are always operational while 1 is backwashing will avoid any disruption in the flow of seawater to ST001.

Storage Tank

ST001 stores the seawater from F001, mixes in the additive salts required for cyanobacteria growth, and dispenses the seawater for Section 100. The singular tank is constructed out of stainless steel and is 16.04 feet in diameter and 96.18 feet in height. In total the tank has a volume of 580,800 gallons and a void fraction of 0.7. To mix the seawater and additives, there will be a turbine agitator that will be operating all day, every day at 58.08 horsepower. This agitator will consume 147,780.50 Btu/hr. The volume was chosen by determining what the most volume of seawater will be required all at once by Section 100.

Bins are located above ST001 that feed in additives required for cyanobacteria growth. The bin that holds Phosphoric Acid in granular form is only 6.3 cu. ft and feeds ST001 at a rate of 0.0075 cu. ft/hr. Nitric Acid in granular form is fed from a 287.00 cu. ft bin and is fed in at a rate of 0.34 cu. ft/hr. Sodium Hydroxide in solid form is held in a 136.13 cu. ft bin and is fed in at a rate of 0.16 cu. ft/hr. Each bin holds 4 weeks worth of salt for ST001.

All of the solids are fed into ST001 by vibratory feeders. The amounts of salt were all calculated from ideal growth and production requirement. Sodium Hydroxide is added in to keep the pH of the media around 11, which is the level that cyanobacteria thrive in, but very few other microorganisms do. This high pH level and the filtration from F001 should reduce any competition from other microorganisms and allow this specific strain to grow uncontested.

Unit Descriptions – Cyanobacteria Growth, Section 100

Heater

F101 is a stainless steel electric heater that heats the water from ST001 for use in growth tanks ST101A, ST102A, ST103A, and ST104A (see Figure 4.3) . Since the growth section is a batch process, this heater will be used only when it is needed. S-104 comes into the F101 at 75.2^{o}F and leaves in stream S-105 at 91.4 ^{o}F. Based on the total time of operation, the heat duty of this unit is 32,977,418.8 BTU/hr.

Pumps

P101A is a stainless steel centrifugal pump that transports water from storage tank ST001 through heater F101 to seed tank ST101A, which will operate at 200 GPM with 74 ft of pressure head. Based on these conditions, the pump will be operated at 3600 RPM with 75HP. The total power requirement for transport 987.5 L of water will be 190,832.52 BTU/hr.

P102A is a stainless steel centrifugal pump that transports water from storage tank ST001 through heater F101 to seed tank ST102A, which will operate at 500 GPM with 79 ft of pressure head. Based on these conditions, the pump will be operated at 3600 RPM with 75HP. The total power requirement for transport 9,000 L of water will be 190,832.52 BTU/hr.

P103A is a stainless steel centrifugal pump that transports water from storage tank ST001 through heater F101 to growth tank ST103A, which will operate at 2500 GPM with 89 ft of pressure head. Based on these conditions, the pump will be operated at 1800 RPM with 200HP. The total power requirement for transport 90,000 L of water will be 508,886.72 BTU/hr.

P104A is a stainless steel centrifugal pump that transports water from storage tank ST001 through heater F101 to seed tank ST101A, which will operate at 5000 GPM with 110 ft of pressure head. Based on these conditions, the pump will be operated at 1800 RPM with 250HP. The total power requirement for transport 900,000 L of water will be 636,108.40 BTU/hr.

P105A is a stainless steel centrifugal pump that transports the contents of seed tank ST101A to seed tank ST102A, which will operate at 200 GPM with 46 ft of pressure head. Based on these conditions, the pump will be operated at 3600 RPM with 75HP. The total power requirement for transport 1,000L (Contents of ST101A) will be 190,832.52 BTU/hr.

P106A is a stainless steel centrifugal pump that transports the contents of seed tank ST102A to growth tank ST103A, which will operate at 500 GPM with 56 ft of pressure head. Based on these conditions, the pump will be operated at 3600 RPM with 75HP. The total power requirement for transport 10,000L (Contents of ST101A) will be 190,832.52 BTU/hr.

P107A is a stainless steel centrifugal pump that transports the contents of growth tank ST103A to growth tank ST104A, which will operate at 5000 GPM with 77 ft of pressure head. Based on these conditions, the pump will be operated at 1800 RPM with 200HP. The total power requirement for transport 100,000L (Contents of ST101A) will be 508,886.72 BTU/hr.

P108A is a stainless steel centrifugal pump that transports the contents of growth tank ST104A to the production tanks via stream S-201A, which will operate at 5000 GPM with 100 ft of pressure head. Based on these conditions, the pump will be operated at 1800 RPM with 250HP. The total power requirement for transport 1,000,000L (Contents of ST101A) will be 636,108.40 BTU/hr.

Seed/Growth Tanks

ST101A is a stainless steel storage tank that is used to grow cells from a concentration of $1.25x10^5$ cells/mL to $1.13x10^7$cells/mL in 2.5 days. Through insulation, this tank is kept at the temperature of 33 ^oC at atmospheric pressure of 14.7 psi. The tank will be 4 ft high with a diameter of 4.007 ft which includes a void space of 0.70. The void space is allotted to account for an agitator of 1HP.

ST102A is a stainless steel storage tank that is used to grow cells from a concentration of $1.13x10^6$ cells/mL to $1.07x10^7$cells/mL in 1.25 days. Through insulation, this tank is kept at the temperature of 33 ^oC at atmospheric pressure of 14.7 psi. The tank will be 9 ft high with a diameter of 8.448 ft which includes a void space of 0.70. The void space is allotted to account for an agitator of 1HP.

ST103A is a stainless steel storage tank that is used to grow cells from a concentration of $1.07x10^6$ cells/mL to $1.01x10^7$cells/mL in 1.25 days. Through insulation, this tank is kept at the temperature of 33 ^oC at atmospheric pressure of 14.7 psi. The tank will be 19 ft high with a diameter of 18.387 ft which includes a void space of 0.70. The void space is allotted to account for an agitator of 4HP.

ST104A is a stainless steel storage tank that is used to grow cells from a concentration of $1.01x10^6$ cells/mL to $1.51x10^7$cells/mL in 2.5 days. Through insulation, this tank is kept at the temperature of 33 ^oC at atmospheric pressure of 14.7 psi. The tank will be 40 ft high with a diameter of 40.073 ft which includes a void space of 0.70. The void space is allotted to account for an agitator of 38HP.

Unit Descriptions – Pressure Swing Adsorption, Section 300

Compressors

C301A is the first of three compressors in the multistage compressor unit C301.The multistage compressor is necessary to raise the pressure of the reactor effluent to a high enough pressure so that ethylene will adsorb on the zeolite catalyst in the adsorption column. This compressor takes the reactor effluent, S-301, and increases the pressure of the stream by 25.7 psi which also results in a 202.1 °F temperature increase.

C301B is the second of three compressors in the multistage compressor unit C301. This compressor takes the gas outlet stream, S-301B, from the first heat exchanger, HX301A, and increases the pressure of the stream by 75.5 psi which also results in a 241.5 °F temperature increase.

C301C is the third of three compressors in the multistage compressor unit C301. This compressor takes the gas outlet stream, S-301D, from the second heat exchanger, HX301B, and increases the pressure of the stream by 198.7 psi which also results in a 222.3 °F temperature increase.

Heat Exchangers

HX301A is the first of three heat exchangers contained in the multistage compressor unit, C301, that cools the outlet stream from C301, S-301A, from 272.1 °F to 105 °F. This requires 5,110,000 BTU/hr of cooling duty which is provided by 171,000 lb/hr of cooling water that is heated from 65 °F to 95 °F. There is a 5 psi pressure drop through the heat exchanger for both the hot and cold streams and the total area for heat transfer is set at 370.51 ft^2.

HX301B is the second of three heat exchangers contained in the multistage compressor unit, C301, that cools the outlet stream from C302, S-301C, from 346.5 °F to 105 °F. This requires 7,570,000 BTU/hr of cooling duty which is provided by 253,000 lb/hr of cooling water that is heated from 65 °F to 95 °F. There is a 5 psi pressure drop through the heat exchanger for both the hot and cold streams and the total area for heat transfer is set at 439.51 ft^2.

HX301C is the third of three heat exchangers contained in the multistage compressor unit, C301, that cools the outlet stream from C303, S-301E, from 327.3 °F to 80 °F. This requires 7,904,000 BTU/hr of cooling duty which is provided by 795,000 lb/hr of cooling water that is heated from 65 °F to 75 °F. There is a 5 psi pressure drop through the heat exchanger for both the hot and cold streams and the total area for heat transfer is set at 628.46 ft^2.

Pumps

P301A is a centrifugal pump which pumps 171,000 lb/hr of cooling water, S-319, with a 5.3 psi pressure increase and 50 ft of static head, so it can be pushed through the first heat exchanger in the multistage compressor unit, HX301A. The pump requires 3,969 BTU/hr of energy to run and creates enough pressure increase to account for the 5 psi pressure drop through HX301A.

P301B is a centrifugal pump which pumps 253,000 lb/hr of cooling water, S-322, with a 5.3 psi pressure increase and 50 ft of static head, so it can be pushed through the second heat exchanger in the multistage compressor unit, HX301B. The pump requires 5,572 BTU/hr of energy to run and creates enough pressure increase to account for the 5 psi pressure drop through HX301B.

P301C is a centrifugal pump which pumps 795,000 lb/hr of cooling water, S-325, with a 5.3 psi pressure increase and 50 ft of static head, so it can be pushed through the third heat exchanger in the multistage compressor unit, HX301C. The pump requires 15,572 BTU/hr of energy to run and creates enough pressure increase to account for the 5 psi pressure drop through HX301C.

Valves

Valves V301/302/303 are responsible for allowing flow of the pressurized reactor effluent stream that is exiting the multistage compressor, C301, through the adsorption towers for ethylene separation. Each valve is opened for a third of the time of process operation to allow the ethylene to adsorb on the zeolite adsorbent contained in the tower. There is a 5 psi pressure drop through each valve which results in a slight temperature decrease of .3 °F for each stream entering the adsorption column.

Valves V304/305/306 are responsible for depressurizing the adsorption columns ADS301/302/303 from 294.6 to 14.7 psia to allow the adsorbed ethylene on the zeolite catalyst to be desorbed and sent out of the tower for collection. Each valve is opened for two thirds of the time of process operation to allow the ethylene to desorb from the zeolite adsorbent contained in the tower. There is a 279.9 psi pressure drop through each valve, since the ethylene is being depressurized to allow for desorption which results in a significant temperature decrease of 39.8 °F for each stream of high purity ethylene leaving the adsorption columns.

V307/308/309 are responsible for opening and closing an outlet from the adsorption towers ADS301/302/303 that would allow flow for the portion of the reactor effluent stream that does not desorbs on the zeolite adsorbent. During desorption of the ethylene there would be no flow in streams S-310/312/314 and these valves would remain closed to allow the ethylene to be desorbed and collected from a different outlet from the adsorption towers.

Adsorption Towers

The adsorption towers ADS301/302/303 are responsible for extracting the ethylene from the pressurized reactor effluent S-302. The columns contain a silver modified silica alumina zeolite adsorbent that selectively removes 90% of the ethylene from the incoming streams S-306/307/308. There is a 15 psi pressure drop through the columns for overhead streams S-312/314/316 that are ethylene poor and are removed from the process loop during the adsorption phase of the towers. During desorption the vessels are depressurized to 14.7 psia and the ethylene desorbs from the towers. The towers are made from carbon steel, are 4.94 ft in diameter, 26.97 ft in height, and weigh 14,883 lb. They contain 286.6 ft^3 of zeolite adsorbent and due to the exothermic process of adsorption yield 163,810 BTU/hr of heat.

Unit Descriptions – Cryogenic Distillation, Section 400

Multistage Compressor

C401 compresses the feed gas from the 200 section so that it can go through HX401. The pressure is increased by 285.3 psi. The flow is decreased from 1,463,720 cu. ft to 70,621.61 by going through 3 different stages. The heat duties for each stage are as follows: 6,123,000, 7,511,000, and 7,076,000 Btu/hr. Overall, the temperature of the gas stream increased by 8.6˚F. The compressor is constructed out of carbon steel and is powered by electricity.

R-C-402 is also a compressor that is used in the nitrogen refrigeration cycle. The unit compresses R-S-426 to R-S-414 so that the nitrogen can be fed back into MHX401. The compressor increases the stream pressure by 935 psi and the temperature by 7.8˚F. The flow is decreased from 828,742.91 cu. ft/hr to 204,199.37 cu. ft/hr. There are 3 stages and the consumed power totals 99,634,600 Btu/hr. The compressor is constructed out of carbon steel and is powered by electricity.

Expanders

R-E-401 is an expander turbine that reduces the pressure of R-S-417 to R-S-418 by 900 psi. The stream is then fed back towards MHX-401. The temperature drops 119.2 ˚F. The flow rate is increased from 61,712.75 cu. ft/hr to 161,219.02 cu. ft/hr. This turbine is used to power R-C042. The produced power is 4,997.93 HP.

Heat Exchangers

HX401 is a shell and tube heat exchanger that is used to do the majority of the cooling of the feed gas stream from C401 by using the bottom stream from D402. The feed gas stream goes through the shell side, while the carbon dioxide from D402 goes through the tube side. The shell side liquid is dropped from 100 ˚F to -15 ˚F. The flow of the two streams is countercurrent and the heat duty of the exchanger is 3,579,080.93 Btu/hr. The shell side stream, S-403, is fed to HX402.

HX402 is also a shell and tube heat exchanger that takes the cooled stream from HX402 and cools it an additional 3.48 ˚F by using the distillate from D402. The shell side stream from HX401 is fed to the first distillation time, D401. The distillate from D402 is heated from -43.5 ˚F to -23.49 ˚F. The flow of the two streams is countercurrent and the heat duty of the exchanger is 109,169.99 Btu/hr. Both HX 401 and HX402 lower the temperature of the gas stream from the 200 section so that the products may be separated using cryogenic distillation.

MHX401 is a multi stream heat exchanger that uses nitrogen and recovers work from S-407,411, and 413. In this exchanger, the oxygen and nitrogen stream, S-407, is heated from -277.05 ˚F to 70 ˚F in S-O2N2, the carbon dioxide stream, S-413, is heated from -117.23 ˚F to 70 ˚F in S-CO2, and the ethylene stream, S-411, is heated from -23.49 ˚F to 70 ˚F in S-PROD. Nitrogen returning from the D401 condenser, stream R-S-424, also goes into the exchanger at -229.4 ˚F and leaves in R-S-426 at 92.2 ˚F. To recover the work put in to cool these streams, nitrogen stream stream R-S-414 goes into the exchanger at 100 ˚F and is cooled to -213 ˚F and leaves as R-S-419. The heat exchanger system is constructed out of carbon steel and is manufactured by Chart Industries. The overall heat duty from this system is -156,099,560 Btu/hr.

Distillation Columns

D401 is a cryogenic distiller which operates at extremely cold temperatures. The temperature at the top of the tower is -226.95 ˚F, while the bottom of the tower operates at -8.44 ˚F. The tower takes the shell side stream from HX402, which includes all the gas products from section 200. The tower separates oxygen and nitrogen from ethylene and carbon dioxide, with oxygen and nitrogen coming off the top of the tower. The tower has 8 trays, is fed on tray 4 and has a tray spacing of 2 feet. The tower is 34 feet high and 4.3 feet in diameter, and is constructed from carbon steel. Attached to this tower is a condenser that operates at a reflux ratio of 3.2, has a heat duty of 15,534,500 Btu/hr, and the area of the condenser is 4,493 sq. feet. The pump for the condenser reflux operates at a pressure of 300 psi, a head of 58 feet, and a flow rate of 9.81 gpm. The reflux is collected in an accumulator that is 733.47 cu. feet large and handles a flow rate of 4,400.82 cu. feet/hr. The reboiler operates at -8.44 ˚F and has a heat duty of 4,698,760 Btu/hr. The reboiler pump also operates at 300 psi, has a head of 63 feet, and a flow rate of 2.72 gpm.

D402 is another cryogenic distiller which separates the bottoms of D401. The temperature at the top of the tower is -43.5 ˚F, while the bottom of the tower operates at -21.23 ˚F. The tower separates ethylene from carbon dioxide, with ethylene coming off the top of the tower. The tower has 83 trays, is fed on stage 30 and has a tray spacing of 2 feet. The tower is 178 feet high and 16 feet in diameter, and is constructed from carbon steel. Attached to this tower is a condenser that operates at a reflux ratio of 3.2, has a heat duty of 65,679,500 Btu/hr, and the area of the condenser is 41,009 sq. feet. The pump for the condenser reflux operates at a pressure of 300 psi, a head of 130 feet, and a flow rate of 18.27 gpm. The reflux is collected in an accumulator that is 2424.38 cu. feet large and handles a flow rate of 14,546.29 cu. feet/hr. The reboiler operates at -21.23 ˚F and has a heat duty of 66,015,900 Btu/hr. The reboiler pump also operates at 300 psi, has a head of 63 feet, and a flow rate of 20.44 gpm.

Flash Drum

R-FL401 is used to separate the mixed R-S-420 from MHX-401 so that the bottoms product, R-S-421 can be used in the condenser in D401. Both streams eventually feed back into MHX401. The vessel operates at 295 psi and at -251.3 ˚F. The vessel is 17.43 feet in diameter and 34.85 feet high, with a total volume of 12,471 cu. ft. The material used is carbon steel and weighs 329,165 lb.

Valves

V401 expands S-405 into S-407 by decreasing the pressure from 300 psi to 20 psi. The temperature also decreases from -226.95 ^{0}F to -277.05 ^{0}F. The stream is expanded so that it can be fed into MHX401.

V402 also expands S-406 into S-408 by decreasing the pressure from 303.72 psi to 200 psi. The temperature also decreases from -8.45 ^{0}F to -32.74 ^{0}F. The stream reduces the pressure of the stream so that the ethylene and carbon dioxide can be separated in D402.

V403 expands S-412 into S-413 by decreasing the pressure from 210.96 psi to 20 psi. The temperature also decreases from -21.20 ^{0}F to -117.22 ^{0}F. The stream is expanded so that it can be fed into MHX401.

R-V404 expands R-S-419 to R-S-420 by decreasing the pressure from 1210 psi to 300 psi. The temperature is also decreased from -213 ˚F to -250.8 ˚F. This valve partially liquefies the stream and feeds into R-FL401.

SECTION XI – SPECIFICATION SHEETS

Specification Sheets – Seawater Purification and Growth Media Manufacturing, Section 000

ST001	
Block Type:	Cone Roof Storage Tank
Function:	Stores seawater from S-003 and dispenses it in S-004
Materials:	**Inlet**
Seawater(gal)	396000
Phosphate(mol/L)	4.26E-05
Nitrate(mol/L)	2.42E-03
Hydroxide(mol/L)	3.45E-04
Operating Conditions:	
Pressure (psi)	14.7
Temperature (°F)	91.4
Design Data:	
Construction Material	Stainless Steel
Volume (gal)	580800
Void Space	0.7
Diameter (ft)	16.03
Height (ft)	96.18
Other Components	
Agitator	Turbine, Closed vessel
Power Requirements(HP)	58.08
Phosphoric Acid Bin(cuft)	6.3
Phosphoric Acid Feeder(cuft/hr)	0.0075
Nitric Acid Bin(cuft)	287
Nitric Acid Feeder(cuft/hr)	0.34
Sodium Hydroxide Bin(cuft)	16.4
Sodium Hydroxide Feeder(cuft/hr)	0.022
Purchase Cost:	$245,139.10
Bare Module Cost:	$282,106.10
Annual Operating Cost:	$91,650.80

P001		
Block Type:	Centrifugal Pump	
Function:	Pump fluid from Sea to F001	
Materials:	**Inlet**	**Outlet**
Stream	S-001	S-002
Operating Conditions:		
Pressure Increase (psi)	57.64	
Pressure Head (ft)	133.14	
Flow Rate (GPM)	421.66	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	190,832.25	
Power Source	Electricity	
Purchase Cost:	$4,322.33	
Bare Module Cost:	$33,728.48	
Annual Operating Cost:	$27,382.06	

F001	
Block Type:	Cylindrical Sand Filter Tank
Function:	Filters S-002 and dispense into ST001
Number of Units:	4
Materials:	**Inlet**
Raw Seawater(gpm)	421.66
Operating Conditions:	
Pressure (psi)	14.7
Temperature (°F)	80
Design Data:	
Construction Material	Polyurethane
Volume (gal)	1100
Media Volume Fraction	0.54
Diameter (ft)	5.25
Height (ft)	8.9
Filtration size(μm)	50
Backwash (gpm)	240
Purchase Cost:	$9,426.62
Bare Module Cost:	$13,477.00
Annual Operating Cost:	$73.44

Specification Sheets – Cyanobacteria Growth, Section 100

P101A		
Block Type:	Centrifugal Pump	
Function:	Pump water through heater F101 to ST101A	
Materials:	**Inlet**	**Outlet**
Stream	S-102A	S-103A
Operating Conditions:		
Pressure Increase (psi)	32.115	
Pressure Head (ft)	74	
Flow Rate (GPM)	200	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	190,832.52	
Power Source	Electricity	
Purchase Cost:	$3,978.99	
Bare Module Cost:	$31,076.85	
Annual Operating Cost:	$9.92	

P102A		
Block Type:	Centrifugal Pump	
Function:	Pump water through heater F101 to ST102A	
Materials:	**Inlet**	**Outlet**
Stream	S-114A	S-115A
Operating Conditions:		
Pressure Increase (psi)	34.286	
Pressure Head (ft)	79	
Flow Rate (GPM)	500	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	190,832.52	
Power Source	Electricity	
Purchase Cost:	$5,233.13	
Bare Module Cost:	$40,565.97	
Annual Operating Cost:	$72.34	

P103A		
Block Type:	Centrifugal Pump	
Function:	Pump water through heater F101 to ST103A	
Materials:	**Inlet**	**Outlet**
Stream	S-117A	S-118A
Operating Conditions:		
Pressure Increase (psi)	38.626	
Pressure Head (ft)	89	
Flow Rate (GPM)	2500	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	508,886.72	
Power Source	Electricity	
Purchase Cost:	$12,269.11	
Bare Module Cost:	$105,648.68	
Annual Operating Cost:	$385.79	

P104A		
Block Type:	Centrifugal Pump	
Function:	Pump water through heater F101 to ST104A	
Materials:	**Inlet**	**Outlet**
Stream	S-120A	S-121A
Operating Conditions:		
Pressure Increase (psi)	47.740	
Pressure Head (ft)	109	
Flow Rate (GPM)	5000	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	636,108.40	
Power Source	Electricity	
Purchase Cost:	$22,710.37	
Bare Module Cost:	$207,076.05	
Annual Operating Cost:	$2,009.33	

P105A		
Block Type:	Centrifugal Pump	
Function:	Pump fluid from ST101A to ST102A	
Materials:	**Inlet**	**Outlet**
Stream	S-107A	S-108A
Operating Conditions:		
Pressure Increase (psi)	20.334	
Pressure Head (ft)	46	
Flow Rate (GPM)	200	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	190,832.52	
Power Source	Electricity	
Purchase Cost:	$3,722.57	
Bare Module Cost:	$29,175.93	
Annual Operating Cost:	$10.05	

P106A		
Block Type:	Centrifugal Pump	
Function:	Pump fluid from ST102A to ST103A	
Materials:	**Inlet**	**Outlet**
Stream	S-109A	S-110A
Operating Conditions:		
Pressure Increase (psi)	24.754	
Pressure Head (ft)	56	
Flow Rate (GPM)	500	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	190,832.52	
Power Source	Electricity	
Purchase Cost:	$4,805.63	
Bare Module Cost:	$37,425.51	
Annual Operating Cost:	$80.37	

P107A		
Block Type:	Centrifugal Pump	
Function:	Pump fluid from ST103A to ST104A	
Materials:	**Inlet**	**Outlet**
Stream	S-111A	S-112A
Operating Conditions:		
Pressure Increase (psi)	34.037	
Pressure Head (ft)	77	
Flow Rate (GPM)	2500	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	508,886.72	
Power Source	Electricity	
Purchase Cost:	$11,372.46	
Bare Module Cost:	$98,912.56	
Annual Operating Cost:	$428.66	

P108A		
Block Type:	Centrifugal Pump	
Function:	Pump fluid from ST104A to production tanks	
Materials:	**Inlet**	**Outlet**
Stream	S-113A	S-201A
Operating Conditions:		
Pressure Increase (psi)	44.204	
Pressure Head (ft)	100	
Flow Rate (GPM)	5000	
Design Data:		
Construction Material	Stainless Steel	
Number of Stages	1	
Pump Efficiency	1	
Power Requirement (BTU/hr)	636,108.40	
Power Source	Electricity	
Purchase Cost:	$21,373.53	
Bare Module Cost:	$196,774.43	
Annual Operating Cost:	$744.20	

ST101A		
Block Type:	Cone Roof Storage Tank	
Function:	Initial seed tank used to grow cells	
Materials:	**Inlet**	**Outlet**
Cell Volume (gal)	4.17	-----
Cells (cells/mL)	1.00E+07	1.13E+07
Water (gal)	260.87	264.17
Operating Conditions:		
Pressure (psi)	14.7	
Temperature (°F)	91.4	
Design Data:		
Construction Material	Stainless Steel	
Volume (gal)	377.39	
Void Space	0.7	
Diameter (ft)	4.007	
Height (ft)	4	
Other Components:		
Agitator (HP)	1	
Purchase Cost:	$9,082.72	
Bare Module Cost:	$11,742.71	
Annual Operating Cost:	$2,114.40	

ST102A		
Block Type:	Cone Roof Storage Tank	
Function:	Second seed tank used to grow cells	
Materials:	**Inlet**	**Outlet**
Cell Volume (gal)	264.17	-----
Cells (cells/mL)	1.13E+07	1.07E+07
Water (gal)	2,377.55	2,641.72
Operating Conditions:		
Pressure (psi)	14.7	
Temperature (°F)	91.4	
Design Data:		
Construction Material	Stainless Steel	
Volume (gal)	3,773.89	
Void Space	0.7	
Diameter (ft)	8.448	
Height (ft)	9	
Other Components:		
Agitator (HP)	1	
Purchase Cost:	$21,296.99	
Bare Module Cost:	$27,340.34	
Annual Operating Cost:	$1,057.70	

ST103A		
Block Type:	Cone Roof Storage Tank	
Function:	Growth tank used to grow cells	
Materials:	**Inlet**	**Outlet**
Cell Volume (gal)	2,641.72	-----
Cells (cells/mL)	1.07E+07	1.01E+07
Water (gal)	23,775.48	26,417.20
Operating Conditions:		
Pressure (psi)	14.7	
Temperature (°F)	91.4	
Design Data:		
Construction Material	Stainless Steel	
Volume (gal)	37,738.86	
Void Space	0.7	
Diameter (ft)	18.387	
Height (ft)	19	
Other Components:		
Agitator (HP)	4	
Purchase Cost:	$65,179.39	
Bare Module Cost:	$83,551.60	
Annual Operating Cost:	$4,230.80	

ST104A		
Block Type:	Cone Roof Storage Tank	
Function:	Second growth tank used to grow cells	
Materials:	**Inlet**	**Outlet**
Cell Volume (gal)	26,417.20	-----
Cells (cells/mL)	1.01E+07	1.51E+07
Water (gal)	237,754.80	264,172.00
Operating Conditions:		
Pressure (psi)	14.7	
Temperature (°F)	91.4	
Design Data:		
Construction Material	Stainless Steel	
Volume (gal)	377,388.57	
Void Space	0.7	
Diameter (ft)	40.073	
Height (ft)	40	
Other Components:		
Agitator (HP)	38	
Purchase Cost:	$213,886.99	
Bare Module Cost:	$274,279.38	
Annual Operating Cost:	$48,231.15	

F101		
Block Type:	Electric Heater	
Function:	Heat stream S-116	
Materials:	**Inlet**	**Outlet**
Material Stream	S-104	S-105
Operating Conditions:		
Temperature (°F)	75.2	91.4
Pressure Drop (psi)	15	
Design Data:		
Construction Material	Stainless Steel	
Heat Duty (BTU/h)	32,977,418.8	
Power Source	Electricity	
Purchase Cost:	$38.97	
Bare Module Cost:	$49.77	
Annual Operating Cost:	$480,696.16	

Specification Sheets – Pressure Swing Adsorption, Section 300

HX301A		
Block Type: Shell and Tube Heat Exchanger Function: Cool S-301A and Heat S-320		
Shell:	Inlet	Outlet
Stream Temperature (°F) Pressure (psia)	S-320 65 20	S-321 95 15
Tube: Stream Temperature (°F) Pressure (psia)	S-301A 272.1 40.4	S-301B 105 35.4
Operating Conditions: Shell Flow Rate (lb/hr) Tube Flow Rate (lb/hr)	171,000 124,030	
Design Data: Construction Material Flow Direction Transfer Area (ft^2) Overall Heat Transfer Coefficient ($BTU/h*ft^2*hr$) Heat Duty (BTU/hr)	Stainless Steel Countercurrent 370.51 150 5,110,000	
Purchase Cost: Bare Module Cost: Annual Operating Cost:	$23,774 $75,365 $12,557	

HX301B		
Block Type: Shell and Tube Heat Exchanger Function: Cool S-301C and Heat S-323		
Shell:	Inlet	Outlet
Stream Temperature (°F) Pressure (psia)	S-323 65 20	S-324 95 15
Tube: Stream Temperature (°F) Pressure (psia)	 S-301C 346.5 110.9	 S-301D 105 105.9
Operating Conditions: Shell Flow Rate (lb/hr) Tube Flow Rate (lb/hr)	 253,000 124,030	
Design Data: Construction Material Flow Direction Transfer Area (ft^2) Overall Heat Transfer Coefficient ($BTU/h*ft^2*hr$) Heat Duty (BTU/hr)	 Stainless Steel Countercurrent 439.51 150 7,570,000	
Purchase Cost: Bare Module Cost: Annual Operating Cost:	$24,838 $78,736 $18,578	

HX301C		
Block Type: Shell and Tube Heat Exchanger Function: Cool S-301E and Heat S-326		
Shell:	Inlet	Outlet
Stream	S-323	S-324
Temperature (°F)	65	75
Pressure (psia)	20	15
Tube:		
Stream	S-301E	S-302
Temperature (°F)	327.3	80
Pressure (psia)	304.6	299.6
Operating Conditions:		
Shell Flow Rate (lb/hr)	795,000	
Tube Flow Rate (lb/hr)	124,030	
Design Data:		
Construction Material	Stainless Steel	
Flow Direction	Countercurrent	
Transfer Area (ft^2)	628.46	
Overall Heat Transfer Coefficient ($BTU/h*ft^2*hr$)	150	
Heat Duty (BTU/hr)	7,904,000	
Purchase Cost:	$27,730	
Bare Module Cost:	$87,904	
Annual Operating Cost:	$58,378	

ADS301/302/303		
Block Type: Adsorption Column		
Function: Selectively Remove ethylene from S-306/307/308		
Materials:	Inlet	Outlet (Overhead)
Stream	S-306/307/308	S-310/312/314
Mass Flow Rate (lb/hr)	41343.33	37237.81
Volumetric Flow Rate (ft^3/hr)	22986	2521.10
Temperature (°F)	79.7	98.6
Pressure (psia)	294.6	279.6
Breakdown (lb/hr)		
Ethylene	4540	455
Oxygen	17186.67	17177.08
Nitrogen	5373.33	5370.34
Carbon Dioxide	14243.33	14235.39
Operating Conditions:		
Max Capacity (lb ethylene)	4086	
Pressure Drop (psi)	15	
Heat of Adsorption (BTU/hr)	163,810	
Residence time(s)	27.44	
Adsorption time (hr/operating-hr)	0.33	
Desorption time (hr/operating-hr)	0.67	
Regeneration of Ethylene-rich Stream:		
Stream	S-315/316/317	
Mass Flow Rate (lb/hr)	4105.52	
Breakdown (lb/hr)		
Ethylene	4085	
Oxygen	9.58	
Nitrogen	3.00	
Carbon Dioxide	7.94	
Temperature (°F)	39.9	
Pressure (psia)	14.7	
Design Data:		
Construction Material	Carbon Steel	
Vessel Weight (lb)	14,883	
Diameter (ft)	4.94	
Height (ft)	27.44	
Adsorbent:		
Adsorbent Type	Silver treated Silica-Alumina Zeolite	
Adsorbent Volume (ft^3)	286.6	
Adsorbent Life (yrs)	3	
Cost for 15 years of adsorbent	$171,960	
Purchase Cost of Tower:	$133,340	
Purchase Cost of Adsorbent:	$171,96	
Bare Module Cost with Adsorbent:	$643,458	

P301A		
Block Type: Centrifugal Pump Function: Pump S-319 Cooling Water to HX301A		
Materials:	Inlet	Outlet
Stream	S-319	S-321
Operating Conditions:		
Discharge pressure (psia) Pressure increase (psia) Hydraulic Static Head (ft-lbf/lb) Volumetric Flow Rate (ft^3/hr)	20 5.3 50 2742.8	
Design Data:		
Construction Material Number of Stages Pump Efficiency Power Requirement (BTU/hr) Power Source	Stainless Steel 1 1 3,969 Electricity	
Purchase Cost: Bare Module Cost: Annual Operating Cost:	$12,531 $41,353 $570	

P301B		
Block Type: Centrifugal Pump Function: Pump S-322 Cooling Water to HX301A		
Materials:	Inlet	Outlet
Stream	S-322	S-323
Operating Conditions: Discharge pressure (psia) Pressure increase (psia) Hydraulic Static Head (ft-lbf/lb) Volumetric Flow Rate (ft^3/hr)	 20 5.3 50 4058.1	
Design Data: Construction Material Number of Stages Pump Efficiency Power Requirement (BTU/hr) Power Source	 Stainless Steel 1 1 5,572 Electricity	
Purchase Cost: Bare Module Cost: Annual Operating Cost:	\$13,620 \$44,946 \$800	

P301C		
Block Type: Centrifugal Pump Function: Pump S-325 Cooling Water to HX301A		
Materials:	Inlet	Outlet
Stream	S-325	S-326
Operating Conditions:		
Discharge pressure (psia) Pressure increase (psia) Hydraulic Static Head (ft-lbf/lb) Volumetric Flow Rate (ft^3/hr)	20 5.3 50 12752	
Design Data:		
Construction Material Number of Stages Pump Efficiency Power Requirement (BTU/hr) Power Source	Stainless Steel 1 1 15,572 Electricity	
Purchase Cost: Bare Module Cost: Annual Operating Cost:	$19,008 $62,725 $2,234	

Specification Sheets – Cryogenic Distillation, Section 400

D401			
Block Type:	Sieve Tray Distillation Tower		
Function:	Separates Ethylene and Carbon Dioxide from Oxygen and Nitrogen		
Materials	**Inlet**	**Distillate**	**Bottoms**
Stream	S-404	S-405	S-406
Phase	VAP	VAP	LIQ
Mass Flow (lb/hr)	124022	67715.84	56305.84
Volumetric Flow (cuft/hr)	52887	13086.89	1222.851
Temperature(^{0}F)	-18.48	-226.95	-8.44
Breakdown (lb/hr)			
Ethylene	13642.38	5.14	13637.24
Oxygen	51593.02	51585.94	7.08
Nitrogen	16122.82	16122.78	0.039
Carbon Dioxide	42663.46	1.97	42661.48
Operating Conditions			
Condenser Pressure(psi)	300		
Condenser Temperature(^{0}F)	-226.95		
Reboiler Pressure(psi)	303.72		
Reboiler Temperature(^{0}F)	-8.44		
Reflux Ratio	3.2		
Design Data			
Construction Material	Carbon Steel	Tray Efficiency	0.7
Weight(lb)	15376	Number of Trays	8
Diameter(ft)	4.3	Feed Stage	
Height(ft)	34	Tray Spacing (ft)	2
Exterior Components			
Condenser Heat Duty(Btu/hr)	15534500		
Condenser Reflux Pump Head(ft)	58	Flow Rate(gpm)	9.81
Accumulator Volume (cuft)	733.47		
Reboiler Heat Duty(Btu/hr)	4698760		
Reboiler Pump Head(ft)	63	Flow Rate(gpm)	2.72
Purchase Cost	$315,382.94		
Bare Module Cost	$1,542,164.16		
Annual Operating Cost	$12,692,531.77		

D402			
Block Type:	Sieve Tray Distillation Tower		
Function:	Separates the Bottoms of D401 into Ethylene and Carbon Dioxide		
Materials	**Inlet**	**Distillate**	**Bottoms**
Stream	S-408	S-409	S-410
Phase	MIX	VAP	LIQ
Mass Flow (lb/hr)	56305.84	13642.38	42663.46
Volumetric Flow (cuft/hr)	3932.716	8690.3	656.06
Temperature(^{0}F)	-32.74	-43.5	-21.23
Breakdown (lb/hr)			
Ethylene	13637.24	13532.02	105.22
Oxygen	7.08	7.08	0
Nitrogen	0.04	0.04	0
Carbon Dioxide	42661.48	103.24	42558.24
Operating Conditions			
Condenser Pressure(psi)	200		
Condenser Temperature(^{0}F)	-43.5		
Reboiler Pressure(psi)	210.96		
Reboiler Temperature(^{0}F)	-21.23		
Reflux Ratio	3.2		
Design Data			
Construction Material	Carbon Steel	Tray Efficiency	0.7
Weight(lb)	736087	Number of Trays	83
Diameter(ft)	16	Feed Stage	30
Height(ft)	178	Tray Spacing (ft)	2
Exterior Components			
Condenser Heat Duty(Btu/hr)	65679500		
Condenser Reflux Pump Head(ft)	130	Flow Rate(gpm)	18.27
Accumulator Volume (cuft)	2424.38		
Reboiler Heat Duty(Btu/hr)	66015900		
Reboiler Pump Head(ft)	63	Flow Rate(gpm)	20.44
Purchase Cost	$2,490,231.47		
Bare Module Cost	$12,891,717.18		
Annual Operating Cost	$14,489,484.80		

HX401		
Block Type:	Shell and Tube Heat Exchanger	
Function:	Cool S-402 so it can be fed to HX402	
Shell	**Inlet**	**Outlet**
Stream	S-402	S-403
Temperature(^{0}F)	100	-15
Pressure(psi)	300	300
Tube		
Stream	S-410	S-412
Temperature(^{0}F)	-21.23	-21.19
Pressure(psi)	210.96	210.96
Operating Conditions		
Shell Flow rate(lb/hr)	124022	
Tube Flow rate(lb/hr)	42663.46	
Design Data		
Construction Material	Carbon Steel	
Flow Direction	Countercurrent	
Transfer Area	617.35	
Overall Heat Transfer Coefficient(Btu/h*sq.ft*R)	149.69	
Heat Duty(Btu/hr)	3579080.93	
Purchase Cost:	$10,208.91	
Bare Module Cost:	$41,326.58	
Annual Operating Cost:	$0.00	

HX402		
Block Type:	Shell and Tube Heat Exchanger	
Function:	Cool S-403 so it can be fed to D401	
Shell	**Inlet**	**Outlet**
Stream	S-403	S-404
Temperature(^{0}F)	-15	-18.48
Pressure(psi)	300	300
Tube		
Stream	S-409	S-411
Temperature(^{0}F)	-43.5	-23.49
Pressure(psi)	200	200
Operating Conditions		
Shell Flow rate(lb/hr)	124022	
Tube Flow rate(lb/hr)	13642.38	
Design Data		
Construction Material	Carbon Steel	
Flow Direction	Countercurrent	
Transfer Area(ft)	47.681	
Overall Heat Transfer Coefficient(Btu/h*sqft*R)	149.69	
Heat Duty(Btu/hr)	109169.99	
Purchase Cost:	$7,798.98	
Bare Module Cost:	$31,570.96	
Annual Operating Cost:	$0.00	

C401		
Block Type:	Multistage Compressor	
Function:	Compresses S-401 to feed into HX401	
Materials:	**Inlet**	**Outlet**
Stream	S-401	S-402
Operating Conditions:		
Pressure Change (psi)	285.3	
Temperature Rise(^{0}F)	8.6	
Inlet Flow Rate (cuft/hr)	1463720	
Outlet Flow Rate (cuft/hr)	70621.61	
Design Data:		
Construction Material	Carbon Steel	
Number of Stages	3	
Consumed Power(Btu/hr)	20710000	
Power Source	Electricity	
Purchase Cost:	$6,630,400.00	
Bare Module Cost:	$26,486,458.88	
Annual Operating Cost:	$3,026,631.46	

R-C402		
Block Type: **Function:**	Multistage Compressor Compresses R-S-426 to R-S-414 to be fed back into R-MHX401	
Materials:	**Inlet**	**Outlet**
Stream	R-S-426	R-S-414
Operating Conditions:		
Pressure Change (psi)	925	
Temperature Rise(^{0}F)	7.8	
Inlet Flow Rate (cuft/hr)	828742.91	
Outlet Flow Rate (cuft/hr)	204199.37	
Design Data:		
Construction Material	Carbon Steel	
Number of Stages	3	
Consumed Power(Btu/hr)	99634600	
Power Source	Electricity	
Purchase Cost:	$6,676,300.00	
Bare Module Cost:	$26,669,815.61	
Annual Operating Cost:	$12,453,313.08	

R-E401		
Block Type:	Expander Turbine	
Function:	Expands R-S-417 to R-S-418 to be fed into MHX401	
Materials:	**Inlet**	**Outlet**
Stream	R-S-426	R-S-414
Operating Conditions:		
Pressure Change (psi)	-900	
Temperature Rise(^{0}F)	-119.2	
Inlet Flow Rate (cuft/hr)	61712.75	
Outlet Flow Rate (cuft/hr)	161219.02	
Design Data:		
Construction Material	Carbon Steel	
Produced Power(HP)	4997.93	
Power Destination	R-C402	
Purchase Cost:	$525,161.76	
Bare Module Cost:	$1,441,857.86	
Annual Operating Cost:	$0.00	

R-FL401			
Block Type:	Flash Drum		
Function:	Splits R-S-420 into two phases of nitrogen to be used in the condenser of D401		
Materials	**Inlet**	**Overhead**	**Bottoms**
Stream	R-S-420	R-S-422	R-S-421
Phase	MIX	VAP	LIQ
Mass Flow (lb/hr)	567487.97	243384.2	324103.77
Volumetric Flow (cuft/hr)	49884.15	42081.58	9033
Temperature(^{0}F)	-250.8	-251.3	.251.3
Breakdown (lb/hr)			
Nitrogen	567487.97	243384.2	324103.77
Operating Conditions			
Pressure(psi)	295		
Temperature(^{0}F)	-251.3		
Equilibrium	Vapor-Liquid Equilibrium		
Design Data			
Construction Material	Carbon Steel	Weight(lb)	329165
Diameter(ft)	17.43	Volume(cuft)	12471
Height(ft)	34.85		
Purchase Cost	$66,900.00		
Bare Module Cost	$355,394.21		
Annual Operating Cost	$0.00		

MHX401		
Block Type:	Multi Stream Heat Exchanger	
Function:	Cools R-S-414 to -213F	
Heating Stream	**Inlet**	**Outlet**
Stream	R-S-414	R-S-419
Temperature(^{0}F)	100	-213
Pressure(psi)	1210	1200
Cooling Stream		
Stream	R-S-424	R-S-426
Temperature(^{0}F)	-229.4	92.2
Pressure(psi)	290	290
Product Streams		
Oxygen/Nitrogen	S-407	S-O2N2
Temperature(^{0}F)	-277.05	70
Pressure(psi)	20	20
Carbon Dioxide	S-413	S-CO2
Temperature(^{0}F)	-117.23	70
Pressure(psi)	20	20
Ethylene	S-411	S-PROD
Temperature(^{0}F)	-23.49	70
Pressure(psi)	200	200
Operating Conditions		
Nitrogen Flow Rate (lb/hr)	1134980	
Design Data		
Construction Material	Carbon Steel	
Manufacturer	Chart Industries	
Heat Duty(Btu/hr)	-156099560	
Purchase Cost (Estimated):	$900,000.00	
Bare Module Cost:	$2,853,000.00	
Annual Operating Cost:	$0.00	

SECTION XII – CONCLUSIONS

Conclusion

This report focuses primarily on the upstream and downstream units of the production of ethylene from photosynthesis. Two separation processes were evaluated for their feasibility for this process: pressure swing adsorption and cryogenic distillation. The catalyst for pressure swing adsorption has not yet been proven in industry and may prove to be unsuitable for this application. As such, we chose to compare it to cryogenic distillation which is a more well understood process.

Looking primarily at the separations section for economics analysis, cryogenic distillation was concluded to be infeasible in obtaining a desired ROI of 15%. Cryogenic distillation is also very susceptible to changes in ethylene prices. The distillation section alone does not yield 15% IRR until ethylene prices reach $0.71/lb. In contrast, pressure swing adsorption is more promising with positive net present value of about $70MM at 15%. The price of ethylene can drop down below $0.30/lb and still yield a positive present value at 15%. For this process to be industrially feasible, the process without the reactor section must have a positive NPV. The NPV without the reactor in place then becomes the maximum negative NPV for the reactor section to achieve an IRR of 15%.

As previously stated, the current state of technology does not yet meet the requirements for this process. In order for this process to be feasible, research on both reactor design and cell engineering must be conducted. A suitable bioreactor that allows for both a gas feed and effluent, while allowing sunlight penetration, is crucial for this process. The cellular production rate must also be significantly increased from the published value through genetic engineering and other means.

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SECTION XIV – REFERENCES

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SECTION XV – APPENDIX

Sand Filter

BAKERCORP | Technical Information Manual | 2.10.2

PRODUCT DATA SHEET

January, 2007

YARDNEY 4-POD SAND FILTER

(Equip. # SFL21988 and earlier)

GENERAL INFORMATION

Skid mounted high rate automatic backwashing sand media filter (4 tanks (pods)) designed for general-purpose water filtration of organic and inorganic solids (Yardney Model # IL5424-4A32). Powered by 110 V external power supply, or battery with solar cell recharge for remote operation.

WEIGHTS AND MEASURES

Capacity:	504 – 756 gpm (Normal flow range) 1000 gpm (Peak flow)
Design Press:	80 psi maximum
Temperature:	Limit to ambient. Consult BakerCorp if temperature exceeds 100 degrees.
Filtration:	To 50 microns
Height:	8'-11" (overall)
Width :	6'-3"
Length:	20'-1"
Weight:	6,326 lbs. – equipment only 14,500 lbs. – media only 28,000 lbs. - operational
Backflush:	240 gpm, automatic

OPERATING REQUIREMENTS

Compressed Air:	5 cfm minimum at 60 psi **(Note: external air supply required)**
Sand Media:	Crushed silica, 0.47MM (#80 grit)
Gravel Media:	#3 crushed rock, ½" x ¾"
Input Power:	Selectable input power of customer supplied 110 V AC or 12V DC from a unit mounted solar package.
Output Power:	12V DC

FEATURES

System Controller:	Automatic Filter Controller. Flush activation based on elapsed time and/or pressure differential.
Piping:	Inlet & outlet pipe is 6" A53B, 3/16" wall; weld fittings are A234; flanges are A106. Backflush piping is 4" schedule 40 PVC.
Solar Panel:	Uni-Solar Model UA-5 (5 watts) module.

FEATURES – con't

Press. Gauge:	2" face, ¼" NPT bottom connection, stainless steel case, plexiglass lens, brass bourdon tube, 0-100 psi range.
Flowmeter:	Six-inch propeller type meter. AWWA C704-92 compliant. Instantaneous flowrate indicator and six-digit totalizer. Accuracy is ±2% of reading. Repeatability of 0.25%. Rated at 90-1200 gpm, 150 psi, 160°F. Tube: epoxy-coated carbon steel; Impeller: high-impact plastic.
Butterfly Valves:	<u>Effluent / Influent:</u> 6" with cast iron body (epoxy coated), EPDM seat, 304 SS stem and aluminum bronze disc. <u>Tank Isolation:</u> 4" grooved ends, EPDM disc coating
Ball Valves:	Four-inch, bronze body and brass ball; seat is carbon/glass-filled PTFE. ¼ turn open or close.
Solenoid Valve:	12V DC, normally closed type 7121V (energizing opens valve).
Differential Press. Switch:	0-30 psid. Two-inch dial, plated steel case, ±3% accuracy.
Air / Vacuum Release Valve:	2" Bernard Model 4415 valve, mounted on backwash, influent and effluent lines
Battery:	Sealed rechargeable lead-acid, 12V, NP2.6-12
Battery Charger:	Power-Sonic Model PSC-12500A, 12 volts.
Tubing:	Pressurized – ¼" 304 ss w/ Hoke fittings; Drain - ¼" polypropylene; Vent – schedule 80 PVC

SURFACE DETAILS

Interior Coating:	3M Skotchkote 134
Exterior Coating:	High Gloss Polyurethane

TESTS/CERTIFICATIONS

Tests Performed:	OEM pressure tested. BakerCorp performs scheduled QMS inspections.

BAKERCORP

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ASPEN REPORTS

ASPEN Block and Stream Diagrams for Section 300

```
BLOCK:  HX301A   MODEL: HEATX
-----------------------------
  HOT SIDE:
  ---------
  INLET STREAM:         S-301A
  OUTLET STREAM:        S-301B
  PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE
  COLD SIDE:
  ----------
  INLET STREAM:         S-320
  OUTLET STREAM:        S-321
  PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                          IN           OUT       RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(LBMOL/HR)          13135.1        13135.1        0.00000
     MASS(LB/HR   )          295030.        295030.        0.00000
     ENTHALPY(BTU/HR  )     -0.131587E+10   -0.131587E+10     0.00000

               ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E           42730.0      LB/HR
   PRODUCT STREAMS CO2E        42730.0      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 EXCHANGER DUTY
  SPECIFIED VALUE             BTU/HR          5110000.0000
  LMTD CORRECTION FACTOR                           1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE     PSIA               35.4000
  COLD SIDE OUTLET PRESSURE     PSIA               15.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  HOT LIQUID    COLD LIQUID     BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD LIQUID     BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD LIQUID     BTU/HR-SQFT-R        149.6937
  HOT LIQUID    COLD 2-PHASE    BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD 2-PHASE    BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD 2-PHASE    BTU/HR-SQFT-R        149.6937
  HOT LIQUID    COLD VAPOR      BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD VAPOR      BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD VAPOR      BTU/HR-SQFT-R        149.6937

              ***  OVERALL RESULTS  ***

STREAMS:
          --------------------------------------
          |                          |
S-301A    ----->|            HOT            |-----> S-301B
T=  2.7210D+02  |                           |     T=  1.0499D+02
P=  4.0400D+01  |                           |     P=  3.5400D+01
V=  1.0000D+00  |                           |     V=  1.0000D+00
          |                          |
S-321     <-----|            COLD           |<----- S-320
T=  9.4998D+01  |                           |     T=  6.5008D+01
P=  1.5000D+01  |                           |     P=  2.0000D+01
V=  0.0000D+00  |                           |     V=  0.0000D+00
```

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            -------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY         BTU/HR          5110000.0000
  CALCULATED (REQUIRED) AREA    SQFT              370.5086
  ACTUAL EXCHANGER AREA        SQFT              370.5086
  PER CENT OVER-DESIGN                          0.0000

HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R        149.6937
  UA (DIRTY)                 BTU/HR-R          55462.7800

LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                          1.0000
  LMTD (CORRECTED)            F                 92.1339
  NUMBER OF SHELLS IN SERIES                        1

PRESSURE DROP:
  HOTSIDE, TOTAL             PSI                5.0000
  COLDSIDE, TOTAL            PSI                5.0000

PRESSURE DROP PARAMETER:
  HOT SIDE:                                422.13
  COLD SIDE:                               73995.

              ***  ZONE RESULTS  ***

TEMPERATURE LEAVING EACH ZONE:

                        HOT
     -------------------------------------------------------------
     |                                         |
S-301A  |                  VAP                   | S-301B
------> |                                        |------>
 272.1  |                                        |  105.0
     |                                         |
S-321   |                  LIQ                   | S-320
<------ |                                        |<------
  95.0  |                                        |   65.0
     |                                         |
```

```
    ----------------------------------------------------------
                         COLD

 ZONE HEAT TRANSFER AND AREA:

 ZONE     HEAT DUTY     AREA     LMTD     AVERAGE U     UA
          BTU/HR        SQFT     F        BTU/HR-SQFT-R  BTU/HR-R
   1   5110000.000    370.5086   92.1339  149.6937     55462.7800

BLOCK:  P301A    MODEL: PUMP
----------------------------
 INLET STREAM:          S-319
 OUTLET STREAM:         S-320
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                        IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)        9491.94       9491.94       0.00000
    MASS(LB/HR   )        171000.       171000.       0.00000
    ENTHALPY(BTU/HR  )    -0.116843E+10   -0.116843E+10   -0.340170E-05

              ***  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                      20.0000
  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	2,742.83
PRESSURE CHANGE PSI	5.30000
NPSH AVAILABLE FT-LBF/LB	33.4458
FLUID POWER HP	1.05724
BRAKE POWER HP	1.56210
ELECTRICITY KW	1.16486
PUMP EFFICIENCY USED	0.67681
NET WORK REQUIRED HP	1.56210
HEAD DEVELOPED FT-LBF/LB	12.2417

S-301A S-301B S-319 S-320 S-321

\-------------------------------

STREAM ID	S-301A	S-301B	S-319	S-320	S-321
FROM :	----	HX301A	----	P301A	HX301A
TO :	HX301A	----	P301A	HX301A	----
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	LIQUID	LIQUID	LIQUID
COMPONENTS: LBMOL/HR					
ETHYLENE	485.4964	485.4964	0.0	0.0	0.0
CO2	970.9201	970.9201	0.0	0.0	0.0
NITROGEN	575.4373	575.4373	0.0	0.0	0.0
OXYGEN	1611.3104	1611.3104	0.0	0.0	0.0
WATER	0.0	0.0	9491.9424	9491.9424	9491.9424
TOTAL FLOW:					
LBMOL/HR	3643.1642	3643.1642	9491.9424	9491.9424	9491.9424
LB/HR	1.2403+05	1.2403+05	1.7100+05	1.7100+05	1.7100+05
CUFT/HR	7.0743+05	6.2132+05	2742.8338	2742.7903	2755.3237
STATE VARIABLES:					
TEMP F	272.1000	104.9922	65.0000	65.0084	94.9978
PRES PSIA	40.4000	35.4000	14.7000	20.0000	15.0000
VFRAC	1.0000	1.0000	0.0	0.0	0.0
LFRAC	0.0	0.0	1.0000	1.0000	1.0000
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-4.0470+04	-4.1872+04	-1.2310+05	-1.2310+05	-1.2256+05
BTU/LB	-1188.7234	-1229.9231	-6832.9367	-6832.9135	-6803.0304
BTU/HR	-1.4744+08	-1.5255+08	-1.1684+09	-1.1684+09	-1.1633+09
ENTROPY:					

```
  BTU/LBMOL-R         1.5593    -0.3514   -39.3720   -39.3719   -38.3735
  BTU/LB-R        4.5802-02 -1.0323-02    -2.1855    -2.1855    -2.1301
 DENSITY:
  LBMOL/CUFT        5.1498-03  5.8636-03    3.4606     3.4607     3.4449
  LB/CUFT            0.1753     0.1996    62.3443    62.3453    62.0617
 AVG MW             34.0446    34.0446    18.0153    18.0153    18.0153
BLOCK:  HX301B   MODEL: HEATX
 -----------------------------
  HOT SIDE:
  ---------
  INLET STREAM:         S-301C
  OUTLET STREAM:        S-301D
  PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE
  COLD SIDE:
  ----------
  INLET STREAM:         S-323
  OUTLET STREAM:        S-324
  PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

            ***  MASS AND ENERGY BALANCE  ***
                         IN           OUT       RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(LBMOL/HR)          17575.8        17575.8        0.00000
     MASS(LB/HR   )          375030.        375030.        0.00000
     ENTHALPY(BTU/HR  )     -0.186016E+10   -0.186016E+10     0.00000

            ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            42730.0      LB/HR
   PRODUCT STREAMS CO2E         42730.0      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 EXCHANGER DUTY
  SPECIFIED VALUE              BTU/HR          7570000.0000
  LMTD CORRECTION FACTOR                             1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE      PSIA                105.9000
  COLD SIDE OUTLET PRESSURE      PSIA                 15.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  HOT LIQUID    COLD LIQUID      BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD LIQUID      BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD LIQUID      BTU/HR-SQFT-R        149.6937
  HOT LIQUID    COLD 2-PHASE     BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD 2-PHASE     BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD 2-PHASE     BTU/HR-SQFT-R        149.6937
  HOT LIQUID    COLD VAPOR       BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD VAPOR       BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD VAPOR       BTU/HR-SQFT-R        149.6937

                 ***  OVERALL RESULTS  ***

STREAMS:
           --------------------------------------
           |                        |
S-301C   ----->|           HOT             |-----> S-301D
T=  3.4650D+02  |                          |     T=  1.0502D+02
P=  1.1090D+02  |                          |     P=  1.0590D+02
V=  1.0000D+00  |                          |     V=  1.0000D+00
           |                        |
S-324    <-----|           COLD            |<----- S-323
T=  9.5274D+01  |                          |     T=  6.5007D+01
P=  1.5000D+01  |                          |     P=  2.0000D+01
V=  0.0000D+00  |                          |     V=  0.0000D+00
```

```
       -------------------------------------

  DUTY AND AREA:
   CALCULATED HEAT DUTY          BTU/HR           7570000.0000
   CALCULATED (REQUIRED) AREA     SQFT              439.8660
   ACTUAL EXCHANGER AREA         SQFT              439.8660
   PER CENT OVER-DESIGN                          0.0000

  HEAT TRANSFER COEFFICIENT:
   AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R        149.6937
   UA (DIRTY)                BTU/HR-R          65845.1557

  LOG-MEAN TEMPERATURE DIFFERENCE:
   LMTD CORRECTION FACTOR                         1.0000
   LMTD (CORRECTED)           F                114.9667
   NUMBER OF SHELLS IN SERIES                      1

  PRESSURE DROP:
   HOTSIDE, TOTAL             PSI                5.0000
   COLDSIDE, TOTAL            PSI                5.0000

  PRESSURE DROP PARAMETER:
   HOT SIDE:                          1144.4
   COLD SIDE:                          34343.

              ***  ZONE RESULTS  ***

  TEMPERATURE LEAVING EACH ZONE:

                      HOT
     ------------------------------------------------------------
     |                                        |
S-301C  |                 VAP                 | S-301D
------> |                                     |------>
 346.5  |                                     |  105.0
     |                                        |
S-324   |                 LIQ                 | S-323
<------ |                                     |<------
  95.3  |                                     |  65.0
     |                                        |
```

```
    ----------------------------------------------------------
                     COLD

 ZONE HEAT TRANSFER AND AREA:

 ZONE     HEAT DUTY     AREA     LMTD     AVERAGE U     UA
         BTU/HR        SQFT      F       BTU/HR-SQFT-R  BTU/HR-R
   1   7570000.000    439.8660   114.9667  149.6937    65845.1557

BLOCK:  P301B    MODEL: PUMP
----------------------------
 INLET STREAM:         S-322
 OUTLET STREAM:        S-323
 PROPERTY OPTION SET:  SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                      IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)         13932.6       13932.6       0.00000
    MASS(LB/HR   )         251000.       251000.       0.00000
    ENTHALPY(BTU/HR  )     -0.171507E+10   -0.171506E+10   -0.322674E-05

              ***  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                      20.0000
  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	4,026.03
PRESSURE CHANGE PSI	5.30000
NPSH AVAILABLE FT-LBF/LB	33.4458
FLUID POWER HP	1.55185
BRAKE POWER HP	2.17497
ELECTRICITY KW	1.62188
PUMP EFFICIENCY USED	0.71350
NET WORK REQUIRED HP	2.17497
HEAD DEVELOPED FT-LBF/LB	12.2417

S-301C S-301D S-322 S-323 S-324

STREAM ID	S-301C	S-301D	S-322	S-323	S-324
FROM :	----	HX301B	----	P301B	HX301B
TO :	HX301B	----	P301B	HX301B	----
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	LIQUID	LIQUID	LIQUID
COMPONENTS: LBMOL/HR					
ETHYLENE	485.4964	485.4964	0.0	0.0	0.0
OXYGEN	1611.3104	1611.3104	0.0	0.0	0.0
NITROGEN	575.4373	575.4373	0.0	0.0	0.0
CO2	970.9201	970.9201	0.0	0.0	0.0
WATER	0.0	0.0	1.3933+04	1.3933+04	1.3933+04
TOTAL FLOW:					
LBMOL/HR	3643.1642	3643.1642	1.3933+04	1.3933+04	1.3933+04
LB/HR	1.2403+05	1.2403+05	2.5100+05	2.5100+05	2.5100+05
CUFT/HR	2.8394+05	2.0618+05	4026.0309	4025.9665	4044.5807
STATE VARIABLES:					
TEMP F	346.5000	105.0190	65.0000	65.0072	95.2739
PRES PSIA	110.9000	105.9000	14.7000	20.0000	15.0000
VFRAC	1.0000	1.0000	0.0	0.0	0.0
LFRAC	0.0	0.0	1.0000	1.0000	1.0000
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-3.9829+04	-4.1907+04	-1.2310+05	-1.2310+05	-1.2255+05
BTU/LB	-1169.9027	-1230.9363	-6832.9367	-6832.9147	-6802.7553
BTU/HR	-1.4510+08	-1.5267+08	-1.7151+09	-1.7151+09	-1.7075+09
ENTROPY:					
BTU/LBMOL-R	0.3899	-2.5740	-39.3720	-39.3720	-38.3646

```
 BTU/LB-R         1.1452-02 -7.5607-02   -2.1855    -2.1855    -2.1296
DENSITY:
 LBMOL/CUFT        1.2831-02  1.7670-02    3.4606     3.4607     3.4448
 LB/CUFT           0.4368     0.6016    62.3443    62.3453    62.0583
AVG MW            34.0446    34.0446    18.0153    18.0153    18.0153

BLOCK:  HX301C   MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:         S-301E
 OUTLET STREAM:        S-302
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE
 COLD SIDE:
 ----------
 INLET STREAM:         S-326
 OUTLET STREAM:        S-327
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

           ***  MASS AND ENERGY BALANCE  ***
                     IN            OUT       RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)          47772.4        47772.4        0.00000
   MASS(LB/HR   )          919030.        919030.        0.00000
   ENTHALPY(BTU/HR  )     -0.557807E+10   -0.557807E+10   -0.170969E-15

           ***  CO2 EQUIVALENT SUMMARY ***
 FEED STREAMS CO2E           42730.0      LB/HR
 PRODUCT STREAMS CO2E        42730.0      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 EXCHANGER DUTY
  SPECIFIED VALUE            BTU/HR         7904000.0000
  LMTD CORRECTION FACTOR                         1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE     PSIA              299.6000
  COLD SIDE OUTLET PRESSURE     PSIA               15.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  HOT LIQUID    COLD LIQUID     BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD LIQUID     BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD LIQUID     BTU/HR-SQFT-R        149.6937
  HOT LIQUID    COLD 2-PHASE    BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD 2-PHASE    BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD 2-PHASE    BTU/HR-SQFT-R        149.6937
  HOT LIQUID    COLD VAPOR      BTU/HR-SQFT-R        149.6937
  HOT 2-PHASE   COLD VAPOR      BTU/HR-SQFT-R        149.6937
  HOT VAPOR     COLD VAPOR      BTU/HR-SQFT-R        149.6937

          ***  OVERALL RESULTS  ***

STREAMS:
          --------------------------------------
          |                        |
S-301E   ----->|          HOT            |-----> S-302
T=  3.2730D+02  |                         |     T=  7.9969D+01
P=  3.0460D+02  |                         |     P=  2.9960D+02
V=  1.0000D+00  |                         |     V=  1.0000D+00
          |                        |
S-327    <-----|          COLD           |<----- S-326
T=  7.4987D+01  |                         |     T=  6.5005D+01
P=  1.5000D+01  |                         |     P=  2.0000D+01
V=  0.0000D+00  |                         |     V=  0.0000D+00
```

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          -------------------------------------

 DUTY AND AREA:
  CALCULATED HEAT DUTY         BTU/HR          7904000.0000
  CALCULATED (REQUIRED) AREA    SQFT              628.4606
  ACTUAL EXCHANGER AREA        SQFT              628.4606
  PER CENT OVER-DESIGN                          0.0000

 HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R        149.6937
  UA (DIRTY)                BTU/HR-R         94076.5611

 LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                          1.0000
  LMTD (CORRECTED)           F                 84.0167
  NUMBER OF SHELLS IN SERIES                        1

 PRESSURE DROP:
  HOTSIDE, TOTAL            PSI                5.0000
  COLDSIDE, TOTAL           PSI                5.0000

 PRESSURE DROP PARAMETER:
  HOT SIDE:                              3329.1
  COLD SIDE:                             3429.1

             ***  ZONE RESULTS  ***

 TEMPERATURE LEAVING EACH ZONE:

                      HOT
     -------------------------------------------------------------
     |                                       |
S-301E |                 VAP                 | S-302
------> |                                    |------>
 327.3 |                                     |  80.0
     |                                       |
S-327  |                LIQ                  | S-326
<------ |                                    |<------
  75.0 |                                     |  65.0
     |                                       |
```

```
    ----------------------------------------------------------
                         COLD

 ZONE HEAT TRANSFER AND AREA:

 ZONE      HEAT DUTY      AREA      LMTD      AVERAGE U      UA
        BTU/HR        SQFT       F        BTU/HR-SQFT-R   BTU/HR-R
   1    7904000.000      628.4606     84.0167   149.6937      94076.5611

BLOCK:  P301C    MODEL: PUMP
----------------------------
 INLET STREAM:         S-325
 OUTLET STREAM:        S-326
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

             ***  MASS AND ENERGY BALANCE  ***
                     IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          44129.2        44129.2        0.00000
    MASS(LB/HR   )          795000.        795000.        0.00000
    ENTHALPY(BTU/HR  )      -0.543218E+10   -0.543217E+10   -0.286889E-05

             ***  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  ***
  EQUIPMENT TYPE: PUMP
  OUTLET PRESSURE  PSIA                        20.0000
  DRIVER EFFICIENCY                            1.00000
  HYDRAULIC STATIC HEAD  FT-LBF/LB                   50.0000

  FLASH SPECIFICATIONS:
  LIQUID PHASE CALCULATION
  NO FLASH PERFORMED
  MAXIMUM NUMBER OF ITERATIONS                       30
  TOLERANCE                                0.000100000
```

*** RESULTS ***

VOLUMETRIC FLOW RATE CUFT/HR	12,751.8
PRESSURE CHANGE PSI	5.30000
NPSH AVAILABLE FT-LBF/LB	83.4458
FLUID POWER HP	4.91523
BRAKE POWER HP	6.12488
ELECTRICITY KW	4.56732
PUMP EFFICIENCY USED	0.80250
NET WORK REQUIRED HP	6.12488
HEAD DEVELOPED FT-LBF/LB	12.2417

S-301E S-302 S-325 S-326 S-327

STREAM ID	S-301E	S-302	S-325	S-326	S-327
FROM :	----	HX301C	----	P301C	HX301C
TO :	HX301C	----	P301C	HX301C	----
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	LIQUID	LIQUID	LIQUID
COMPONENTS: LBMOL/HR					
ETHYLENE	485.4964	485.4964	0.0	0.0	0.0
OXYGEN	1611.3104	1611.3104	0.0	0.0	0.0
NITROGEN	575.4373	575.4373	0.0	0.0	0.0
CO2	970.9201	970.9201	0.0	0.0	0.0
WATER	0.0	0.0	4.4129+04	4.4129+04	4.4129+04
TOTAL FLOW:					
LBMOL/HR	3643.1642	3643.1642	4.4129+04	4.4129+04	4.4129+04
LB/HR	1.2403+05	1.2403+05	7.9500+05	7.9500+05	7.9500+05
CUFT/HR	1.0068+05	6.7806+04	1.2752+04	1.2752+04	1.2767+04
STATE VARIABLES:					
TEMP F	327.3000	79.9687	65.0000	65.0047	74.9868
PRES PSIA	304.6000	299.6000	14.7000	20.0000	15.0000
VFRAC	1.0000	1.0000	0.0	0.0	0.0
LFRAC	0.0	0.0	1.0000	1.0000	1.0000
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-4.0047+04	-4.2217+04	-1.2310+05	-1.2310+05	-1.2292+05
BTU/LB	-1176.3249	-1240.0514	-6832.9367	-6832.9171	-6822.9750

BTU/HR	-1.4590+08	-1.5380+08	-5.4322+09	-5.4322+09	-5.4243+09
ENTROPY:					
BTU/LBMOL-R	-1.8874	-5.1578	-39.3720	-39.3720	-39.0333
BTU/LB-R	-5.5438-02	-0.1515	-2.1855	-2.1855	-2.1667
DENSITY:					
LBMOL/CUFT	3.6186-02	5.3729-02	3.4606	3.4607	3.4564
LB/CUFT	1.2320	1.8292	62.3443	62.3453	62.2688
AVG MW	34.0446	34.0446	18.0153	18.0153	18.0153

ASPEN Block and Stream Diagrams for Section 400

```
BLOCK:  MHX     MODEL: MHEATX
 ------------------------------

   HOT SIDE:    INLET STREAM     OUTLET STREAM
                ------------     -------------
                N2IN             14

   COLD SIDE:   INLET STREAM     OUTLET STREAM
                ------------     -------------
                19               20
                13               CO2
                11               PRODUCT
                22               O2N2

   PROPERTIES FOR STREAM N2IN
   PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

   PROPERTIES FOR STREAM 13
   PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

   PROPERTIES FOR STREAM 11
   PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

   PROPERTIES FOR STREAM 22
   PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

   PROPERTIES FOR STREAM 19
   PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                        IN            OUT       RELATIVE DIFF.
    TOTAL BALANCE
      MOLE(LBMOL/HR)          408013.        408013.       0.620500E-08
      MASS(LB/HR   )       0.114518E+08   0.114518E+08    0.619311E-08
      ENTHALPY(BTU/HR  )   -0.717092E+09  -0.717092E+09  -0.477715E-10
```

```
          ***  CO2 EQUIVALENT SUMMARY ***
 FEED STREAMS CO2E            42663.5      LB/HR
 PRODUCT STREAMS CO2E          42663.5      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  ***


SPECIFICATIONS FOR STREAM N2IN    :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE             F                -180.000
PRESSURE DROP                 PSI                0.0
MAXIMUM NO. ITERATIONS                               30
CONVERGENCE TOLERANCE                                  0.000100000

SPECIFICATIONS FOR STREAM 13      :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE             F                 70.0000
PRESSURE DROP                 PSI                0.0
MAXIMUM NO. ITERATIONS                               30
CONVERGENCE TOLERANCE                                  0.000100000

SPECIFICATIONS FOR STREAM 11      :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE             F                 70.0000
PRESSURE DROP                 PSI                0.0
MAXIMUM NO. ITERATIONS                               30
CONVERGENCE TOLERANCE                                  0.000100000

SPECIFICATIONS FOR STREAM 22      :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE             F                 70.0000
PRESSURE DROP                 PSI                0.0
MAXIMUM NO. ITERATIONS                               30
CONVERGENCE TOLERANCE                                  0.000100000

SPECIFICATIONS FOR STREAM 19      :
TWO    PHASE      FLASH
```

```
PRESSURE DROP              PSI              0.0
MAXIMUM NO. ITERATIONS                           30
CONVERGENCE TOLERANCE                              0.000100000

            ***  RESULTS  ***

INLET               OUTLET      OUTLET      OUTLET
STREAM    DUTY       TEMPERATURE  PRESSURE    VAPOR FRAC
      BTU/HR      F          PSIA

N2IN     -0.56474E+09   -180.00     1215.0       1.0000
13       0.31787E+07    70.00     20.000       1.0000
11       0.49926E+06    70.00     200.00       1.0000
22       0.53333E+07    70.00     20.000       1.0000
19       0.55573E+09    86.82     290.00       1.0000


       -----------------------------------------
       |                          |
N2IN    |                          | 14
--------->|       0.20218E+06 LBMOL/HR        |--------->
  100.00 |                          |  -180.00
       |                          |
CO2     |                          | 13
<---------|        970.77    LBMOL/HR        |<---------
   70.00 |                          |  -117.23
       |                          |
PRODUCT  |                          | 11
<---------|        484.93    LBMOL/HR        |<---------
   70.00 |                          |   -23.49
       |                          |
O2N2    |                          | 22
<---------|        2187.9    LBMOL/HR        |<---------
   70.00 |                          |  -277.05
       |                          |
20      |                          | 19
<---------|       0.20218E+06 LBMOL/HR        |<---------
   86.82 |                          |  -251.98
       |                          |
       -----------------------------------------
```

```
BLOCK:  MHX     MODEL: MHEATX
------------------------------

 HOT SIDE:    INLET STREAM     OUTLET STREAM
              ------------     -------------
              N2IN             14

 COLD SIDE:   INLET STREAM     OUTLET STREAM
              ------------     -------------
              19               20
              13               CO2
              11               PRODUCT
              22               O2N2

 PROPERTIES FOR STREAM N2IN
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 13
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 11
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 22
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 19
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                       IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          408013.       408013.       0.620500E-08
    MASS(LB/HR   )       0.114518E+08   0.114518E+08   0.619311E-08
    ENTHALPY(BTU/HR  )     -0.717092E+09   -0.717092E+09   -0.477715E-10

              ***  CO2 EQUIVALENT SUMMARY ***
```

FEED STREAMS CO2E 42663.5 LB/HR
PRODUCT STREAMS CO2E 42663.5 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 ***

SPECIFICATIONS FOR STREAM N2IN :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F -180.000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 13 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 70.0000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 11 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 70.0000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 22 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 70.0000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 19 :
TWO PHASE FLASH
PRESSURE DROP PSI 0.0

MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
N2IN	-0.56474E+09	-180.00	1215.0	1.0000
13	0.31787E+07	70.00	20.000	1.0000
11	0.49926E+06	70.00	200.00	1.0000
22	0.53333E+07	70.00	20.000	1.0000
19	0.55573E+09	86.82	290.00	1.0000

```
       ----------------------------------------
       |                          |
N2IN   |                          | 14
--------->|   0.20218E+06 LBMOL/HR   |--------->
 100.00 |                          |  -180.00
       |                          |
CO2    |                          | 13
<---------|   970.77   LBMOL/HR      |<---------
  70.00 |                          |  -117.23
       |                          |
PRODUCT |                         | 11
<---------|   484.93   LBMOL/HR      |<---------
  70.00 |                          |  -23.49
       |                          |
O2N2   |                          | 22
<---------|   2187.9   LBMOL/HR      |<---------
  70.00 |                          |  -277.05
       |                          |
20     |                          | 19
<---------|   0.20218E+06 LBMOL/HR   |<---------
  86.82 |                          |  -251.98
       |                          |
       ----------------------------------------
```

```
BLOCK:  MHX     MODEL: MHEATX
------------------------------

 HOT SIDE:    INLET STREAM     OUTLET STREAM
              ------------     -------------
              N2IN             14

 COLD SIDE:   INLET STREAM     OUTLET STREAM
              ------------     -------------
              19               20
              13               CO2
              11               PRODUCT
              22               O2N2

 PROPERTIES FOR STREAM N2IN
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 13
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 11
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 22
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 19
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                         IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          408013.       408013.       0.620500E-08
    MASS(LB/HR   )       0.114518E+08   0.114518E+08   0.619311E-08
    ENTHALPY(BTU/HR  )     -0.717092E+09  -0.717092E+09  -0.477715E-10

              ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            42663.5     LB/HR
```

```
 PRODUCT STREAMS CO2E         42663.5      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  ***


 SPECIFICATIONS FOR STREAM N2IN    :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE             F                  -180.000
 PRESSURE DROP                  PSI                0.0
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                                   0.000100000

 SPECIFICATIONS FOR STREAM 13      :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE             F                    70.0000
 PRESSURE DROP                  PSI                0.0
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                                   0.000100000

 SPECIFICATIONS FOR STREAM 11      :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE             F                    70.0000
 PRESSURE DROP                  PSI                0.0
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                                   0.000100000

 SPECIFICATIONS FOR STREAM 22      :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE             F                    70.0000
 PRESSURE DROP                  PSI                0.0
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                                   0.000100000

 SPECIFICATIONS FOR STREAM 19      :
 TWO    PHASE      FLASH
 PRESSURE DROP                  PSI                0.0
 MAXIMUM NO. ITERATIONS                                30
```

CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
N2IN	-0.56474E+09	-180.00	1215.0	1.0000
13	0.31787E+07	70.00	20.000	1.0000
11	0.49926E+06	70.00	200.00	1.0000
22	0.53333E+07	70.00	20.000	1.0000
19	0.55573E+09	86.82	290.00	1.0000

```
        -----------------------------------------
        |                              |
 N2IN   |                              | 14
 --------->|   0.20218E+06 LBMOL/HR    |--------->
   100.00 |                            | -180.00
        |                              |
 CO2    |                              | 13
 <---------|   970.77   LBMOL/HR       |<---------
    70.00 |                            | -117.23
        |                              |
 PRODUCT |                             | 11
 <---------|   484.93   LBMOL/HR       |<---------
    70.00 |                            |  -23.49
        |                              |
 O2N2   |                              | 22
 <---------|   2187.9   LBMOL/HR       |<---------
    70.00 |                            | -277.05
        |                              |
 20     |                              | 19
 <---------|   0.20218E+06 LBMOL/HR    |<---------
    86.82 |                            | -251.98
        |                              |
        -----------------------------------------
```

```
BLOCK:  MHX     MODEL: MHEATX
------------------------------

 HOT SIDE:   INLET STREAM    OUTLET STREAM
             ------------    -------------
             N2IN            14

 COLD SIDE:  INLET STREAM    OUTLET STREAM
             ------------    -------------
             19              20
             13              CO2
             11              PRODUCT
             22              O2N2

 PROPERTIES FOR STREAM N2IN
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 13
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 11
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 22
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 19
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                            IN           OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          408013.      408013.      0.620500E-08
    MASS(LB/HR  )        0.114518E+08   0.114518E+08   0.619311E-08
    ENTHALPY(BTU/HR  )     -0.717092E+09  -0.717092E+09  -0.477715E-10

                  ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E           42663.5      LB/HR
  PRODUCT STREAMS CO2E        42663.5      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  ***


SPECIFICATIONS FOR STREAM N2IN    :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE           F              -180.000
PRESSURE DROP               PSI              0.0
MAXIMUM NO. ITERATIONS                         30
CONVERGENCE TOLERANCE                            0.000100000

SPECIFICATIONS FOR STREAM 13      :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE           F               70.0000
PRESSURE DROP               PSI              0.0
MAXIMUM NO. ITERATIONS                         30
CONVERGENCE TOLERANCE                            0.000100000

SPECIFICATIONS FOR STREAM 11      :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE           F               70.0000
PRESSURE DROP               PSI              0.0
MAXIMUM NO. ITERATIONS                         30
CONVERGENCE TOLERANCE                            0.000100000

SPECIFICATIONS FOR STREAM 22      :
TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE           F               70.0000
PRESSURE DROP               PSI              0.0
MAXIMUM NO. ITERATIONS                         30
CONVERGENCE TOLERANCE                            0.000100000

SPECIFICATIONS FOR STREAM 19      :
TWO    PHASE      FLASH
PRESSURE DROP               PSI              0.0
MAXIMUM NO. ITERATIONS                         30
CONVERGENCE TOLERANCE                            0.000100000
```

*** RESULTS ***

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
N2IN	-0.56474E+09	-180.00	1215.0	1.0000
13	0.31787E+07	70.00	20.000	1.0000
11	0.49926E+06	70.00	200.00	1.0000
22	0.53333E+07	70.00	20.000	1.0000
19	0.55573E+09	86.82	290.00	1.0000

```
         ----------------------------------------
         |                          |
 N2IN    |                          | 14
--------->|   0.20218E+06 LBMOL/HR       |--------->
  100.00 |                          |  -180.00
         |                          |
 CO2     |                          | 13
<---------|    970.77    LBMOL/HR       |<---------
   70.00 |                          |  -117.23
         |                          |
 PRODUCT |                          | 11
<---------|    484.93    LBMOL/HR       |<---------
   70.00 |                          |   -23.49
         |                          |
 O2N2    |                          | 22
<---------|    2187.9    LBMOL/HR       |<---------
   70.00 |                          |  -277.05
         |                          |
 20      |                          | 19
<---------|   0.20218E+06 LBMOL/HR       |<---------
   86.82 |                          |  -251.98
         |                          |
         ----------------------------------------
```

```
BLOCK:  MHX     MODEL: MHEATX
------------------------------

 HOT SIDE:    INLET STREAM     OUTLET STREAM
              ------------     -------------
              N2IN             14

 COLD SIDE:   INLET STREAM     OUTLET STREAM
              ------------     -------------
              19               20
              13               CO2
              11               PRODUCT
              22               O2N2

 PROPERTIES FOR STREAM N2IN
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 13
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 11
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 22
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

 PROPERTIES FOR STREAM 19
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

             ***  MASS AND ENERGY BALANCE  ***
                         IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          408013.        408013.       0.620500E-08
    MASS(LB/HR   )        0.114518E+08   0.114518E+08   0.619311E-08
    ENTHALPY(BTU/HR  )     -0.717092E+09  -0.717092E+09  -0.477715E-10

             ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            42663.5      LB/HR
  PRODUCT STREAMS CO2E          42663.5      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 ***

SPECIFICATIONS FOR STREAM N2IN :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F -180.000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 13 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 70.0000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 11 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 70.0000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 22 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 70.0000
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 19 :
TWO PHASE FLASH
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
N2IN	-0.56474E+09	-180.00	1215.0	1.0000
13	0.31787E+07	70.00	20.000	1.0000
11	0.49926E+06	70.00	200.00	1.0000
22	0.53333E+07	70.00	20.000	1.0000
19	0.55573E+09	86.82	290.00	1.0000

```
        ----------------------------------------
        |                          |
 N2IN   |                          | 14
--------->|   0.20218E+06 LBMOL/HR   |--------->
  100.00 |                          |  -180.00
        |                          |
 CO2    |                          | 13
<---------|    970.77   LBMOL/HR    |<---------
   70.00 |                          |  -117.23
        |                          |
 PRODUCT |                         | 11
<---------|    484.93   LBMOL/HR    |<---------
   70.00 |                          |   -23.49
        |                          |
 O2N2   |                          | 22
<---------|    2187.9   LBMOL/HR    |<---------
   70.00 |                          |  -277.05
        |                          |
 20     |                          | 19
<---------|   0.20218E+06 LBMOL/HR   |<---------
   86.82 |                          |  -251.98
        |                          |
        ----------------------------------------
```

BLOCK: B1 MODEL: MCOMPR

INLET STREAMS: 401 TO STAGE 1
OUTLET STREAMS: 3 FROM STAGE 3
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	3643.58	3643.58	0.00000
MASS(LB/HR)	124022.	124022.	0.00000
ENTHALPY(BTU/HR)	-0.152635E+09	-0.152907E+09	0.177849E-02

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 42663.5 LB/HR
PRODUCT STREAMS CO2E 42663.5 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 CENTRIFUGAL COMPRESSOR
NUMBER OF STAGES 3
FINAL PRESSURE, PSIA 305.000

COMPRESSOR SPECIFICATIONS PER STAGE

STAGE NUMBER	MECHANICAL EFFICIENCY	ISENTROPIC EFFICIENCY
1	1.000	0.7200
2	1.000	0.7200
3	1.000	0.7200

COOLER SPECIFICATIONS PER STAGE

STAGE PRESSURE DROP TEMPERATURE
NUMBER PSI F

1	5.000	100.0
2	5.000	100.0
3	5.000	100.0

*** RESULTS ***

FINAL PRESSURE, PSIA	300.000
TOTAL WORK REQUIRED, HP	8,032.51
TOTAL COOLING DUTY , BTU/HR	-0.207101+08

*** PROFILE ***

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE PSIA	PRESSURE RATIO	OUTLET TEMPERATURE F
1	40.39	2.748	299.2
2	111.0	3.136	340.1
3	305.0	2.878	321.1

STAGE NUMBER	INDICATED HORSEPOWER HP	BRAKE HORSEPOWER HP
1	2491.	2491.
2	2902.	2902.
3	2640.	2640.

STAGE NUMBER	HEAD DEVELOPED FT-LBF/LB	VOLUMETRIC FLOW CUFT/HR
1	0.2863E+05	0.1464E+07
2	0.3335E+05	0.6161E+06
3	0.3035E+05	0.2041E+06

COOLER PROFILE

STAGE OUTLET OUTLET COOLING VAPOR
NUMBER TEMPERATURE PRESSURE LOAD FRACTION

	F	PSIA	BTU/HR	
1	100.0	35.39	-.6123E+07	1.000
2	100.0	106.0	-.7511E+07	1.000
3	100.0	300.0	-.7076E+07	1.000

BLOCK: B4 MODEL: MCOMPR

INLET STREAMS: 20 TO STAGE 1
OUTLET STREAMS: N2REC FROM STAGE 3
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	202185.	202185.	0.00000
MASS(LB/HR)	0.566390E+07	0.566390E+07	0.00000
ENTHALPY(BTU/HR)	0.378774E+07	-0.273576E+07	1.72227

*** 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 ***

ISENTROPIC CENTRIFUGAL COMPRESSOR
NUMBER OF STAGES 3
FINAL PRESSURE, PSIA 1,215.00

COMPRESSOR SPECIFICATIONS PER STAGE

STAGE NUMBER	MECHANICAL EFFICIENCY	ISENTROPIC EFFICIENCY
1	1.000	0.7200
2	1.000	0.7200

3	1.000	0.7200

COOLER SPECIFICATIONS PER STAGE

STAGE NUMBER	PRESSURE DROP PSI	TEMPERATURE F
1	0.000	100.0
2	0.000	100.0
3	0.000	100.0

*** RESULTS ***

FINAL PRESSURE, PSIA	1,215.00
TOTAL WORK REQUIRED, HP	189,119.
TOTAL COOLING DUTY , BTU/HR	-0.487724+09

*** PROFILE ***

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE PSIA	PRESSURE RATIO	OUTLET TEMPERATURE F
1	467.5	1.612	197.4
2	753.7	1.612	213.2
3	1215.	1.612	212.8

STAGE NUMBER	INDICATED HORSEPOWER HP	BRAKE HORSEPOWER HP
1	0.6162E+05	0.6162E+05
2	0.6346E+05	0.6346E+05
3	0.6404E+05	0.6404E+05

STAGE NUMBER	HEAD DEVELOPED FT-LBF/LB	VOLUMETRIC FLOW CUFT/HR
1	0.1551E+05	0.4092E+07

```
  2     0.1597E+05    0.2607E+07
  3     0.1612E+05    0.1624E+07

                COOLER PROFILE

 STAGE     OUTLET        OUTLET      COOLING     VAPOR
 NUMBER    TEMPERATURE     PRESSURE    LOAD       FRACTION
        F            PSIA       BTU/HR

  1       100.0        467.5      -.1431E+09   1.000
  2       100.0        753.7      -.1697E+09   1.000
  3       100.0        1215.      -.1749E+09   1.000

BLOCK:  COND     MODEL: HEATER
------------------------------
 INLET STREAM:        16
 OUTLET STREAM:        17
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                       IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          11628.7        11628.7        0.00000
    MASS(LB/HR   )          325761.        325761.        0.00000
    ENTHALPY(BTU/HR  )     -0.472309E+08   -0.316961E+08   -0.328912

              ***  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  ***
 TWO    PHASE  PV  FLASH
 PRESSURE DROP                 PSI                  5.00000
 VAPOR FRACTION                                    1.00000
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                              0.000100000
```

```
           ***  RESULTS  ***
 OUTLET TEMPERATURE    F                     -251.99
 OUTLET PRESSURE       PSIA                  290.00
 HEAT DUTY             BTU/HR              0.15535E+08
 OUTLET VAPOR FRACTION                         1.0000
 PRESSURE-DROP CORRELATION PARAMETER                 3161.1



 V-L PHASE EQUILIBRIUM :

   COMP          F(I)        X(I)        Y(I)        K(I)
   N2          1.0000      1.0000      1.0000      1.0000

BLOCK:  FLASH    MODEL: FLASH2
------------------------------
 INLET STREAM:         15
 OUTLET VAPOR STREAM:   18
 OUTLET LIQUID STREAM:  16
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

            ***  MASS AND ENERGY BALANCE  ***
                        IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          202185.       202185.       0.00000
    MASS(LB/HR  )        0.566390E+07   0.566390E+07    0.00000
    ENTHALPY(BTU/HR  )     -0.567480E+09  -0.567480E+09  -0.210068E-15

            ***  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  ***
 TWO    PHASE  PQ  FLASH
 PRESSURE DROP        PSI                    5.00000
```

```
SPECIFIED HEAT DUTY   BTU/HR                    0.0
MAXIMUM NO. ITERATIONS                        30
CONVERGENCE TOLERANCE                           0.000100000

              ***  RESULTS  ***
OUTLET TEMPERATURE    F                       -251.41
OUTLET PRESSURE       PSIA                    295.00
VAPOR FRACTION                              0.94248



V-L PHASE EQUILIBRIUM :

  COMP          F(I)        X(I)        Y(I)        K(I)
  N2           1.0000      1.0000      1.0000      1.0000

BLOCK:  HX1      MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:         3
 OUTLET STREAM:        4
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE
 COLD SIDE:
 ----------
 INLET STREAM:         9
 OUTLET STREAM:        12
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

            ***  MASS AND ENERGY BALANCE  ***
                      IN          OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          4614.35        4614.35        0.00000
    MASS(LB/HR   )       166685.       166685.        0.00000
    ENTHALPY(BTU/HR  )     -0.323262E+09   -0.323262E+09   -0.184385E-15

            ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E           85221.6      LB/HR
  PRODUCT STREAMS CO2E         85221.6      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 -15.0000
LMTD CORRECTION FACTOR 1.00000

PRESSURE SPECIFICATION:
HOT SIDE PRESSURE DROP PSI 0.0000
COLD SIDE PRESSURE DROP PSI 0.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:

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

*** OVERALL RESULTS ***

STREAMS:

```
            |                            |
3       ----->|            HOT             |-----> 4
T=  1.0000D+02  |                            |     T= -1.5000D+01
P=  3.0000D+02  |                            |     P=  3.0000D+02
V=  1.0000D+00  |                            |     V=  1.0000D+00
            |                            |
12      <-----|            COLD            |<----- 9
T= -2.1196D+01  |                            |     T= -2.1227D+01
P=  2.1096D+02  |                            |     P=  2.1096D+02
V=  6.3457D-01  |                            |     V=  0.0000D+00
            --------------------------------------

DUTY AND AREA:
 CALCULATED HEAT DUTY         BTU/HR          3579080.9286
 CALCULATED (REQUIRED) AREA    SQFT               617.3451
 ACTUAL EXCHANGER AREA        SQFT               617.3451
 PER CENT OVER-DESIGN                              0.0000

HEAT TRANSFER COEFFICIENT:
 AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R        149.6937
 UA (DIRTY)                 BTU/HR-R          92412.6384

LOG-MEAN TEMPERATURE DIFFERENCE:
 LMTD CORRECTION FACTOR                           1.0000
 LMTD (CORRECTED)            F                 38.7293
 NUMBER OF SHELLS IN SERIES                         1

PRESSURE DROP:
 HOTSIDE, TOTAL             PSI                0.0000
 COLDSIDE, TOTAL            PSI                0.0000

PRESSURE DROP PARAMETER:
 HOT SIDE:                              0.0000
 COLD SIDE:                             0.0000

                 ***  ZONE RESULTS  ***

TEMPERATURE LEAVING EACH ZONE:

                      HOT
```

```
      -----------------------------------------------------------
      |                                       |
3     |                 VAP                   | 4
------> |                                     |------>
 100.0 |                                      |  -15.0
      |                                       |
12    |                 BOIL                  | 9
<------ |                                     |<------
 -21.2 |                                      |  -21.2
      |                                       |
      -----------------------------------------------------------
                        COLD

 ZONE HEAT TRANSFER AND AREA:

 ZONE      HEAT DUTY      AREA      LMTD      AVERAGE U      UA
           BTU/HR         SQFT       F        BTU/HR-SQFT-R   BTU/HR-R
   1    3579080.929     617.3451    38.7293   149.6937      92412.6384

BLOCK:  HX2      MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:          4
 OUTLET STREAM:         5
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE
 COLD SIDE:
 ----------
 INLET STREAM:          10
 OUTLET STREAM:         11
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                     IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)         4128.51       4128.51       0.00000
    MASS(LB/HR   )         137664.       137664.       0.00000
    ENTHALPY(BTU/HR  )     -0.146776E+09   -0.146776E+09    0.00000

              ***  CO2 EQUIVALENT SUMMARY ***
```

```
FEED STREAMS CO2E              42766.8   LB/HR
PRODUCT STREAMS CO2E           42766.8   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 MIN OUTLET TEMP APPR
  SPECIFIED VALUE           F            5.0000
  LMTD CORRECTION FACTOR                  1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE PRESSURE DROP      PSI          0.0000
  COLD SIDE PRESSURE DROP      PSI          0.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  HOT LIQUID    COLD LIQUID    BTU/HR-SQFT-R      149.6937
  HOT 2-PHASE   COLD LIQUID    BTU/HR-SQFT-R      149.6937
  HOT VAPOR     COLD LIQUID    BTU/HR-SQFT-R      149.6937
  HOT LIQUID    COLD 2-PHASE   BTU/HR-SQFT-R      149.6937
  HOT 2-PHASE   COLD 2-PHASE   BTU/HR-SQFT-R      149.6937
  HOT VAPOR     COLD 2-PHASE   BTU/HR-SQFT-R      149.6937
  HOT LIQUID    COLD VAPOR     BTU/HR-SQFT-R      149.6937
  HOT 2-PHASE   COLD VAPOR     BTU/HR-SQFT-R      149.6937
  HOT VAPOR     COLD VAPOR     BTU/HR-SQFT-R      149.6937

           ***  OVERALL RESULTS  ***
```

```
STREAMS:
           -------------------------------------
           |                        |
4       ----->|           HOT           |-----> 5
T= -1.5000D+01  |                        |     T= -1.8475D+01
P=  3.0000D+02  |                        |     P=  3.0000D+02
V=  1.0000D+00  |                        |     V=  1.0000D+00
           |                        |
11      <-----|           COLD          |<----- 10
T= -2.3487D+01  |                        |     T= -4.3503D+01
P=  2.0000D+02  |                        |     P=  2.0000D+02
V=  1.0000D+00  |                        |     V=  1.0000D+00
           -------------------------------------

DUTY AND AREA:
 CALCULATED HEAT DUTY          BTU/HR          109169.3245
 CALCULATED (REQUIRED) AREA    SQFT                47.6809
 ACTUAL EXCHANGER AREA         SQFT                47.6809
 PER CENT OVER-DESIGN                               0.0000

HEAT TRANSFER COEFFICIENT:
 AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R      149.6937
 UA (DIRTY)                    BTU/HR-R          7137.5351

LOG-MEAN TEMPERATURE DIFFERENCE:
 LMTD CORRECTION FACTOR                             1.0000
 LMTD (CORRECTED)              F                   15.2951
 NUMBER OF SHELLS IN SERIES                              1

PRESSURE DROP:
 HOTSIDE, TOTAL                PSI                  0.0000
 COLDSIDE, TOTAL               PSI                  0.0000

PRESSURE DROP PARAMETER:
 HOT SIDE:                                          0.0000
 COLD SIDE:                                         0.0000

              ***  ZONE RESULTS  ***
```

```
 TEMPERATURE LEAVING EACH ZONE:

                    HOT
     -------------------------------------------------------------
     |                                       |
4     |                 VAP                  | 5
------> |                                    |------>
 -15.0  |                                    |  -18.5
     |                                       |
11    |                 VAP                  | 10
<------ |                                    |<------
 -23.5  |                                    |  -43.5
     |                                       |
     -------------------------------------------------------------
                    COLD

 ZONE HEAT TRANSFER AND AREA:

 ZONE      HEAT DUTY      AREA      LMTD      AVERAGE U      UA
        BTU/HR        SQFT       F       BTU/HR-SQFT-R   BTU/HR-R
   1    109169.324       47.6809     15.2951   149.6937       7137.5351

BLOCK:  MIX      MODEL: MIXER
-----------------------------
 INLET STREAMS:        17         18
 OUTLET STREAM:        19
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                      IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          202185.        202185.        0.00000
    MASS(LB/HR   )         0.566390E+07    0.566390E+07     0.00000
    ENTHALPY(BTU/HR  )      -0.551945E+09   -0.551945E+09     0.00000

              ***  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 ***
TWO PHASE FLASH
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000
OUTLET PRESSURE: MINIMUM OF INLET STREAM PRESSURES

BLOCK: TOW1 MODEL: RADFRAC

INLETS - 5 STAGE 4
OUTLETS - 6 STAGE 1
7 STAGE 8
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

****
* *
* FEED PRESSURE IS LOWER THAN STAGE PRESSURE. *
* *
****

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	3643.58	3643.58	-0.124808E-15
MASS(LB/HR)	124022.	124022.	-0.430028E-12
ENTHALPY(BTU/HR)	-0.156595E+09	-0.167431E+09	0.647193E-01

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E 42663.5 LB/HR
PRODUCT STREAMS CO2E 42663.5 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  ****
               *********************

****   INPUT PARAMETERS   ****

 NUMBER OF STAGES                              8
 ALGORITHM OPTION                              STANDARD
 ABSORBER OPTION                               NO
 INITIALIZATION OPTION                         STANDARD
 HYDRAULIC PARAMETER CALCULATIONS              NO
 INSIDE LOOP CONVERGENCE METHOD                BROYDEN
 DESIGN SPECIFICATION METHOD                   NESTED
 MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS        25
 MAXIMUM NO. OF INSIDE LOOP ITERATIONS         10
 MAXIMUM NUMBER OF FLASH ITERATIONS            30
 FLASH TOLERANCE                               0.000100000
 OUTSIDE LOOP CONVERGENCE TOLERANCE            0.000100000

****   COL-SPECS   ****

 MOLAR VAPOR DIST / TOTAL DIST                 1.00000
 MOLAR REFLUX RATIO                            3.20000
 MASS DISTILLATE RATE          LB/HR           67,715.8

****    PROFILES   ****

 P-SPEC        STAGE   1  PRES, PSIA           300.000

               ******************
               ****  RESULTS  ****
               ******************


***   COMPONENT SPLIT FRACTIONS   ***

                  OUTLET STREAMS
                  --------------
           6          7
 COMPONENT:
 N2        1.0000      .24646E-05
```

CO2	.46270E-04	.99995
O2	.99986	.13716E-03
C2H4	.37694E-03	.99962

*** SUMMARY OF KEY RESULTS ***

TOP STAGE TEMPERATURE	F	-226.948
BOTTOM STAGE TEMPERATURE	F	-8.44568
TOP STAGE LIQUID FLOW	LBMOL/HR	7,001.23
BOTTOM STAGE LIQUID FLOW	LBMOL/HR	1,455.70
TOP STAGE VAPOR FLOW	LBMOL/HR	2,187.89
BOILUP VAPOR FLOW	LBMOL/HR	994.409
MOLAR REFLUX RATIO		3.20000
MOLAR BOILUP RATIO		0.68312
CONDENSER DUTY (W/O SUBCOOL)	BTU/HR	-0.155337+08
REBOILER DUTY	BTU/HR	4,697,700.

**** MAXIMUM FINAL RELATIVE ERRORS ****

DEW POINT	0.23665E-03	STAGE= 2
BUBBLE POINT	0.31182E-04	STAGE= 2
COMPONENT MASS BALANCE	0.15991E-05	STAGE= 8 COMP=N2
ENERGY BALANCE	0.74749E-05	STAGE= 4

**** PROFILES ****

NOTE REPORTED VALUES FOR STAGE LIQUID AND VAPOR RATES ARE THE FLOWS FROM THE STAGE INCLUDING ANY SIDE PRODUCT.

STAGE	TEMPERATURE F	PRESSURE PSIA	ENTHALPY BTU/LBMOL LIQUID	ENTHALPY BTU/LBMOL VAPOR	HEAT DUTY BTU/HR
1	-226.95	300.00	-4605.3	-2492.9	-.15534+08
2	-205.28	303.00	-46004.	-2411.9	
3	-85.049	303.12	-0.10037E+06	-22043.	
4	-33.922	303.24	-0.10273E+06	-61155.	
5	-15.807	303.36	-0.10426E+06	-81772.	

7	-9.2168	303.60	-0.10717E+06	-91944.	
8	-8.4457	303.72	-0.11127E+06	-96455.	.46977+07

STAGE	FLOW RATE LBMOL/HR		FEED RATE LBMOL/HR			PRODUCT RATE LBMOL/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	7001.	2188.			2187.8857		
2	2433.	9189.					
3	1980.	4621.	3643.5826				
4	2273.	524.4					
5	2407.	817.4					
7	2450.	989.9					
8	1456.	994.4			1455.6968		

**** MASS FLOW PROFILES ****

STAGE	FLOW RATE LB/HR		FEED RATE LB/HR			PRODUCT RATE LB/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.2196E+06	0.6772E+05				.67716+05	
2	0.8290E+05	0.2873E+06					
3	0.7488E+05	0.1506E+06		.12402+06			
4	0.8637E+05	0.1857E+05					
5	0.9174E+05	0.3007E+05					
7	0.9394E+05	0.3710E+05					
8	0.5631E+05	0.3763E+05			.56306+05		

**** MOLE-X-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.15956	0.16558E-02	0.83412	0.46689E-02
2	0.30729E-01	0.26410	0.45647	0.24870
3	0.74008E-02	0.59394	0.72221E-01	0.32644
4	0.16112E-02	0.61587	0.29679E-01	0.35284
5	0.27823E-03	0.62789	0.90432E-02	0.36279
7	0.69145E-05	0.64459	0.65726E-03	0.35475
8	0.97442E-06	0.66591	0.15192E-03	0.33394

**** MOLE-Y-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.26306	0.20501E-04	0.73684	0.83782E-04

2	0.18420	0.12664E-02	0.81096	0.35772E-02
3	0.14072	0.13907	0.58921	0.13100
4	0.27942E-01	0.39417	0.27228	0.30561
5	0.44787E-02	0.52675	0.82261E-01	0.38651
7	0.10885E-03	0.58926	0.59625E-02	0.40467
8	0.15610E-04	0.61337	0.13970E-02	0.38522

**** K-VALUES ****

STAGE	N2	CO2	O2	C2H4
1	1.6487	0.12382E-01	0.88338	0.17945E-01
2	5.9946	0.47929E-02	1.7765	0.14378E-01
3	19.015	0.23415	8.1586	0.40130
4	17.341	0.64003	9.1733	0.86613
5	16.096	0.83892	9.0962	1.0654
7	15.742	0.91417	9.0717	1.1407
8	16.020	0.92110	9.1955	1.1536

**** MASS-X-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.14251	0.23233E-02	0.85099	0.41761E-02
2	0.25268E-01	0.34117	0.42876	0.20480
3	0.54825E-02	0.69124	0.61112E-01	0.24217
4	0.11878E-02	0.71331	0.24994E-01	0.26051
5	0.20453E-03	0.72513	0.75934E-02	0.26707
7	0.50519E-05	0.73988	0.54853E-03	0.25956
8	0.70572E-06	0.75767	0.12568E-03	0.24220

**** MASS-Y-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.23809	0.29152E-04	0.76180	0.75941E-04
2	0.16504	0.17826E-02	0.82997	0.32097E-02
3	0.12095	0.18780	0.57849	0.11276
4	0.22102E-01	0.48981	0.24601	0.24208
5	0.34109E-02	0.63024	0.71562E-01	0.29478
7	0.81355E-04	0.69193	0.50906E-02	0.30290
8	0.11554E-04	0.71326	0.11812E-02	0.28555

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********************************
***** HYDRAULIC PARAMETERS *****
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*** DEFINITIONS ***

MARANGONI INDEX = SIGMA - SIGMATO
FLOW PARAM = (ML/MV)*SQRT(RHOV/RHOL)
QR = QV*SQRT(RHOV/(RHOL-RHOV))
F FACTOR = QV*SQRT(RHOV)
 WHERE:
 SIGMA IS THE SURFACE TENSION OF LIQUID FROM THE STAGE
 SIGMATO IS THE SURFACE TENSION OF LIQUID TO THE STAGE
 ML IS THE MASS FLOW OF LIQUID FROM THE STAGE
 MV IS THE MASS FLOW OF VAPOR TO THE STAGE
 RHOL IS THE MASS DENSITY OF LIQUID FROM THE STAGE
 RHOV IS THE MASS DENSITY OF VAPOR TO THE STAGE
 QV IS THE VOLUMETRIC FLOW RATE OF VAPOR TO THE STAGE
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	TEMPERATURE F	
STAGE	LIQUID FROM	VAPOR TO
1	-226.95	-205.28
2	-205.28	-85.049
3	-85.049	-20.847
4	-33.922	-15.807
5	-15.807	-10.736
7	-9.2168	-8.4457
8	-8.4457	-8.4457

	MASS FLOW LB/HR		VOLUME FLOW CUFT/HR		MOLECULAR WEIGHT	
STAGE	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO
1	0.21959E+06	0.28731E+06	4464.3	65501.	31.364	31.266
2	82901.	0.15062E+06	1369.8	54544.	34.067	32.592
3	74878.	0.14259E+06	1362.8	58920.	37.815	34.212
4	86374.	30068.	1787.1	10136.	37.998	36.783

5	91737.	35431.	2004.6	11735.	38.108	37.234
7	93940.	37635.	2074.7	12274.	38.341	37.846
8	56306.	0.0000	1222.9	0.0000	38.680	

	DENSITY LB/CUFT		VISCOSITY CP		SURFACE TENSION DYNE/CM
STAGE	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM
1	49.188	4.3863	0.77545E-01	0.11281E-01	18.442
2	60.522	2.7614	0.21046	0.13123E-01	16.663
3	54.943	2.4201	0.16852	0.14126E-01	10.105
4	48.333	2.9664	0.12603	0.11916E-01	7.7229
5	45.763	3.0192	0.11404	0.11836E-01	6.8696
7	45.278	3.0663	0.11107	0.11936E-01	6.5759
8	46.045		0.11268		6.5378

STAGE	MARANGONI INDEX DYNE/CM	FLOW PARAM	QR CUFT/HR	REDUCED F-FACTOR (LB-CUFT)**.5/HR
1		0.22824	20495.	0.13718E+06
2	-1.7794	0.11757	11926.	90638.
3	-6.5582	0.11021	12648.	91661.
4	-2.3818	0.71166	2591.9	17458.
5	-.85328	0.66505	3118.8	20391.
7	-.68760E-01	0.64957	3308.0	21492.
8	-.38102E-01		0.0000	0.0000

****

***** TRAY SIZING CALCULATIONS *****

****

****

*** SECTION 1 ***

****

STARTING STAGE NUMBER 2

ENDING STAGE NUMBER 7
FLOODING CALCULATION METHOD B960

DESIGN PARAMETERS

PEAK CAPACITY FACTOR 1.00000
SYSTEM FOAMING FACTOR 1.00000
FLOODING FACTOR 0.80000
MINIMUM COLUMN DIAMETER FT 1.00000
MINIMUM DC AREA/COLUMN AREA 0.100000

TRAY SPECIFICATIONS

TRAY TYPE FLEXI
NUMBER OF PASSES 1
TRAY SPACING FT 2.00000

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

STAGE WITH MAXIMUM DIAMETER 3
COLUMN DIAMETER FT 4.15972
DC AREA/COLUMN AREA 0.10000
DOWNCOMER VELOCITY FT/SEC 0.27856
FLOW PATH LENGTH FT 2.85793
SIDE DOWNCOMER WIDTH FT 0.65089
SIDE WEIR LENGTH FT 3.02250
CENTER DOWNCOMER WIDTH FT 0.0
CENTER WEIR LENGTH FT 0.0
OFF-CENTER DOWNCOMER WIDTH FT 0.0
OFF-CENTER SHORT WEIR LENGTH FT 0.0
OFF-CENTER LONG WEIR LENGTH FT 0.0
TRAY CENTER TO OCDC CENTER FT 0.0

**** SIZING PROFILES ****

STAGE	DIAMETER	TOTAL AREA	ACTIVE AREA	SIDE DC AREA
	FT	SQFT	SQFT	SQFT
2	4.0612	12.954	10.363	1.2954

3	4.1597	13.590	10.872	1.3590
4	2.6714	5.6049	2.8994	1.3527
5	2.9083	6.6432	3.6084	1.5174
6	2.9774	6.9623	3.8301	1.5661
7	2.9869	7.0071	3.8661	1.5705

BLOCK: TOW2 MODEL: RADFRAC

INLETS - 8 STAGE 30
OUTLETS - 10 STAGE 1
9 STAGE 60
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

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*                                    *
*    FEED PRESSURE IS LOWER THAN STAGE PRESSURE.          *
*                                    *
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*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	1455.70	1455.70	-0.312392E-15
MASS(LB/HR)	56305.8	56305.8	-0.144955E-07
ENTHALPY(BTU/HR)	-0.161977E+09	-0.160645E+09	-0.822104E-02

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E 42661.5 LB/HR
PRODUCT STREAMS CO2E 42661.5 LB/HR
NET STREAMS CO2E PRODUCTION 0.225144E-02 LB/HR
UTILITIES CO2E PRODUCTION 0.00000 LB/HR
TOTAL CO2E PRODUCTION 0.225144E-02 LB/HR

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**** INPUT DATA ****
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**** INPUT PARAMETERS ****

NUMBER OF STAGES	60
ALGORITHM OPTION	STANDARD
ABSORBER OPTION	NO
INITIALIZATION OPTION	STANDARD
HYDRAULIC PARAMETER CALCULATIONS	NO
INSIDE LOOP CONVERGENCE METHOD	BROYDEN
DESIGN SPECIFICATION METHOD	NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS	25
MAXIMUM NO. OF INSIDE LOOP ITERATIONS	10
MAXIMUM NUMBER OF FLASH ITERATIONS	30
FLASH TOLERANCE	0.000100000
OUTSIDE LOOP CONVERGENCE TOLERANCE	0.000100000

**** COL-SPECS ****

MOLAR VAPOR DIST / TOTAL DIST		1.00000
MOLAR REFLUX RATIO		30.0000
MASS BOTTOMS RATE	LB/HR	42,663.5

**** PROFILES ****

P-SPEC STAGE 1 PRES, PSIA 200.000

****
**** RESULTS ****
****

*** COMPONENT SPLIT FRACTIONS ***

	OUTLET STREAMS	
	10	9
COMPONENT:		
N2	1.0000	0.0000
CO2	.24226E-02	.99758
O2	1.0000	0.0000

C2H4 .99228 .77235E-02

*** SUMMARY OF KEY RESULTS ***

TOP STAGE TEMPERATURE	F	-43.5032
BOTTOM STAGE TEMPERATURE	F	-21.2269
TOP STAGE LIQUID FLOW	LBMOL/HR	14,547.8
BOTTOM STAGE LIQUID FLOW	LBMOL/HR	970.769
TOP STAGE VAPOR FLOW	LBMOL/HR	484.928
BOILUP VAPOR FLOW	LBMOL/HR	11,363.7
MOLAR REFLUX RATIO		30.0000
MOLAR BOILUP RATIO		11.7059
CONDENSER DUTY (W/O SUBCOOL)	BTU/HR	-0.646733+08
REBOILER DUTY	BTU/HR	0.660048+08

**** MAXIMUM FINAL RELATIVE ERRORS ****

DEW POINT	0.49366E-05	STAGE= 44
BUBBLE POINT	0.95821E-05	STAGE= 46
COMPONENT MASS BALANCE	0.26680E-05	STAGE= 30 COMP=O2
ENERGY BALANCE	0.50932E-05	STAGE= 41

**** PROFILES ****

NOTE REPORTED VALUES FOR STAGE LIQUID AND VAPOR RATES ARE THE FLOWS FROM THE STAGE INCLUDING ANY SIDE PRODUCT.

STAGE	TEMPERATURE	PRESSURE	ENTHALPY BTU/LBMOL		HEAT DUTY
	F	PSIA	LIQUID	VAPOR	BTU/HR
1	-43.503	200.00	15412.	20024.	-.64673+08
2	-42.300	204.00	15237.	19863.	
3	-42.248	204.12	15007.	19671.	
4	-42.196	204.24	14744.	19449.	
28	-37.769	207.12	-36486.	-23836.	
29	-37.177	207.24	-43623.	-29974.	
30	-36.564	207.36	-50821.	-36214.	

31	-36.427	207.48	-52082.	-37317.	
59	-21.316	210.84	-0.17514E+06	-0.16879E+06	
60	-21.227	210.96	-0.17548E+06	-0.16930E+06	.66005+08

STAGE	FLOW RATE		FEED RATE			PRODUCT RATE	
	LBMOL/HR		LBMOL/HR			LBMOL/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.1455E+05	484.9					484.9275
2	0.1462E+05	0.1503E+05					
3	0.1462E+05	0.1511E+05					
4	0.1462E+05	0.1511E+05					
28	0.1366E+05	0.1427E+05					
29	0.1352E+05	0.1414E+05		142.2692			
30	0.1482E+05	0.1386E+05	1313.4276				
31	0.1480E+05	0.1385E+05					
59	0.1233E+05	0.1137E+05					
60	970.8	0.1136E+05				970.7693	

**** MASS FLOW PROFILES ****

STAGE	FLOW RATE		FEED RATE			PRODUCT RATE	
	LB/HR		LB/HR			LB/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.4095E+06	0.1364E+05					.13642+05
2	0.4119E+06	0.4231E+06					
3	0.4121E+06	0.4255E+06					
4	0.4123E+06	0.4257E+06					
28	0.4431E+06	0.4535E+06					
29	0.4466E+06	0.4568E+06		5354.3103			
30	0.4985E+06	0.4549E+06	.50952+05				
31	0.4992E+06	0.4558E+06					
59	0.5417E+06	0.4989E+06					
60	0.4266E+05	0.4991E+06				.42663+05	

**** MOLE-X-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.18309E-06	0.57689E-02	0.47778E-04	0.99418
2	0.17377E-07	0.68111E-02	0.65002E-05	0.99318
3	0.70834E-08	0.80072E-02	0.22320E-05	0.99199
4	0.64453E-08	0.93801E-02	0.17915E-05	0.99062

28	0.56540E-08	0.27542	0.16113E-05	0.72458
29	0.55374E-08	0.31246	0.15900E-05	0.68754
30	0.16247E-08	0.34981	0.72337E-06	0.65019
31	0.88004E-10	0.35635	0.69868E-07	0.64365
59	0.34288E-49	0.99434	0.37165E-38	0.56559E-02
60	0.99737E-51	0.99613	0.22803E-39	0.38675E-02

**** MOLE-Y-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.29251E-05	0.48428E-02	0.45606E-03	0.99470
2	0.27154E-06	0.57391E-02	0.60948E-04	0.99420
3	0.11070E-06	0.67479E-02	0.20928E-04	0.99323
4	0.10075E-06	0.79056E-02	0.16799E-04	0.99208
28	0.10499E-06	0.23407	0.17077E-04	0.76592
29	0.10576E-06	0.26614	0.17195E-04	0.73384
30	0.31948E-07	0.29874	0.79883E-05	0.70125
31	0.17385E-08	0.30451	0.77408E-06	0.69549
59	0.12746E-47	0.99152	0.65358E-37	0.84832E-02
60	0.37132E-49	0.99419	0.40145E-38	0.58087E-02

**** K-VALUES ****

STAGE	N2	CO2	O2	C2H4
1	15.977	0.83947	9.5454	1.0005
2	15.627	0.84261	9.3764	1.0010
3	15.628	0.84272	9.3766	1.0013
4	15.631	0.84281	9.3775	1.0015
28	18.575	0.84980	10.600	1.0571
29	19.106	0.85169	10.817	1.0674
30	19.671	0.85395	11.045	1.0786
31	19.762	0.85445	11.082	1.0806
59	37.172	0.99716	17.586	1.4999
60	37.229	0.99805	17.605	1.5019

**** MASS-X-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.18222E-06	0.90204E-02	0.54318E-04	0.99093
2	0.17285E-07	0.10644E-01	0.73856E-05	0.98935
3	0.70411E-08	0.12505E-01	0.25343E-05	0.98749
4	0.64019E-08	0.14637E-01	0.20325E-05	0.98536
28	0.48813E-08	0.37355	0.15890E-05	0.62645

29	0.46950E-08	0.41621	0.15399E-05	0.58379
30	0.13531E-08	0.45770	0.68818E-06	0.54230
31	0.73068E-10	0.46482	0.66263E-07	0.53518
59	0.21870E-49	0.99639	0.27078E-38	0.36127E-02
60	0.63575E-51	0.99753	0.16603E-39	0.24688E-02

**** MASS-Y-PROFILE ****

STAGE	N2	CO2	O2	C2H4
1	0.29127E-05	0.75759E-02	0.51873E-03	0.99190
2	0.27026E-06	0.89739E-02	0.69292E-04	0.99096
3	0.11012E-06	0.10545E-01	0.23780E-04	0.98943
4	0.10015E-06	0.12347E-01	0.19076E-04	0.98763
28	0.92525E-07	0.32405	0.17190E-04	0.67593
29	0.91728E-07	0.36262	0.17034E-04	0.63737
30	0.27269E-07	0.40059	0.77883E-05	0.59940
31	0.14798E-08	0.40718	0.75259E-06	0.59282
59	0.81381E-48	0.99458	0.47667E-37	0.54243E-02
60	0.23685E-49	0.99629	0.29251E-38	0.37105E-02

****
***** HYDRAULIC PARAMETERS *****
****

*** DEFINITIONS ***

MARANGONI INDEX = SIGMA - SIGMATO
FLOW PARAM = (ML/MV)*SQRT(RHOV/RHOL)
QR = QV*SQRT(RHOV/(RHOL-RHOV))
F FACTOR = QV*SQRT(RHOV)
WHERE:
SIGMA IS THE SURFACE TENSION OF LIQUID FROM THE STAGE
SIGMATO IS THE SURFACE TENSION OF LIQUID TO THE STAGE
ML IS THE MASS FLOW OF LIQUID FROM THE STAGE
MV IS THE MASS FLOW OF VAPOR TO THE STAGE
RHOL IS THE MASS DENSITY OF LIQUID FROM THE STAGE
RHOV IS THE MASS DENSITY OF VAPOR TO THE STAGE

QV IS THE VOLUMETRIC FLOW RATE OF VAPOR TO THE STAGE

STAGE	TEMPERATURE F LIQUID FROM	TEMPERATURE F VAPOR TO
1	-43.503	-42.300
2	-42.300	-42.248
3	-42.248	-42.196
4	-42.196	-42.142
28	-37.769	-37.177
29	-37.177	-36.537
30	-36.564	-36.427
31	-36.427	-36.269
59	-21.316	-21.227
60	-21.227	-21.227

	MASS FLOW LB/HR		VOLUME FLOW CUFT/HR		MOLECULAR WEIGHT	
STAGE	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO
1	0.40946E+06	0.42311E+06	14551.	0.26392E+06	28.146	28.146
2	0.41186E+06	0.42551E+06	14680.	0.26513E+06	28.162	28.162
3	0.41208E+06	0.42572E+06	14674.	0.26496E+06	28.182	28.180
4	0.41232E+06	0.42596E+06	14665.	0.26478E+06	28.203	28.201
28	0.44313E+06	0.45677E+06	12450.	0.25101E+06	32.448	32.300
29	0.44664E+06	0.46028E+06	12151.	0.24953E+06	33.039	32.869
30	0.49850E+06	0.45584E+06	13131.	0.24657E+06	33.635	32.912
31	0.49920E+06	0.45654E+06	13077.	0.24616E+06	33.740	33.023
59	0.54173E+06	0.49906E+06	8341.8	0.21469E+06	43.920	43.917
60	42663.	0.0000	656.06	0.0000	43.948	

	DENSITY LB/CUFT		VISCOSITY CP		SURFACE TENSION DYNE/CM
STAGE	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM
1	28.140	1.6032	0.75014E-01	0.85457E-02	8.8495
2	28.055	1.6049	0.74554E-01	0.85503E-02	8.7809
3	28.083	1.6068	0.74620E-01	0.85556E-02	8.7183
4	28.115	1.6087	0.74700E-01	0.85615E-02	8.7130

28	35.594	1.8198	0.94700E-01	0.95588E-02	8.1017
29	36.758	1.8446	0.97863E-01	0.97004E-02	8.0324
30	37.964	1.8487	0.10114	0.97132E-02	7.9646
31	38.175	1.8546	0.10170	0.97419E-02	7.9516
59	64.941	2.3246	0.16943	0.12949E-01	6.9447
60	65.030		0.16960		6.9407

STAGE	MARANGONI INDEX DYNE/CM	FLOW PARAM	QR CUFT/HR	REDUCED F-FACTOR (LB-CUFT)**.5/HR
1		0.23099	64868.	0.33416E+06
2	-.68679E-01	0.23151	65308.	0.33588E+06
3	-.62570E-01	0.23153	65272.	0.33585E+06
4	-.53243E-02	0.23155	65230.	0.33583E+06
28	-.64400E-01	0.21936	58265.	0.33861E+06
29	-.69311E-01	0.21737	57356.	0.33890E+06
30	-.11285	0.24133	55786.	0.33525E+06
31	-.13043E-01	0.24101	55625.	0.33523E+06
59	-.50292E-02	0.20537	41366.	0.32733E+06
60	-.40035E-02		0.0000	0.0000

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***********************************
***** TRAY SIZING CALCULATIONS *****
***********************************


*******************
*** SECTION   1 ***
*******************

STARTING STAGE NUMBER                 2
ENDING STAGE NUMBER                  59
FLOODING CALCULATION METHOD        B960

DESIGN PARAMETERS
-----------------
PEAK CAPACITY FACTOR            1.00000
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SYSTEM FOAMING FACTOR		1.00000
FLOODING FACTOR		0.80000
MINIMUM COLUMN DIAMETER	FT	1.00000
MINIMUM DC AREA/COLUMN AREA		0.100000

TRAY SPECIFICATIONS

TRAY TYPE		FLEXI
NUMBER OF PASSES		1
TRAY SPACING	FT	2.00000

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

STAGE WITH MAXIMUM DIAMETER		2
COLUMN DIAMETER	FT	16.0634
DC AREA/COLUMN AREA		0.10000
DOWNCOMER VELOCITY	FT/SEC	0.20122
FLOW PATH LENGTH	FT	11.0363
SIDE DOWNCOMER WIDTH	FT	2.51353
SIDE WEIR LENGTH	FT	11.6719
CENTER DOWNCOMER WIDTH	FT	0.0
CENTER WEIR LENGTH	FT	0.0
OFF-CENTER DOWNCOMER WIDTH	FT	0.0
OFF-CENTER SHORT WEIR LENGTH	FT	0.0
OFF-CENTER LONG WEIR LENGTH	FT	0.0
TRAY CENTER TO OCDC CENTER	FT	0.0

**** SIZING PROFILES ****

STAGE	DIAMETER	TOTAL AREA	ACTIVE AREA	SIDE DC AREA
	FT	SQFT	SQFT	SQFT
2	16.063	202.66	162.13	20.266
3	16.057	202.50	162.00	20.250
4	16.050	202.31	161.85	20.231
5	16.041	202.09	161.67	20.209
6	16.030	201.81	161.45	20.181
7	16.017	201.50	161.20	20.150
8	16.002	201.12	160.90	20.112

9	15.985	200.68	160.55	20.068
10	15.965	200.18	160.14	20.018
11	15.941	199.59	159.67	19.959
12	15.914	198.90	159.12	19.890
13	15.882	198.11	158.49	19.811
14	15.846	197.20	157.76	19.720
15	15.803	196.15	156.92	19.615
16	15.755	194.95	155.96	19.495
17	15.699	193.57	154.86	19.357
18	15.635	192.00	153.60	19.200
19	15.562	190.21	152.17	19.021
20	15.478	188.17	150.53	18.817
21	15.383	185.85	148.68	18.585
22	15.274	183.24	146.59	18.324
23	15.151	180.29	144.23	18.029
24	15.011	176.98	141.59	17.698
25	14.854	173.29	138.63	17.329
26	14.677	169.19	135.35	16.919
27	14.480	164.68	131.74	16.468
28	14.261	159.74	127.79	15.974
29	14.022	154.43	123.54	15.443
30	14.563	166.56	133.25	16.656
31	14.519	165.56	132.45	16.556
32	14.466	164.35	131.48	16.435
33	14.402	162.91	130.33	16.291
34	14.326	161.20	128.96	16.120
35	14.236	159.17	127.33	15.917
36	14.129	156.78	125.42	15.678
37	14.003	154.00	123.20	15.400
38	13.856	150.79	120.63	15.079
39	13.687	147.13	117.70	14.713
40	13.494	143.01	114.41	14.301
41	13.278	138.47	110.77	13.847
42	13.040	133.55	106.84	13.355
43	12.785	128.38	102.70	12.838
44	12.519	123.08	98.467	12.308
45	12.250	117.85	94.280	11.785
46	11.988	112.87	90.292	11.287
47	11.743	108.30	86.641	10.830
48	11.523	104.28	83.427	10.428

49	11.333	100.88	80.704	10.088
50	11.176	98.091	78.473	9.8091
51	11.049	95.874	76.700	9.5874
52	10.949	94.155	75.324	9.4155
53	10.873	92.847	74.278	9.2847
54	10.815	91.868	73.494	9.1868
55	10.773	91.144	72.915	9.1144
56	10.741	90.614	72.491	9.0614
57	10.718	90.230	72.184	9.0230
58	10.702	89.953	71.962	8.9953
59	10.690	89.755	71.804	8.9755

BLOCK: VALVE MODEL: VALVE

INLET STREAM: 7
OUTLET STREAM: 8
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	1455.70	1455.70	0.00000
MASS(LB/HR)	56305.8	56305.8	0.00000
ENTHALPY(BTU/HR)	-0.161977E+09	-0.161977E+09	0.00000

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 42661.5 LB/HR
PRODUCT STREAMS CO2E 42661.5 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 ***

VALVE OUTLET PRESSURE PSIA 200.000
VALVE FLOW COEF CALC. NO

FLASH SPECIFICATIONS:
NPHASE 2
MAX NUMBER OF ITERATIONS 30

CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

VALVE PRESSURE DROP PSI 103.720

BLOCK: VALVE2 MODEL: VALVE

INLET STREAM: 6
OUTLET STREAM: 22
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	2187.89	2187.89	0.00000
MASS(LB/HR)	67715.8	67715.8	0.00000
ENTHALPY(BTU/HR)	-0.545417E+07	-0.545417E+07	0.00000

*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 1.97402 LB/HR
PRODUCT STREAMS CO2E 1.97402 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 ***

VALVE OUTLET PRESSURE PSIA 20.0000
VALVE FLOW COEF CALC. NO

FLASH SPECIFICATIONS:
NPHASE 2
MAX NUMBER OF ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

VALVE PRESSURE DROP PSI 280.000

BLOCK: VALVE3 MODEL: VALVE

INLET STREAM: 14
OUTLET STREAM: 15
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	202185.	202185.	0.00000
MASS(LB/HR)	0.566390E+07	0.566390E+07	0.00000
ENTHALPY(BTU/HR)	-0.567480E+09	-0.567480E+09	0.00000

*** 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 ***

VALVE OUTLET PRESSURE PSIA 300.000
VALVE FLOW COEF CALC. NO

FLASH SPECIFICATIONS:
NPHASE 2
MAX NUMBER OF ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

VALVE PRESSURE DROP PSI 915.000

BLOCK: VALVE4 MODEL: VALVE

INLET STREAM: 12
OUTLET STREAM: 13
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

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             ***  MASS AND ENERGY BALANCE  ***
                         IN          OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          970.769       970.769       0.00000
    MASS(LB/HR   )          42663.5       42663.5       0.00000
    ENTHALPY(BTU/HR  )     -0.166776E+09   -0.166776E+09    0.00000

             ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            42558.1      LB/HR
  PRODUCT STREAMS CO2E         42558.1      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  ***

  VALVE OUTLET PRESSURE     PSIA                   20.0000
  VALVE FLOW COEF CALC.                            NO

               FLASH SPECIFICATIONS:
  NPHASE                                   2
  MAX NUMBER OF ITERATIONS                          30
  CONVERGENCE TOLERANCE                             0.000100000

               ***  RESULTS  ***

  VALVE PRESSURE DROP       PSI                   190.960

10 11 12 13 14
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STREAM ID           10        11        12        13        14
FROM :             TOW2      HX2       HX1       VALVE4    MHX
TO   :             HX2       MHX       VALVE4    MHX       VALVE3

SUBSTREAM: MIXED
PHASE:             VAPOR     VAPOR     MIXED     MIXED     VAPOR
COMPONENTS: LBMOL/HR
 N2             1.4185-03  1.4185-03    0.0        0.0     2.0218+05
 CO2               2.3484     2.3484   967.0149   967.0149    0.0
```

O2	0.2212	0.2212	0.0	0.0	0.0
C2H4	482.3565	482.3565	3.7545	3.7545	0.0
COMPONENTS: MOLE FRAC					
N2	2.9251-06	2.9251-06	0.0	0.0	1.0000
CO2	4.8428-03	4.8428-03	0.9961	0.9961	0.0
O2	4.5606-04	4.5606-04	0.0	0.0	0.0
C2H4	0.9947	0.9947	3.8675-03	3.8675-03	0.0
COMPONENTS: LB/HR					
N2	3.9736-02	3.9736-02	0.0	0.0	5.6639+06
CO2	103.3535	103.3535	4.2558+04	4.2558+04	0.0
O2	7.0767	7.0767	0.0	0.0	0.0
C2H4	1.3532+04	1.3532+04	105.3270	105.3270	0.0
COMPONENTS: MASS FRAC					
N2	2.9127-06	2.9127-06	0.0	0.0	1.0000
CO2	7.5759-03	7.5759-03	0.9975	0.9975	0.0
O2	5.1873-04	5.1873-04	0.0	0.0	0.0
C2H4	0.9919	0.9919	2.4688-03	2.4688-03	0.0
TOTAL FLOW:					
LBMOL/HR	484.9275	484.9275	970.7694	970.7694	2.0218+05
LB/HR	1.3642+04	1.3642+04	4.2663+04	4.2663+04	5.6639+06
CUFT/HR	8690.2822	9452.1277	1.1880+04	1.3300+05	3.0609+05
STATE VARIABLES:					
TEMP F	-43.5032	-23.4870	-21.1960	-117.2255	-180.0000
PRES PSIA	200.0000	200.0000	210.9600	20.0000	1215.0000
VFRAC	1.0000	1.0000	0.6346	0.7648	1.0000
LFRAC	0.0	0.0	0.3654	0.2352	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	2.0024+04	2.0249+04	-1.7180+05	-1.7180+05	-2806.7397
BTU/LB	711.7641	719.7664	-3909.1117	-3909.1117	-100.1925
BTU/HR	9.7102+06	9.8193+06	-1.6678+08	-1.6678+08	-5.6748+08
ENTROPY:					
BTU/LBMOL-R	-20.9801	-20.4517	-11.7957	-8.6973	-16.0558
BTU/LB-R	-0.7458	-0.7270	-0.2684	-0.1979	-0.5731
DENSITY:					
LBMOL/CUFT	5.5801-02	5.1304-02	8.1716-02	7.2992-03	0.6605
LB/CUFT	1.5698	1.4433	3.5913	0.3208	18.5041
AVG MW	28.1328	28.1328	43.9481	43.9481	28.0135

15 16 17 18 19

STREAM ID	15	16	17	18	19
FROM :	VALVE3	FLASH	COND	FLASH	MIX
TO :	FLASH	COND	MIX	MIX	MHX
SUBSTREAM: MIXED					
PHASE:	MIXED	LIQUID	VAPOR	VAPOR	MIXED
COMPONENTS: LBMOL/HR					
N2	2.0218+05	1.1629+04	1.1629+04	1.9056+05	2.0218+05
CO2	0.0	0.0	0.0	0.0	0.0
O2	0.0	0.0	0.0	0.0	0.0
C2H4	0.0	0.0	0.0	0.0	0.0
COMPONENTS: MOLE FRAC					
N2	1.0000	1.0000	1.0000	1.0000	1.0000
CO2	0.0	0.0	0.0	0.0	0.0
O2	0.0	0.0	0.0	0.0	0.0
C2H4	0.0	0.0	0.0	0.0	0.0
COMPONENTS: LB/HR					
N2	5.6639+06	3.2576+05	3.2576+05	5.3381+06	5.6639+06
CO2	0.0	0.0	0.0	0.0	0.0
O2	0.0	0.0	0.0	0.0	0.0
C2H4	0.0	0.0	0.0	0.0	0.0
COMPONENTS: MASS FRAC					
N2	1.0000	1.0000	1.0000	1.0000	1.0000
CO2	0.0	0.0	0.0	0.0	0.0
O2	0.0	0.0	0.0	0.0	0.0
C2H4	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
LBMOL/HR	2.0218+05	1.1629+04	1.1629+04	1.9056+05	2.0218+05
LB/HR	5.6639+06	3.2576+05	3.2576+05	5.3381+06	5.6639+06
CUFT/HR	9.1524+05	9968.6194	5.7590+04	9.2309+05	9.9868+05
STATE VARIABLES:					
TEMP F	-250.8338	-251.4061	-251.9853	-251.4061	-251.9847
PRES PSIA	300.0000	295.0000	290.0000	295.0000	290.0000
VFRAC	0.9452	0.0	1.0000	1.0000	0.9968
LFRAC	5.4810-02	1.0000	0.0	0.0	3.1783-03
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-2806.7397	-4061.5781	-2725.6770	-2730.1630	-2729.9050

BTU/LB	-100.1925	-144.9866	-97.2988	-97.4589	-97.4497
BTU/HR	-5.6748+08	-4.7231+07	-3.1696+07	-5.2025+08	-5.5195+08
ENTROPY:					
BTU/LBMOL-R	-14.4792	-20.4841	-14.0478	-14.0912	-14.0684
BTU/LB-R	-0.5169	-0.7312	-0.5015	-0.5030	-0.5022
DENSITY:					
LBMOL/CUFT	0.2209	1.1665	0.2019	0.2064	0.2025
LB/CUFT	6.1885	32.6786	5.6565	5.7829	5.6714
AVG MW	28.0135	28.0135	28.0135	28.0135	28.0135

20 22 3 4 401

STREAM ID	20	22	3	4	401
FROM :	MHX	VALVE2	B1	HX1	----
TO :	B4	MHX	HX1	HX2	B1
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
COMPONENTS: LBMOL/HR					
N2	2.0218+05	575.5364	575.5379	575.5379	575.5379
CO2	0.0	4.4854-02	969.4081	969.4081	969.4081
O2	0.0	1612.1211	1612.3423	1612.3423	1612.3423
C2H4	0.0	0.1833	486.2943	486.2943	486.2943
COMPONENTS: MOLE FRAC					
N2	1.0000	0.2631	0.1580	0.1580	0.1580
CO2	0.0	2.0501-05	0.2661	0.2661	0.2661
O2	0.0	0.7368	0.4425	0.4425	0.4425
C2H4	0.0	8.3782-05	0.1335	0.1335	0.1335
COMPONENTS: LB/HR					
N2	5.6639+06	1.6123+04	1.6123+04	1.6123+04	1.6123+04
CO2	0.0	1.9740	4.2663+04	4.2663+04	4.2663+04
O2	0.0	5.1586+04	5.1593+04	5.1593+04	5.1593+04
C2H4	0.0	5.1424	1.3642+04	1.3642+04	1.3642+04
COMPONENTS: MASS FRAC					
N2	1.0000	0.2381	0.1300	0.1300	0.1300
CO2	0.0	2.9152-05	0.3440	0.3440	0.3440
O2	0.0	0.7618	0.4160	0.4160	0.4160
C2H4	0.0	7.5941-05	0.1100	0.1100	0.1100
TOTAL FLOW:					

LBMOL/HR	2.0218+05	2187.8858	3643.5826	3643.5826	3643.5826
LB/HR	5.6639+06	6.7716+04	1.2402+05	1.2402+05	1.2402+05
CUFT/HR	4.0918+06	2.0819+05	7.0622+04	5.3434+04	1.4637+06
STATE VARIABLES:					
TEMP F	86.8187	-277.0531	100.0000	-15.0000	91.4000
PRES PSIA	290.0000	20.0000	300.0000	300.0000	14.6959
VFRAC	1.0000	1.0000	1.0000	1.0000	1.0000
LFRAC	0.0	0.0	0.0	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	18.7341	-2492.8970	-4.1966+04	-4.2948+04	-4.1891+04
BTU/LB	0.6688	-80.5450	-1232.9028	-1261.7613	-1230.7101
BTU/HR	3.7877+06	-5.4542+06	-1.5291+08	-1.5649+08	-1.5263+08
ENTROPY:					
BTU/LBMOL-R	-5.8876	-7.0589	-4.8520	-6.8170	1.2093
BTU/LB-R	-0.2102	-0.2281	-0.1425	-0.2003	3.5528-02
DENSITY:					
LBMOL/CUFT	4.9412-02	1.0509-02	5.1593-02	6.8189-02	2.4893-03
LB/CUFT	1.3842	0.3253	1.7561	2.3210	8.4731-02
AVG MW	28.0135	30.9504	34.0384	34.0384	34.0384

5 6 7 8 9

STREAM ID	5	6	7	8	9
FROM :	HX2	TOW1	TOW1	VALVE	TOW2
TO :	TOW1	VALVE2	VALVE	TOW2	HX1
MAX CONV. ERROR:	2.0275-08	0.0	0.0	0.0	0.0
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	LIQUID	MIXED	LIQUID
COMPONENTS: LBMOL/HR					
N2	575.5379	575.5364	1.4185-03	1.4185-03	0.0
CO2	969.4081	4.4854-02	969.3633	969.3633	967.0149
O2	1612.3423	1612.1211	0.2212	0.2212	0.0
C2H4	486.2943	0.1833	486.1110	486.1110	3.7545
COMPONENTS: MOLE FRAC					
N2	0.1580	0.2631	9.7442-07	9.7442-07	0.0
CO2	0.2661	2.0501-05	0.6659	0.6659	0.9961

O2	0.4425	0.7368	1.5192-04	1.5192-04	0.0
C2H4	0.1335	8.3782-05	0.3339	0.3339	3.8675-03
COMPONENTS: LB/HR					
N2	1.6123+04	1.6123+04	3.9736-02	3.9736-02	0.0
CO2	4.2663+04	1.9740	4.2661+04	4.2661+04	4.2558+04
O2	5.1593+04	5.1586+04	7.0767	7.0767	0.0
C2H4	1.3642+04	5.1424	1.3637+04	1.3637+04	105.3270
COMPONENTS: MASS FRAC					
N2	0.1300	0.2381	7.0572-07	7.0572-07	0.0
CO2	0.3440	2.9152-05	0.7577	0.7577	0.9975
O2	0.4160	0.7618	1.2568-04	1.2568-04	0.0
C2H4	0.1100	7.5941-05	0.2422	0.2422	2.4688-03
TOTAL FLOW:					
LBMOL/HR	3643.5826	2187.8858	1455.6969	1455.6969	970.7694
LB/HR	1.2402+05	6.7716+04	5.6306+04	5.6306+04	4.2663+04
CUFT/HR	5.2887+04	1.3087+04	1222.8509	3932.7157	656.0595
STATE VARIABLES:					
TEMP F	-18.4751	-226.9482	-8.4457	-32.7360	-21.2269
PRES PSIA	300.0000	300.0000	303.7200	200.0000	210.9600
VFRAC	1.0000	1.0000	0.0	0.1053	0.0
LFRAC	0.0	0.0	1.0000	0.8947	1.0000
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-4.2978+04	-2492.8970	-1.1127+05	-1.1127+05	-1.7548+05
BTU/LB	-1262.6416	-80.5450	-2876.7311	-2876.7311	-3993.0028
BTU/HR	-1.5659+08	-5.4542+06	-1.6198+08	-1.6198+08	-1.7036+08
ENTROPY:					
BTU/LBMOL-R	-6.8846	-11.7851	-21.6243	-21.5510	-20.2044
BTU/LB-R	-0.2023	-0.3808	-0.5591	-0.5572	-0.4597
DENSITY:					
LBMOL/CUFT	6.8894-02	0.1672	1.1904	0.3702	1.4797
LB/CUFT	2.3450	5.1743	46.0447	14.3173	65.0299
AVG MW	34.0384	30.9504	38.6796	38.6796	43.9481

CO2 N2IN N2REC O2N2 PRODUCT

STREAM ID	CO2	N2IN	N2REC	O2N2	PRODUCT
FROM :	MHX	----	B4	MHX	MHX
TO :	----	MHX	----	----	----

SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
COMPONENTS: LBMOL/HR					
N2	0.0	2.0218+05	2.0218+05	575.5364	1.4185-03
CO2	967.0149	0.0	0.0	4.4854-02	2.3484
O2	0.0	0.0	0.0	1612.1211	0.2212
C2H4	3.7545	0.0	0.0	0.1833	482.3565
COMPONENTS: MOLE FRAC					
N2	0.0	1.0000	1.0000	0.2631	2.9251-06
CO2	0.9961	0.0	0.0	2.0501-05	4.8428-03
O2	0.0	0.0	0.0	0.7368	4.5606-04
C2H4	3.8675-03	0.0	0.0	8.3782-05	0.9947
COMPONENTS: LB/HR					
N2	0.0	5.6639+06	5.6639+06	1.6123+04	3.9736-02
CO2	4.2558+04	0.0	0.0	1.9740	103.3535
O2	0.0	0.0	0.0	5.1586+04	7.0767
C2H4	105.3270	0.0	0.0	5.1424	1.3532+04
COMPONENTS: MASS FRAC					
N2	0.0	1.0000	1.0000	0.2381	2.9127-06
CO2	0.9975	0.0	0.0	2.9152-05	7.5759-03
O2	0.0	0.0	0.0	0.7618	5.1873-04
C2H4	2.4688-03	0.0	0.0	7.5941-05	0.9919
TOTAL FLOW:					
LBMOL/HR	970.7694	2.0218+05	2.0218+05	2187.8858	484.9275
LB/HR	4.2663+04	5.6639+06	5.6639+06	6.7716+04	1.3642+04
CUFT/HR	2.7393+05	1.0176+06	1.0176+06	6.2141+05	1.2591+04
STATE VARIABLES:					
TEMP F	70.0000	100.0000	100.0000	70.0000	70.0000
PRES PSIA	20.0000	1215.0000	1215.0000	20.0000	200.0000
VFRAC	1.0000	1.0000	1.0000	1.0000	1.0000
LFRAC	0.0	0.0	0.0	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-1.6852+05	-13.5310	-13.5310	-55.2291	2.1279+04
BTU/LB	-3834.6053	-0.4830	-0.4830	-1.7844	756.3624
BTU/HR	-1.6360+08	-2.7358+06	-2.7358+06	-1.2083+05	1.0319+07
ENTROPY:					
BTU/LBMOL-R	-7.2824-02	-8.8076	-8.8076	0.4340	-18.3134
BTU/LB-R	-1.6571-03	-0.3144	-0.3144	1.4023-02	-0.6510

DENSITY:					
LBMOL/CUFT	3.5439-03	0.1987	0.1987	3.5208-03	3.8513-02
LB/CUFT	0.1557	5.5660	5.5660	0.1090	1.0835
AVG MW	43.9481	28.0135	28.0135	30.9504	28.1328

Sample Calculations of Process Units

HX301-B

Finding mass flow rate of cooling water, *m*

Temperatures known:

$T_{c,I}$ = 65°F

$T_{c,o}$ = 95°F

$T_{h,I}$ = 346°F

$T_{h,o}$ = 105°F

Heat Duty (given from ASPEN): Q = 7,570,000 $\frac{\text{Btu}}{\text{hr}}$

Specific heat capacity for cooling water: C_p = 0.998 $\frac{\text{Btu}}{\text{lb}*\text{R}}$

$$m = \frac{Q}{(T_{c,o} - T_{c,i}) * \mathrm{C_p}}$$

Plugging in given values, obtain $m \approx 253{,}000\frac{\text{lb}}{\text{hr}}$

Finding area of heat transfer, *A*

Assume overall transfer coefficient, U = 150 $\frac{\text{Btu}}{\text{ft}^2*\text{hr}*\text{R}}$

Need log mean temperature difference of streams, ΔT_{lm}

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{h,o}) - (T_{c,o} - T_{c,i})}{\ln \frac{(T_{h,i} - T_{h,o})}{(T_{c,o} - T_{c,i})}} = 101.4°F$$

Aspen uses a correction factor and instead uses ΔT_{lm} = 114.97

Using that value, we can find *A* using

$$A = \frac{Q}{U * \Delta T_{lm}} = 439.86$$

ADS301

To find the diameter of the column, D_{tower}

The tower takes S-302 volumetric flow rate for 5 minutes at a time, therefore the flow through the tower at any time is V = 67,815 $\frac{ft^3}{hr}$

It is a heuristic that the velocity through an adsorption column is in the range of 0.15 to 0.45 $\frac{m}{s}$. We will choose a velocity, *v*, of 0.3$\frac{m}{s}$ which is 3543.3 $\frac{ft}{hr}$.

The tower diameter can be calculated using this:

$$D_{tower} = \sqrt{\frac{4 * V}{\Pi v}}$$

Which yields D_{tower} = 4.94 ft

To find the amount of adsorbent required

Given the amount of ethylene needed to be adsorbed and assuming a 90% efficiency of ethylene adsorption, the amount of ethylene each column can hold is found using:

$$m_{Ethylene} * \frac{1}{3} * 0.9 * \frac{1}{4}$$

The 1/3 accounts for the fact that the ethylene from the reactor effluent is separated using 3 columns. The column will be designed so that it adsorbs ethylene in 5 minute intervals and desorb ethylene in 10 minute intervals. So ethylene is adsorbed in each column for 5 minutes, 4 times in an hour thus the tower only needs to hold 25% of the ethylene it processes per hour. The $m_{Ethylene}$ coming from section 200 is 13620 $\frac{lb}{hr}$. And therefore the ethylene capacity per tower is 1021.5 lb of ethylene.

The ethylene adsorption isotherm included in the report shows that at this operating pressure 4 mol ethylene per kg adsorbent

Converting ethylene to moles and using the isotherm, the amount of adsorbent can be found:

$$1021.5\ lb\ ethylene * \frac{453592\ g}{1\ lb} * \frac{mol\ ethylene}{28.05\ g\ ethylene} * \frac{1\ kg\ adsorbent}{4\ mol\ ethylene} * \frac{2.2lb}{kg} = 9086\ lb\ adsorpent$$

To make sure that the packed bed does not get saturated, we assumed that we will pack the tower with 4 times as much adsorbent, so 35825 lb of adsorbent is required.

The volume of the tower can be found by finding the volume that the adsorbent takes up.

$$Volume\ of\ adsorpent = \frac{35825\ lb\ ethylene}{125\frac{lb\ ethylene}{ft^3}} = 286.6\ ft^3$$

The height of the tower can be determined by dividing the volume required by the cross section of the tower, and adding 12 feet, according to heuristics.

$$\frac{286.6ft^3}{\frac{\Pi * (4.94\ ft)^2}{4}} + 12\ ft\ = 26.97ft$$

The residence time of each tower can be computed by dividing the volume of the column by the flow rate of the ethylene:

$$\tau = \frac{\frac{\Pi*(4.94\ ft)^2}{4}*26.97ft}{67815\frac{ft^3}{hr}} * 3600\frac{s}{hr} = 27.44s$$

MSDS Sheets

Fisher Scientific

Part of Thermo Fisher Scientific

Material Safety Data Sheet

Creation Date 11-Feb-2010 **Revision Date** 11-Feb-2010 **Revision Number** 1

1. PRODUCT AND COMPANY IDENTIFICATION

Product Name	**Sodium hydroxide**
Cat No.	**BP359-212; BP359-500; S318-1; S318-3; S318-3LC; S318-5; S318-10; S318-10LC; S318-50; S318-50LC; S318-100; S318-500; S320-1; S320-3; S320-10; S320-50; S320-500; S392-12; S392-50; S392-212; S392SAM-1; S392SAM-2; S392SAM-3; S399-1; S399-1LC; S399-50; S399-212; S399-500; S612-3; S612-50; S612-500LB; S612-3500LB; S613-3; S613-10; S613-50; S613-500LB**
Synonyms	Caustic soda; Lye (Pellets/Granular/Beads/NF/FCC/EP/BP/JP/Certified ACS)
Recommended Use	Laboratory chemicals

Company
Fisher Scientific
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Emergency Telephone Number
CHEMTREC®, Inside the USA: 800-424-9300
CHEMTREC®, Outside the USA: 703-527-3887

2. HAZARDS IDENTIFICATION

DANGER!

Emergency Overview

Causes severe burns by all exposure routes. Water reactive. Hygroscopic.

Appearance White **Physical State** Solid **odor** odorless

Target Organs Eyes, Respiratory system, Skin, Gastrointestinal tract (GI)

Potential Health Effects

Acute Effects
Principle Routes of Exposure

Eyes	Causes severe burns. May cause blindness or permanent eye damage.
Skin	Causes severe burns. May be harmful in contact with skin.
Inhalation	Causes severe burns. May be harmful if inhaled.
Ingestion	Causes severe burns. May be harmful if swallowed.

Chronic Effects Prolonged skin contact may defat the skin and produce dermatitis.

See Section 11 for additional Toxicological information.

Aggravated Medical Conditions Preexisting eye disorders. Skin disorders.

3. COMPOSITION/INFORMATION ON INGREDIENTS

Haz/Non-haz

Component	CAS-No	Weight %
Sodium hydroxide	1310-73-2	> 95
Sodium carbonate	497-19-8	< 3

4. FIRST AID MEASURES

Eye Contact Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Immediate medical attention is required.

Skin Contact Wash off immediately with plenty of water for at least 15 minutes. Immediate medical attention is required.

Inhalation Move to fresh air. If breathing is difficult, give oxygen. Do not use mouth-to-mouth resuscitation if victim ingested or inhaled the substance; induce artificial respiration with a respiratory medical device. Immediate medical attention is required.

Ingestion Do not induce vomiting. Call a physician or Poison Control Center immediately.

Notes to Physician Treat symptomatically.

5. FIRE-FIGHTING MEASURES

Flash Point Not applicable
Method No information available.

Autoignition Temperature No information available.
Explosion Limits
Upper No data available
Lower No data available

Suitable Extinguishing Media Substance is nonflammable; use agent most appropriate to extinguish surrounding fire..

Unsuitable Extinguishing Media Carbon dioxide (CO_2).

Hazardous Combustion Products No information available.

Sensitivity to mechanical impact No information available.
Sensitivity to static discharge No information available.

Specific Hazards Arising from the Chemical
Thermal decomposition can lead to release of irritating gases and vapors. Water reactive. Corrosive Material. Causes severe burns by all exposure routes.

Protective Equipment and Precautions for Firefighters
As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear

NFPA	**Health** 3	**Flammability** 0	**Instability** 1	**Physical hazards** N/A

6. ACCIDENTAL RELEASE MEASURES

Personal Precautions Use personal protective equipment. Ensure adequate ventilation. Evacuate personnel to safe areas. Keep people away from and upwind of spill/leak. Avoid dust formation. Do not get in eyes, on skin, or on clothing.

Environmental Precautions Should not be released into the environment.

Methods for Containment and Clean Up Avoid dust formation. Sweep up or vacuum up spillage and collect in suitable container for disposal.

7. HANDLING AND STORAGE

Handling Use only under a chemical fume hood. Wear personal protective equipment. Avoid dust formation. Do not breathe dust. Do not get in eyes, on skin, or on clothing.

Storage Keep containers tightly closed in a dry, cool and well-ventilated place. Corrosives area.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Engineering Measures Use only under a chemical fume hood. Ensure that eyewash stations and safety showers are close to the workstation location.

Exposure Guidelines

Component	ACGIH TLV	OSHA PEL	NIOSH IDLH
Sodium hydroxide	Ceiling: 2 mg/m^3	(Vacated) Ceiling: 2 mg/m^3 TWA: 2 mg/m^3	IDLH: 10 mg/m^3 Ceiling: 2 mg/m^3

Component	Quebec	Mexico OEL (TWA)	Ontario TWAEV
Sodium hydroxide	Ceiling: 2 mg/m^3	Peak: 2 mg/m^3	CEV: 2 mg/m^3

NIOSH IDLH: *Immediately Dangerous to Life or Health*

Personal Protective Equipment

Eye/face Protection Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166

Skin and body protection Wear appropriate protective gloves and clothing to prevent skin exposure

Respiratory Protection Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced

9. PHYSICAL AND CHEMICAL PROPERTIES

Physical State Solid
Appearance White

9. PHYSICAL AND CHEMICAL PROPERTIES

odor	odorless
Odor Threshold	No information available.
pH	14 (5 % Solution)
Vapor Pressure	1 mmHg @ 739 °C
Vapor Density	No information available.
Viscosity	No information available.
Boiling Point/Range	1390°C / 2534°F@ 760 mmHg
Melting Point/Range	318°C / 604.4°F
Decomposition temperature	No information available.
Flash Point	Not applicable
Evaporation Rate	No information available.
Specific Gravity	2.13
Solubility	Soluble in water
log Pow	No data available
Molecular Weight	40
Molecular Formula	NaOH

10. STABILITY AND REACTIVITY

Stability	Hygroscopic. Water reactive.
Conditions to Avoid	Avoid dust formation. Incompatible products. Excess heat. Exposure to air or moisture over prolonged periods.
Incompatible Materials	Water, Metals, Acids
Hazardous Decomposition Products	Carbon monoxide (CO), Carbon dioxide (CO_2), Sodium oxides
Hazardous Polymerization	Hazardous polymerization does not occur
Hazardous Reactions .	None under normal processing.

11. TOXICOLOGICAL INFORMATION

Acute Toxicity

Component Information

Component	LD50 Oral	LD50 Dermal	LC50 Inhalation
Sodium hydroxide	Not listed	1350 mg/kg (Rabbit)	Not listed
Sodium carbonate	4090 mg/kg (Rat)	Not listed	Not listed

Irritation	Causes severe burns by all exposure routes
Toxicologically Synergistic Products	No information available.

Chronic Toxicity

Carcinogenicity	There are no known carcinogenic chemicals in this product

Sensitization No information available.

Mutagenic Effects Mutagenic effects have occurred in experimental animals.

Reproductive Effects No information available.

Developmental Effects No information available.

Teratogenicity No information available.

Other Adverse Effects See actual entry in RTECS for complete information.

Endocrine Disruptor Information No information available

12. ECOLOGICAL INFORMATION

Ecotoxicity

Do not empty into drains.

Component	Freshwater Algae	Freshwater Fish	Microtox	Water Flea
Sodium carbonate	EC50 120 h 242 mg/L	Lepomis macrochirus: LC50: 300 mg/L/96h Gambusia affinis: LC50: 740 mg/L/96h	Not listed	EC50 48 h 265 mg/L

Persistence and Degradability No information available

Bioaccumulation/ Accumulation No information available

Mobility No information available

13. DISPOSAL CONSIDERATIONS

Waste Disposal Methods Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification

14. TRANSPORT INFORMATION

DOT

UN-No UN1823
Proper Shipping Name Sodium hydroxide, solid
Hazard Class 8
Packing Group II

TDG

14. TRANSPORT INFORMATION

UN-No UN1823
Proper Shipping Name SODIUM HYDROXIDE, SOLID
Hazard Class 8
Packing Group II

IATA

UN-No UN1823
Proper Shipping Name SODIUM HYDROXIDE, SOLID
Hazard Class 8
Packing Group II

IMDG/IMO

UN-No UN1823
Proper Shipping Name SODIUM HYDROXIDE, SOLID
Hazard Class 8
Packing Group II

15. REGULATORY INFORMATION

International Inventories

Component	TSCA	DSL	NDSL	EINECS	ELINCS	NLP	PICCS	ENCS	AICS	CHINA	KECL
Sodium hydroxide	X	X	-	215-185-5	-		X	X	X	X	KE-31487 X
Sodium carbonate	X	X	-	207-838-8	-		X	X	X	X	KE-31380 X

Legend:
X - Listed
E - Indicates a substance that is the subject of a Section 5(e) Consent order under TSCA.
F - Indicates a substance that is the subject of a Section 5(f) Rule under TSCA.
N - Indicates a polymeric substance containing no free-radical initiator in its inventory name but is considered to cover the designated polymer made with any free-radical initiator regardless of the amount used.
P - Indicates a commenced PMN substance
R - Indicates a substance that is the subject of a Section 6 risk management rule under TSCA.
S - Indicates a substance that is identified in a proposed or final Significant New Use Rule
T - Indicates a substance that is the subject of a Section 4 test rule under TSCA.
XU - Indicates a substance exempt from reporting under the Inventory Update Rule, i.e. Partial Updating of the TSCA Inventory Data Base Production and Site Reports (40 CFR 710(B).
Y1 - Indicates an exempt polymer that has a number-average molecular weight of 1,000 or greater.
Y2 - Indicates an exempt polymer that is a polyester and is made only from reactants included in a specified list of low concern reactants that comprises one of the eligibility criteria for the exemption rule.

U.S. Federal Regulations

TSCA 12(b) Not applicable

SARA 313
Not applicable

SARA 311/312 Hazardous Categorization

Acute Health Hazard	No
Chronic Health Hazard	No
Fire Hazard	No
Sudden Release of Pressure Hazard	No
Reactive Hazard	No

Clean Water Act

Component	CWA - Hazardous Substances	CWA - Reportable Quantities	CWA - Toxic Pollutants	CWA - Priority Pollutants
Sodium hydroxide	X	1000 lb	-	-

Clean Air Act
Not applicable

OSHA
Not applicable

CERCLA
This material, as supplied, contains one or more substances regulated as a hazardous substance under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302)

Component	Hazardous Substances RQs	CERCLA EHS RQs
Sodium hydroxide	1000 lb	-

California Proposition 65
This product does not contain any Proposition 65 chemicals.

State Right-to-Know

Component	Massachusetts	New Jersey	Pennsylvania	Illinois	Rhode Island
Sodium hydroxide	X	X	X	-	X

U.S. Department of Transportation

Reportable Quantity (RQ):	Y
DOT Marine Pollutant	N
DOT Severe Marine Pollutant	N

U.S. Department of Homeland Security

This product does not contain any DHS chemicals.

Other International Regulations

Mexico - Grade No information available

Canada

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

WHMIS Hazard Class
E Corrosive material

16. OTHER INFORMATION

Prepared By	Regulatory Affairs Thermo Fisher Scientific Tel: (412) 490-8929
Creation Date	11-Feb-2010
Print Date	11-Feb-2010
Revision Summary	"***", and red text indicates revision

Disclaimer
The information provided on this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guide for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered as a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other material or in any process, unless specified in the text.

End of MSDS

Material Safety Data Sheet

Phosphoric Acid

1. PRODUCT AND COMPANY IDENTIFICATION

Product Name: Phosphoric Acid

Synonyms/Generic Names: Orthophosphoric Acid.

Product Use: Industrial, Manufacturing or Laboratory use

Manufacturer: Columbus Chemical Industries, Inc.
N4335 Temkin Rd. Columbus, WI. 53925

For More Information Call: 920-623-2140
(Monday – Friday 8:00-4:30)

IN CASE OF EMERGENCY CALL: CHEMTREC 800-424-9300
(24 Hours/Day, 7 Days/Week)

2. COMPOSITION/INFORMATION ON INGREDIENTS

Weight %	Component	CAS #	EINECS# / ELINCS#	Classification*
85%	Phosphoric Acid	7664-38-2	231-633-2	C; R34, **

*Symbol and R phrase according to EC Annex1
** Subject to the reporting requirements of SARA Title III Section 313

3. HAZARDS IDENTIFICATION

Clear, colorless solution with caustic odor.

R34 – Causes burns.

S1/2, S26, S45

Routes of Entry: Skin, eyes, inhalation and ingestion.

Ingredients found on carcinogen lists:

INGREDIENT NAME	NTP STATUS	IARC STATUS	OSHA LIST	ACGIH
Phosphoric Acid	Not Listed	Not Listed	Not Listed	Not Listed

4. FIRST AID INFORMATION

Inhalation: Inhalation of mists can cause corrosive action on mucous membranes. Symptoms include burning, choking, coughing, wheezing, laryngitis, shortness of breath, headache or nausea. Move casualty to fresh air and keep at rest. Get medical attention if symptoms persist.

Eyes: Symptoms include eye burns, watering eyes. Rinse with plenty of water for a minimum of 15 minutes and seek medical attention immediately.

Skin: Symptoms include burning, itching, redness, inflammation and/or swelling of exposed tissues. Immediately flush with plenty of water for at least 15 minutes while removing contaminated clothing and wash using soap. Get medical attention if necessary.

Ingestion: **Do Not Induce Vomiting!** Causes corrosive burns of the mouth, gullet and gastrointestinal tract if swallowed. Symptoms include burning, choking, nausea, vomiting and severe pain. Wash out mouth with water and give a glass of water or milk. Get medical attention immediately.

5. FIRE-FIGHTING MEASURES

FLAMMABLE PROPERTIES:

Flash Point:	Not Flammable
Flash Point method:	Not Applicable
Autoignition Temperature:	Not Applicable
Upper Flame Limit (volume % in air):	Not Applicable
Lower Flame Limit (volume % in air):	Not Applicable

Extinguishing Media: Product is not flammable. Use appropriate media for adjacent fire. Cool containers with water, keep away from common metals.

Special fire-fighting procedures: Wear self-contained, approved breathing apparatus and full protective clothing, including eye protection and boots.

Hazardous combustion products: Emits toxic fumes under fire conditions. (See also Stability and Reactivity section).

Unusual fire and explosion hazards: Material can react with metals to produce flammable hydrogen gas. Forms flammable gases with aldehydes, cyanides, mercaptins, and sulfides.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions: See section 8 for recommendations on the use of personal protective equipment.

Environmental precautions: Cleanup personnel need personal protection from inhalation and skin/eye contact. Evacuate and ventilate the area. Prevent spillage from entering drains. Cautiously add water to spill, taking care to avoid splashing and spattering. Neutralize diluted spill with soda ash or lime. Absorb neutralized spill with vermiculite or other inert absorbent material, then place in a suitable container for disposal. Clean surfaces thoroughly with water to remove residual contamination. Any release to the environment may be subject to federal/national or local reporting requirements. Dispose of all waste or cleanup materials in accordance with local regulations. Containers, even when empty, will retain residue and vapors.

7. HANDLING AND STORAGE

Normal handling: See section 8 for recommendations on the use of personal protective equipment. Use with adequate ventilation. Wash thoroughly after using. Keep container closed when not in use.

Storage: Store in cool, dry well ventilated area. Keep away from incompatible materials (see section 10 for incompatibilities). Drains for storage or use areas for this material should have retention basins for pH adjustment and dilution of spills.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Occupational exposure controls: (consult local authorities for acceptable exposure limits)

Chemical name	Regulatory List	Value and type
Phosphoric Acid	UK OES	1 mg/m^3
	STEL	3 mg/m^3 (10 minutes)
	USA OSHA PEL	1 mg/m^3
	STEL	3 mg/m^3 (15 minutes)
	USA ACGIH TLV	1 mg/m^3
	STEL	3 mg/m^3 (15 minutes)
	USA OSHA PEL	1 mg/m^3
	STEL	3 mg/m^3 (15 minutes)
	USA NIOSH REL	1 mg/m^3
	STEL	3 mg/m^3 (15 minutes)
	Mexico PEL	1 mg/m^3
	STEL	3 mg/m^3 (15 minutes)
	OSHA IDLH	1000 mg/m^3
	France VME	1 mg/m^3
	France VLE (STEL)	3 mg/m^3 (15 minutes)

TWA: Time Weighted Average over 8 hours of work.
TLV: Threshold Limit Value over 8 hours of work.
REL: Recommended Exposure Limit
STEL: Short Term Exposure Limit during x minutes.
IDLH: Immediately Dangerous to Life or Health

Ventilation: Provide local exhaust, preferably mechanical.

Respiratory protection: If necessary use an approved respirator with acid vapor cartridges.

Eye protection: Wear chemical safety glasses with a face shield for splash protection.

Skin and body protection: Wear neoprene or rubber gloves, apron and other protective clothing appropriate to the risk of exposure.

Other Recommendations: Provide eyewash stations, quick-drench showers and washing facilities accessible to areas of use and handling. Have supplies and equipment for neutralization and running water available.

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance:	Clear, colorless, viscous liquid
Physical state:	Liquid
Odor:	Acidic
Odor Threshold:	Not Available
Specific Gravity:	1.6900
pH:	1
Melting Point/Freezing Point:	42°C (108°F)
Boiling Point/Range:	213°C (415°F)
Flammability:	Not Flammable (See section 5)
Flash point:	Not Flammable (See section 5)
Evaporation Rate (Butyl Acetate =1):	Not Available
Explosive Limits:	Not Explosive (See section 5)
Vapor Pressure (at 20ºC):	0.03 mmHg
Vapor Density (air =1):	3.4
Solubility:	Completely soluble in water
Partition coefficient/n-octanol/water:	Not Available
% Volatile:	Not Available
Autoignition Temperature:	See section 5

10. STABILITY AND REACTIVITY

Stability: Stable

Conditions to avoid: Incompatible materials.

Incompatibility: Bases, combustible material, metals.

Hazardous decomposition products: Phosphorus oxides.

Hazardous polymerization: Will not occur.

11. TOXICOLOGICAL INFORMATION

Acute Effects: See section 4 for symptoms of exposure and effects. Likely routes of exposure are skin, eyes and inhalation.
Target organs: Blood, liver, skin, eyes and bone marrow.

Acute Toxicity Data:

Phosphoric acid	LD50 [oral, rat]; 1530 mg/kg
	LC50 [rabbit]; 1.689 mg/L (1 hour)
	LD50 Dermal (rabbit); 2740 mg/kg

Chronic Effects: May affect liver, conjunctivitis, dermatitis, pulmonary edema.

Teratogenicity: Negative
Mutagenicity: Negative
Embryotoxicity: Negative
Synergistic Products/Effects: Not Available

12. ECOLOGICAL INFORMATION

Ecotoxicity (aquatic and terrestrial): DL50 12 hours@ pH of 3 – 3.5
DL50 (12 hours): pH 4.6 (Daphnia Magna)

Persistence and Degradability: Not Available

Bioaccumulative Potential: Not Available

Mobility in Soil: Not Available

Other Adverse Effects: Not Available

13. DISPOSAL CONSIDERATIONS

RCRA:
Hazardous waste? Yes RCRA ID number: DOO2

Waste Residues: Carefully dilute with water, neutralize per spill procedures in section 6. Neutralized material may be flushed to sewer (REGULATIONS PERMITTING!) or disposed of through a licensed contractor. Users should review their operations in terms of the applicable federal/nation or local regulations and consult with appropriate regulatory agencies before discharging or disposing of waste material.

Product containers: Containers, if thoroughly cleaned, preferably by rinsing three times and handling the rinse water as waste residues, may be disposed of or recycled as non-hazardous waste. Users should review their operations in terms of the applicable federal/national or local regulations and consult with appropriate regulatory agencies before discharging or disposing of waste material.

The information offered in section 13 is for the product as shipped. Use and/or alterations to the product may significantly change the characteristics of the material and alter the waste classification and proper disposal methods.

14. TRANSPORTATION INFORMATION

DOT: UN1805, Phosphoric Acid solution, 8, pg III

TDG: UN1805, Phosphoric Acid liquid, 8, pg III

PIN: Not Available

IDMG: UN1805, 8, pg III
Marine Pollutant: No

IATA/ICAO: UN1805, 8, pg III

RID/ADR: Class 8, Item 17(c), corrosive, UN1805

15. REGULATORY INFORMATION

TSCA Inventory Status: All ingredients are listed on the TSCA inventory.

Federal and State Regulations:
Illinois toxic substances disclosure to employee act: Phosphoric acid
Illinois chemical safety act: Phosphoric acid
New York release reporting list: Phosphoric acid
Rhode Island RTK hazardous substances: Phosphoric acid
Pennsylvania RTK: Phosphoric acid
Minnesota: Phosphoric acid
Massachusetts RTK: Phosphoric acid
Massachusetts spill list: Phosphoric acid
New Jersey: Phosphoric acid
New Jersey spill list: Phosphoric acid
Louisiana spill reporting: Phosphoric acid
California Director's list of hazardous substances: Phosphoric acid

SARA 302/304/311/312 extremely hazardous substances: Phosphoric Acid
SARA 313 toxic chemical notification and release reporting: Phosphoric Acid
CERCLA: Hazardous Substances: Phosphoric Acid, 5000lbs.

California Proposition 65:	No
WHMIS Canada:	Class E - corrosive liquid.
DSCL (EEC):	R34 – Causes burns.

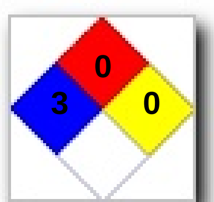
HMIS (U.S.A.)

Health Hazard	**3**
Fire Hazard	**0**
Reactivity	**0**

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

Flammability

Health



Reactivity

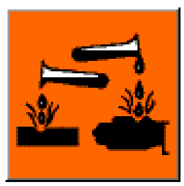
Specific hazard

Protective Equipment:

ADR (Europe):

TDG (Canada):

DSCL (Europe):



1. OTHER INFORMATION

Current Issue Date: November 30, 2005
Previous Issue Date: N/A
Prepared by: Sherry Brock (920) 623-2140

Material Safety Data Sheet

Nitric Acid

1. PRODUCT AND COMPANY IDENTIFICATION

Product Name: Nitric Acid

Synonyms/Generic Names: Aqua Fortis, Azotic acid, Hydrogen nitrate.

Product Use: Industrial, Manufacturing or Laboratory use

Manufacturer: Columbus Chemical Industries, Inc.
N4335 Temkin Rd. Columbus, WI. 53925

For More Information Call: 920-623-2140
(Monday – Friday 8:00-4:30)

IN CASE OF EMERGENCY CALL: CHEMTREC
(24 Hours/Day, 7 Days/Week) 800-424-9300

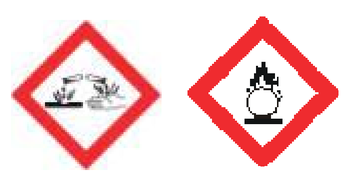
2. COMPOSITION/INFORMATION ON INGREDIENTS

Weight %	Component	CAS #	EINECS# / ELINCS#	Classification*
68 - 70%	Nitric Acid	7697-37-2	231-714-2	O; R8 -C; R35, **

*Symbol and R phrase according to EC Annex1
** Subject to the reporting requirements of SARA Title III Section 313

3. HAZARDS IDENTIFICATION

Clear, colorless to yellow solution with caustic odor.



R35 – Causes severe burns.
R8 – Contact with combustible material may cause fire.

S1/2, S23, S26, S36, S45

Routes of Entry: Skin, eyes, inhalation and ingestion.

Ingredients found on carcinogen lists:

INGREDIENT NAME	NTP STATUS	IARC STATUS	OSHA LIST	ACGIH
Nitric Acid	Not Listed	Not Listed	Not Listed	Not Listed

4. FIRST AID INFORMATION

Inhalation: Inhalation of mists can cause corrosive action on mucous membranes. Symptoms include burning, choking, coughing, wheezing, laryngitis, shortness of breath, headache or nausea. Move casualty to fresh air and keep at rest. May be fatal if inhaled, may cause delayed pulmonary edema. Get medical attention.

Eyes: Contact rapidly causes severe damage. Symptoms include eye burns, watering eyes. Permanent damage to cornea may result. In case of eye contact, rinse with plenty of water and seek medical attention immediately.

Skin: Severe and rapid corrosion from contact. Extent of damage depends on duration of contact. Symptoms include burning, itching, redness, inflammation and/or swelling of exposed tissues. harmful if absorbed through skin. Immediately flush with plenty of water for at least 15 minutes while removing contaminated clothing and wash using soap. Get medical attention immediately.

Ingestion: **Do Not Induce Vomiting!** Severe and rapid corrosive burns of the mouth, gullet and gastrointestinal tract will result if swallowed. Symptoms include burning, choking, nausea, vomiting and severe pain. Wash out mouth with water and give a glass of water or milk. Get medical attention immediately.

5. FIRE-FIGHTING MEASURES

FLAMMABLE PROPERTIES:

Flash Point:	Not Flammable
Flash Point method:	Not Applicable
Autoignition Temperature:	Not Applicable
Upper Flame Limit (volume % in air):	Not Applicable
Lower Flame Limit (volume % in air):	Not Applicable

Extinguishing Media: Product is not flammable. Use appropriate media for adjacent fire. Use flooding quantities of water to cool containers, keep away from common metals.

Special fire-fighting procedures: Wear self-contained, approved breathing apparatus and full protective clothing, including eye protection and boots. Material can react violently with water (spattering and misting) and react with metals to produce flammable hydrogen gas.

Hazardous combustion products: Emits toxic fumes under fire conditions. (See also Stability and Reactivity section).

Unusual fire and explosion hazards: Strong Oxidizer! Contact with organic material may cause fire. Material will react with metals to produce flammable hydrogen gas.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions: See section 8 for recommendations on the use of personal protective equipment.

Environmental precautions: Cleanup personnel need personal protection from inhalation and skin/eye contact. Evacuate and ventilate the area. Prevent spillage from entering drains. Cautiously add water to spill, taking care to avoid splashing and spattering. Neutralize diluted spill with soda ash or lime. Absorb neutralized spill with vermiculite or other inert absorbent material, then place in a suitable container for disposal. Clean surfaces thoroughly with water to remove residual contamination. Any release to the environment may be subject to federal/national or local reporting requirements. Dispose of all waste or cleanup materials in accordance with local regulations. Containers, even when empty, will retain residue and vapors.

7. HANDLING AND STORAGE

Normal handling: See section 8 for recommendations on the use of personal protective equipment. Use with adequate ventilation. Wash thoroughly after using. Keep container closed when not in use.

Storage: Store in cool, dry well ventilated area. Keep away from incompatible materials (see section 10 for incompatibilities). Drains for storage or use areas for this material should have retention basins for pH adjustment and dilution of spills.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Occupational exposure controls: (consult local authorities for acceptable exposure limits)

Chemical name	Regulatory List	Value and type
Nitric Acid	UK OES	5 mg/m^3 TWA
	STEL	10 mg/m^3 (10 minutes)
	USA OSHA PEL	5 mg/m^3 TWA
	STEL	10 mg/m^3 (15 minutes)
	USA ACGIH	5 mg/m^3 TLV
	USA NIOSH	5 mg/m^3 REL
	STEL	10 mg/m^3 (15 minutes)
	USA OSHA - IDLH	25 ppm
	VME France	5 mg/m^3 TWA 8 hr
	VLE France (STEL)	10 mg/m^3 (15 minutes)

TWA: Time Weighted Average over 8 hours of work.
TLV: Threshold Limit Value over 8 hours of work.
REL: Recommended Exposure Limit
STEL: Short Term Exposure Limit during x number of minutes.
IDLH: Immediately Dangerous to Life or Health

Ventilation: Provide local exhaust, preferably mechanical.

Respiratory protection: If necessary use an approved respirator with acid vapor cartridges.

Eye protection: Wear chemical safety glasses with a face shield for splash protection.

Skin and body protection: Wear neoprene or rubber gloves, apron and other protective clothing appropriate to the risk of exposure.

Other Recommendations: Provide eyewash stations, quick-drench showers and washing facilities accessible to areas of use and handling. Have supplies and equipment for neutralization and running water available.

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance:	Clear, colorless to slight brown liquid
Physical state:	Liquid
Odor:	Acrid, suffocating odor
Odor Threshold:	Unknown
Specific Gravity:	1.4200
pH:	1
Melting Point/Freezing Point:	-42°C (-44°F)
Boiling Point/Range:	122°C (252°F)
Flammability:	Not Flammable (See section 5)
Flash point:	Not Flammable (See section 5)
Evaporation Rate (Butyl Acetate =1):	Not Available
Explosive Limits:	Not Explosive (See section 5)
Vapor Pressure (at 25ºC):	10 mmHg
Vapor Density (air =1):	2.5
Solubility:	Completely soluble in water
Partition coefficient/n-octanol/water:	-2.3 @ 25 ºC
% Volatile:	Not Available
Autoignition Temperature:	See section 5

10. STABILITY AND REACTIVITY

Stability: Stable

Conditions to avoid: Uncontrolled addition of water, contact with combustible materials.

Incompatibility: Moisture, bases, organic material, metals, hydrogen sulfide, carbides, alcohols, organic solvents, carbides, cyanides, sulfides.

Hazardous decomposition products: Oxides of nitrogen.

Hazardous polymerization: Will not occur.

11. TOXICOLOGICAL INFORMATION

Acute Effects: See section 4 for symptoms of exposure and effects. Likely routes of exposure are skin, eyes and inhalation.
Target organs: Teeth, eyes, skin, respiratory system.

Acute Toxicity Data:

Nitric acid	LC_{50} (rat): 0.8 mg/L

Chronic Effects: Not Available

Teratogenicity: None found
Mutagenicity: None found
Embryotoxicity: None found
Synergistic Products/Effects: Not Available

12. ECOLOGICAL INFORMATION

Ecotoxicity (aquatic and terrestrial): Aquatic fish; LC50 (96 hrs): 72 mg/l (Gambusia affinis)

Persistence and Degradability: Not Available

Bioaccumulative Potential: Not Available

Mobility in Soil: Not Available

Other Adverse Effects: Not Available

13. DISPOSAL CONSIDERATIONS

RCRA:
Hazardous waste? Yes RCRA ID number: DOO2

Waste Residues: Carefully dilute with water, neutralize per spill procedures in section 6. Neutralized material may be flushed to sewer (REGULATIONS PERMITTING!) or disposed of through a licensed contractor. Users should review their operations in terms of the applicable federal/nation or local regulations and consult with appropriate regulatory agencies before discharging or disposing of waste material.

Product containers: Containers, if thoroughly cleaned, preferably by rinsing three times and handling the rinse water as waste residues, may be disposed of or recycled as non-hazardous waste. Users should review their operations in terms of the applicable federal/national or local regulations and consult with appropriate regulatory agencies before discharging or disposing of waste material.

The information offered in section 13 is for the product as shipped. Use and/or alterations to the product may significantly change the characteristics of the material and alter the waste classification and proper disposal methods.

14. TRANSPORTATION INFORMATION

DOT: UN2031, Nitric Acid, 8, pg II

TDG: UN2031, Nitric Acid, 8, pg II

PIN: Not Available

IDMG: UN2031, Nitric Acid, 8, pg II
Marine Pollutant: No

IATA/ICAO: UN2031, Nitric Acid, 8, pg II

RID/ADR: Class 8, Item 2(b), corrosive

15. REGULATORY INFORMATION

TSCA Inventory Status: All ingredients are listed on the TSCA inventory.

Federal and State Regulations:
Pennsylvania RTK: Nitric Acid
Massachusetts RTK: Nitric Acid

SARA 302/304/311/312 extremely hazardous substances: Nitric Acid
SARA 313 toxic chemical notification and release reporting: Nitric Acid
CERCLA: Hazardous Substances: Nitric Acid 1000 lbs

California Proposition 65: No.
WHMIS Canada: Class E - corrosive liquid.
DSCL (EEC): R35 – Causes severe burns, R8 - Contact with combustible material may cause fire.

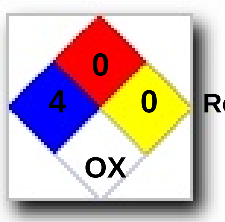
HMIS (U.S.A.)

Health Hazard	3
Fire Hazard	0
Reactivity	2

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

Flammability

Health



Reactivity

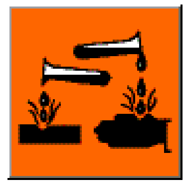
Specific hazard

Protective Equipment:

ADR (Europe):

TDG (Canada):

DSCL (Europe):



1. OTHER INFORMATION

Current Issue Date: November 30, 2005
Previous Issue Date: N/A
Prepared by: Sherry Brock (920) 623-2140

Material Safety Data Sheet

Carbon Dioxide

Airgas

Section 1. Chemical product and company identification

Product name : Carbon Dioxide

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

Product use : Synthetic/Analytical chemistry.

Synonym : Carbonic Acid, Carbon Dioxide Liquid, Carbon Dioxide, Refrigerated Liquid, Carbonic Anhydride

MSDS # : 001013

Date of Preparation/Revision : **1/20/2012.**

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

Section 2. Hazards identification

Physical state : Gas or Liquid.

Emergency overview : WARNING!

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

Do not puncture or incinerate container. Avoid contact with eyes, skin and clothing. May cause target organ damage, based on animal data. Wash thoroughly after handling. Keep container closed. Avoid breathing gas. Use with adequate ventilation.

Contact with rapidly expanding gas, liquid, or solid can cause frostbite.

Target organs : May cause damage to the following organs: lungs.

Routes of entry : Inhalation Dermal Eyes

Potential acute health effects

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

Skin : Moderately irritating to the skin. Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.

Inhalation : Moderately irritating to the respiratory system.

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

Potential chronic health effects

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

Target organs : May cause damage to the following organs: lungs.

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

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

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

Section 4. First aid measures

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

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

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

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

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

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

Section 5. Fire-fighting measures

Flammability of the product : Non-flammable.

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

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

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

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

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

Section 6. Accidental release measures

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

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

Methods for cleaning up : Immediately contact emergency personnel. Stop leak if without risk. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Section 7. Handling and storage

Handling : Wash thoroughly after handling. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Avoid contact with skin and clothing. Use with adequate ventilation. Avoid contact with eyes. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement. Never allow any unprotected part of the body to touch uninsulated pipes or vessels that contain cryogenic liquids. Prevent entrapment of liquid in closed systems or piping without pressure relief devices. Some materials may become brittle at low temperatures and will easily fracture.

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

Section 8. Exposure controls/personal protection

Engineering controls : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits.

Personal protection

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

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

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

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

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

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

Insulated gloves suitable for low temperatures

Personal protection in case of a large spill : Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product. Full chemical-resistant suit and self-contained breathing apparatus should be worn only by trained and authorized persons.

Product name

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

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight : 44.01 g/mole

Molecular formula : C-O2

Melting/freezing point : Sublimation temperature: -79°C (-110.2 to °F)

Critical temperature : 30.9°C (87.6°F)

Vapor pressure : 830 (psig)

Vapor density : 1.53 (Air = 1) Liquid Density@BP: Solid density = 97.5 lb/ft3 (1562 kg/m3)

Specific Volume (ft^3/lb) : 8.7719

Gas Density (lb/ft^3) : 0.114

Section 10. Stability and reactivity

Stability and reactivity : The product is stable.

Hazardous decomposition products : Under normal conditions of storage and use, hazardous decomposition products should not be produced.

Hazardous polymerization : Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

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

IDLH : 40000 ppm

Chronic effects on humans : May cause damage to the following organs: lungs.

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

Specific effects

Carcinogenic effects : No known significant effects or critical hazards.

Mutagenic effects : No known significant effects or critical hazards.

Reproduction toxicity : No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Toxicity of the products of biodegradation : not available

Environmental fate : Not available.

Environmental hazards : This product shows a low bioaccumulation potential.

Toxicity to the environment : Not available.

Section 13. Disposal considerations

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

Section 14. Transport information

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

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

Section 15. Regulatory information

United States

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

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

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

Canada

WHMIS (Canada) : Class A: Compressed gas.

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

Section 16. Other information

United States

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

Canada

Label requirements : Class A: Compressed gas.

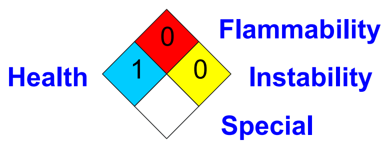
Hazardous Material Information System (U.S.A.) :

Health	*	1
Flammability		0
Physical hazards		0

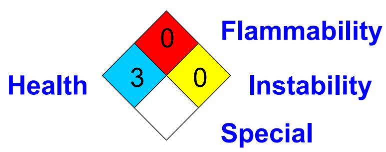
liquid:

Health		3
Fire hazard		0
Reactivity		0
Personal protection		

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



liquid:



Notice to reader

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

Material Safety Data Sheet

Nitrogen

Airgas

Section 1. Chemical product and company identification

Product name	:	Nitrogen
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. Liquid – cryogenic coolant.
Synonym	:	nitrogen (dot); nitrogen gas; Nitrogen NF, LIN, Cryogenic Liquid Nitrogen, Liquid Nitrogen
MSDS #	:	001040
Date of Preparation/Revision	:	**1/14/2011.**
In case of emergency	:	1-866-734-3438

Section 2. Hazards identification

Physical state	:	Gas. [NORMALLY A COLORLESS GAS: MAY BE A CLEAR COLORLESS LIQUID AT LOW TEMPERATURES. SOLD AS A COMPRESSED GAS OR LIQUID IN STEEL CYLINDERS.]
Emergency overview	:	WARNING! GAS: CONTENTS UNDER PRESURE. Do not puncture or incinerate container. Can cause rapid suffocation. May cause severe frostbite. LIQUID: Extremely cold liquid and gas under pressure. Can cause rapid suffocation. May cause severe frostbite. Do not puncture or incinerate container. Contact with rapidly expanding gases or liquids can cause frostbite.
Routes of entry	:	Inhalation
Potential acute health effects		
Eyes	:	Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Skin	:	Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Inhalation	:	Acts as a simple asphyxiant.
Ingestion	:	Ingestion is not a normal route of exposure for gases. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Medical conditions aggravated by over-exposure	:	Acute or chronic respiratory conditions may be aggravated by overexposure to this gas.

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Nitrogen	7727-37-9	100	Oxygen Depletion [Asphyxiant]

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 : None expected.

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

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

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

Section 5. Fire-fighting measures

Flammability of the product : Non-flammable.

Products of combustion : Decomposition products may include the following materials: nitrogen oxides

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 : High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
Never allow any unprotected part of the body to touch uninsulated pipes or vessels that contain cryogenic liquids. Prevent entrapment of liquid in closed systems or piping without pressure relief devices. Some materials may become brittle at low temperatures and will easily fracture.

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

Section 8. Exposure controls/personal protection

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

Product name

Nitrogen	Oxygen Depletion [Asphyxiant]

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 28.02 g/mole
Molecular formula	: N2
Boiling/condensation point	: -195.8°C (-320.4°F)
Melting/freezing point	: -210°C (-346°F)
Critical temperature	: -146.9°C (-232.4°F)
Vapor density	: 0.967 (Air = 1) Liquid Density@BP: 50.46 lb/ft3 (808.3 kg/m3)
Specific Volume (ft^3/lb)	: 13.8889
Gas Density (lb/ft^3)	: 0.072

Section 10. Stability and reactivity

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

Section 11. Toxicological information

Toxicity data

Other toxic effects on humans	: No specific information is available in our database regarding the other toxic effects of this material to humans.
Specific effects	
Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Nitrogen

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Environmental fate : Not available.

Environmental hazards : No known significant effects or critical hazards.

Toxicity to the environment : Not available.

Section 13. Disposal considerations

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

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1066 UN1977	NITROGEN, COMPRESSED Nitrogen, refrigerated liquid	2.2	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: 75 kg **Cargo aircraft** Quantity limitation: 150 kg
TDG Classification	UN1066 UN1977	NITROGEN, COMPRESSED Nitrogen, refrigerated liquid	2.2	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **Passenger Carrying Road or Rail Index** 75
Mexico Classification	UN1066 UN1977	NITROGEN, COMPRESSED Nitrogen, refrigerated liquid	2.2	Not applicable (gas).		-

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

Section 15. Regulatory information

United States

U.S. Federal regulations : **TSCA 8(a) IUR**: Partial exemption
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: Nitrogen
SARA 311/312 MSDS distribution - chemical inventory - hazard identification:
Nitrogen: Sudden release of pressure

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

Section 16. Other information

United States

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

Canada

Label requirements : Class A: Compressed gas.

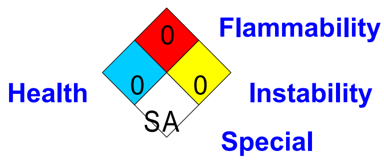
Hazardous Material Information System (U.S.A.) :

Health	0
Flammability	0
Physical hazards	0

liquid:

Health	3
Fire hazard	0
Reactivity	0
Personal protection	

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



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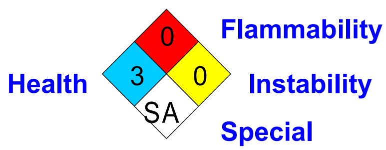


Notice to reader

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

Oxygen

Section 1. Chemical product and company identification

Product name : Oxygen

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 : Molecular oxygen; Oxygen molecule; Pure oxygen; O2; Liquid-oxygen-; UN 1072; UN 1073; Dioxygen; Oxygen USP, Aviator's Breathing Oxygen (ABO)

MSDS # : 001043

Date of Preparation/Revision : **6/16/2011.**

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

Section 2. Hazards identification

Physical state : Gas.

Emergency overview : DANGER!

GAS:
OXIDIZER.
CONTACT WITH COMBUSTIBLE MATERIAL MAY CAUSE FIRE.
CONTENTS UNDER PRESURE.
Do not puncture or incinerate container.
May cause severe frostbite.
LIQUID:
OXIDIZER.
CONTACT WITH COMBUSTIBLE MATERIAL MAY CAUSE FIRE.
Extremely cold liquid and gas under pressure.
May cause severe frostbite.

Do not puncture or incinerate container. Store in tightly-closed container. Avoid contact with combustible materials.

Contact with rapidly expanding gases or liquids can cause frostbite.

Routes of entry : Inhalation

Potential acute health effects

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

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

Inhalation : Respiratory system irritation after overexposure to high oxygen concentrations.

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

Medical conditions aggravated by over-exposure : Acute or chronic respiratory conditions may be aggravated by overexposure to this gas.

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Oxygen	7782-44-7	100	

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 : None expected.

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

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

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 : No specific data.

Fire hazards in the presence of various substances : Extremely flammable in the presence of the following materials or conditions: reducing materials, combustible materials and organic materials.

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. Contact with combustible material may cause fire. This material increases the risk of fire and may aid combustion. 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). Eliminate all ignition sources if safe to do so. Do not touch or walk through spilled material. 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 : High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Store in tightly-closed container. Avoid contact with combustible materials. 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 tightly closed. Keep container in a cool, well-ventilated area. Separate from acids, alkalies, reducing agents and combustibles. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).
For additional information concerning storage and handling refer to Compressed Gas Association pamphlets P-1 Safe Handling of Compressed Gases in Containers and P-12 Safe Handling of Cryogenic Liquids available from the Compressed Gas Association, Inc.

Section 8. Exposure controls/personal protection

Engineering controls : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits.

Personal protection

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

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

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

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

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

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

Insulated gloves suitable for low temperatures

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

Product name

Oxygen

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight : 32 g/mole

Molecular formula : O2

Boiling/condensation point : -183°C (-297.4°F)

Melting/freezing point : -218.4°C (-361.1°F)

Critical temperature : -118.6°C (-181.5°F)

Vapor density : 1.105 (Air = 1) Liquid Density@BP: 71.23 lb/ft3 (1141 kg/m3)

Specific Volume (ft ^{3}/lb) : 12.0482

Gas Density (lb/ft ^{3}) : 0.083

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, reducing materials and combustible materials.

Hazardous decomposition products : Under normal conditions of storage and use, hazardous decomposition products should not be produced.

Hazardous polymerization : Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

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

Specific effects

Carcinogenic effects : No known significant effects or critical hazards.

Mutagenic effects : No known significant effects or critical hazards.

Reproduction toxicity : No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Environmental fate : Not available.

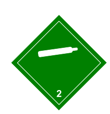
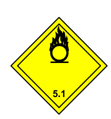
Environmental hazards : This product shows a low bioaccumulation potential.

Toxicity to the environment : Not available.

Section 13. Disposal considerations

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

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1072 UN1073	OXYGEN, COMPRESSED Oxygen, refrigerated liquid	2.2	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: 75 kg **Cargo aircraft** Quantity limitation: 150 kg **Special provisions** A52
TDG Classification	UN1072 UN1073	OXYGEN, COMPRESSED Oxygen, refrigerated liquid	2.2	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **ERAP Index** 3000 **Passenger Carrying Ship**

						Index 50 **Passenger Carrying Road or Rail Index** 75 **Special provisions** 42
Mexico Classification	UN1072 UN1073	OXYGEN, COMPRESSED Oxygen, refrigerated liquid	2.2	Not applicable (gas).	 	-

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

Section 15. Regulatory information

United States

U.S. Federal regulations : **TSCA 8(a) IUR**: Partial exemption
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: Oxygen
SARA 311/312 MSDS distribution - chemical inventory - hazard identification:
Oxygen: Fire hazard, Sudden release of pressure, 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.
Class C: Oxidizing material.

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

Section 16. Other information

United States

Label requirements : GAS:
OXIDIZER.
CONTACT WITH COMBUSTIBLE MATERIAL MAY CAUSE FIRE.
CONTENTS UNDER PRESURE.
Do not puncture or incinerate container.
May cause severe frostbite.
LIQUID:
OXIDIZER.
CONTACT WITH COMBUSTIBLE MATERIAL MAY CAUSE FIRE.
Extremely cold liquid and gas under pressure.
May cause severe frostbite.

Canada

Label requirements : Class A: Compressed gas.
Class C: Oxidizing material.

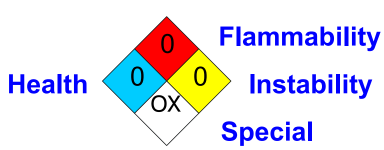
Hazardous Material Information System (U.S.A.) :

Health	0
Flammability	0
Physical hazards	0

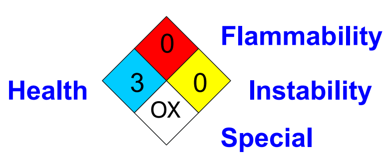
liquid:

Health	3
Fire hazard	0
Reactivity	0
Personal protection	

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



liquid:



Notice to reader

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Material Safety Data Sheet

Ethylene

Section 1. Chemical product and company identification

Product name : Ethylene

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 : ACETENE ;ATHYLEN (GERMAN) ; BICARBURRETTED HYDROGEN ; ELAYL ; ETHENE ; ETHYLENE (ACGIH, DOT, OSHA) ; ETHYLENE, REFRIGERATED LIQUID (CRYOGENIC LIQUID) (UN1038) (DOT) ; LIQUID ETHYLENE ; OLEFIANT GAS UN1038 (DOT) ; UN1962 (DOT)

MSDS # : 001022

Date of Preparation/Revision : **5/11/2011.**

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

Section 2. Hazards identification

Physical state : Gas or Liquid.

Emergency overview : WARNING!

GAS:
CONTENTS UNDER PRESURE.
Extremely flammable
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 can cause frostbite.

Target organs : May cause damage to the following organs: lungs, heart, muscle tissue.

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: lungs, heart, muscle tissue.

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

See toxicological information (Section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Ethylene	74-85-1	100	**ACGIH TLV (United States, 2/2010).** TWA: 200 ppm 8 hour(s).

Section 4. First aid measures

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

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

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

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

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

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

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 490°C (914°F)

Flash point : Closed cup: -135.85°C (-212.5°F).

Flammable limits : Lower: 2.7% Upper: 36%

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.

Storage : Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame). Segregate from oxidizing materials. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Section 8. Exposure controls/personal protection

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

Personal protection

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

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

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

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

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

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

Product name	
Ethylene	**ACGIH TLV (United States, 2/2010).** TWA: 200 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight : 28.06 g/mole

Molecular formula : C2-H4

Boiling/condensation point : -104°C (-155.2°F)

Melting/freezing point : -169.2°C (-272.6°F)

Critical temperature : 10°C (50°F)

Vapor density : 1 (Air = 1) Liquid Density@BP: 35.3 lb/ft3 (566 kg/m3)

Specific Volume (ft ^{3}/lb) : 13.8007

Gas Density (lb/ft ^{3}) : 0.07246

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 : **CARCINOGENIC EFFECTS**: A4 (Not classifiable for humans or animals.) by ACGIH, 3 (Not classifiable for humans.) by IARC.
May cause damage to the following organs: lungs, heart, muscle tissue.

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

Specific effects

Carcinogenic effects : No known significant effects or critical hazards.

Mutagenic effects : No known significant effects or critical hazards.

Reproduction toxicity : No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

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

Environmental fate : Not available.

Environmental hazards : No known significant effects or critical hazards.

Toxicity to the environment : Not available.

Section 13. Disposal considerations

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

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1962	ETHYLENE, COMPRESSED	2.1	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: Forbidden. **Cargo aircraft** Quantity limitation: Forbidden. **Special provisions**
	UN1038	ETHYLENE, REFRIGERATED LIQUID	2.1			

						T75, TP5
TDG Classification	UN1962 UN1038	ETHYLENE, COMPRESSED ETHYLENE, REFRIGERATED LIQUID	2.1 2.1	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **ERAP Index** 3000 **Passenger Carrying Ship Index** Forbidden **Passenger Carrying Road or Rail Index** Forbidden
Mexico Classification	UN1962 UN1038	ETHYLENE, COMPRESSED ETHYLENE, REFRIGERATED LIQUID	2.1 2.1	Not applicable (gas).		-

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

Section 15. Regulatory information

United States

U.S. Federal regulations : **TSCA 8(a) IUR**: Partial exemption
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: Ethylene
SARA 311/312 MSDS distribution - chemical inventory - hazard identification:
Ethylene: Fire hazard, reactive, Sudden release of pressure, Delayed (chronic) health hazard

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

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

SARA 313

	Product name	CAS number	Concentration
Form R - Reporting requirements :	Ethylene	74-85-1	100
Supplier notification :	Ethylene	74-85-1	100

SARA 313 notifications must not be detached from the MSDS and any copying and redistribution of the MSDS shall include copying and redistribution of the notice attached to copies of the MSDS subsequently redistributed.

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.
Class D-2B: Material causing other toxic effects (Toxic).

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

Section 16. Other information

United States

Label requirements : GAS:
CONTENTS UNDER PRESURE.
Extremely flammable
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.
Class D-2B: Material causing other toxic effects (Toxic).

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

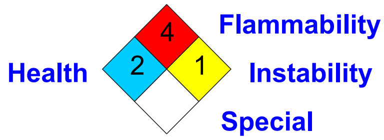
Health	*	2
Flammability		4
Physical hazards		0

liquid:

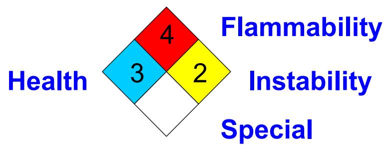
Health	*	3

Fire hazard	4
Reactivity	1
Personal protection	

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



liquid:



Notice to reader

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