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Department of Chemical & Biomolecular Engineering
University of Pennsylvania
Spring 2010

Faculty Advisors: Dr. Stuart W. Churchill and Dr. Warren D. Seider

Project Recommendation by: John A. Wismer, Arkema, Inc.

Professor Leonard A. Fabiano
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21 April 2010

Dear Mr. Fabiano, Dr. Churchill, and Dr. Seider,

This spring, our design team was presented with the task of evaluating the long term potential of producing biofuels from algae for our client, a venture capital firm interested in alternative energy. The project, suggested by Mr. John A. Wismer of Arkema, Inc., called for the design of an algal cultivation process, a lipid extraction process, and a method processing the lipids into an n-alkane product suitable for transportation fuel. To effectively evaluate the potential of an algae-to-fuel project, the economics of each process was determined and compared to the current price of diesel, which is $3/gallon.

The algae cultivation process was modeled primarily after the Simgae™ Algal Biomass Production System developed by Diversified Energy Corporation and details a simple, cost effective process. The lipid extraction stage was modeled using OriginOil, Inc.'s Single-Step Extraction™ process. In this process, Quantum Fracturing™, combined with pulses of electromagnetic fields, fractured the algae cell wall to release the lipids. The triglyceride component of the lipid stream was then transported to a petroleum refinery by rail and converted into an n-alkane product using a catalytic hydrotreating process.

The analysis indicates that a venture combining all three modules of the supply chain would be profitable. At an n-alkane selling price of $3/gallon and a 15% discount rate, the projected net present value (NPV) of the project is $289,406,000. However, there is great uncertainty in various cost requirements since the technologies are new and unproven. The total capital investment of $2.8 billion, primarily from the algae cultivation process, poses a significant barrier that may discourage investors. The processes design, economic analysis, and recommendations are discussed in more detail in this report.

Liane S. Carlson	Michael Y. Lee
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I. INTRODUCTION AND PROJECT CHARTER

A. ABSTRACT

Once considered infeasible and unviable, recently there has been renewed interest in the development of algae-derived transportation fuels. Currently, there are no commercialized algae to fuel ventures, and much debate is centered on the economic viability of such a process. Research conducted by NASA, among others, has expressed skepticism that terrestrially cultivated algae can ever compete with conventional fuels. The purpose of this project is to evaluate the economic feasibility of an algae-to-fuel venture that incorporates the state-of-the-art technologies available in the open literature.

Our challenge is to produce 20 thousand barrels per day of n-alkane product that meets the current diesel fuel specifications. To arrive at a recommendation, separate models were built for algae cultivation, lipid extraction, and lipid processing at a scale necessary to reach this target.

This analysis departs from prior studies on two major fronts. First, this analysis considers OriginOil's new method of lipid extraction instead of conventional hexane extraction. Second, the objective of the lipid processing module is to produce n-alkanes from triglycerides, as opposed to producing FAME biodiesel. The n-alkane product from this process is comparable to petroleum-based diesel fuels. Thus it can be readily incorporated into existing energy infrastructure as a diesel blending stock or as a feedstock for other processing units in the refinery.

Our economic analysis shows that an algae-to-fuel venture is profitable if the fuel is sold at $3/gallon, the current price of diesel. However, the commercialization of such a process is difficult due to the large total capital investment. At $2.2 billion, the capital investment of algae cultivation is nearly 40 times that of processing, which results in annual depreciation and fixed costs of nearly half of the revenue. Investors would be hesitant to invest such a large amount of money in an algae cultivation process where there is high uncertainty in the cost requirements.

Algae-to-fuel economics can be improved by realizing higher value uses of the algae biomass. Biomass composes of over half of algae product, and their potential uses in pharmaceuticals, chemicals, and biomass power generation far surpass their value as animal feed. Proposed carbon-cap-and-trade programs may bring additional revenue. Thus, any algae-to-fuel venture should seek to optimize the value of its byproducts. Governments can support algae-to-fuel ventures by offering tax credits or mandating a market for renewable fuels, but the benefits of these measures are unclear. Additional analysis should address the uncertainties of various costs and look to reduce capital investment.

B. MOTIVATION

In the 21st century, many nations, government agencies and research institutes are in a race to develop economically viable renewable energy sources amid the ever increasing petroleum prices and environmental pressure on governments to cut greenhouse emissions.[1] The need to find renewable sources of energy has led to large investments in alternative energies like wind, solar and geothermal.

Auto companies are looking into the applications of H_2 as a fuel. Many companies, including petroleum refining companies, are looking into the applications of algae as a source of biofuels.

The world is highly dependent on petroleum-based fuels as the primary transportation fuel. In the recent years, fluctuating gas prices in the United States, a high dependence on imported foreign oil, and the heightened awareness of greenhouse gas emissions led to an increase in research and development of alternative fuel sources. One of the most promising processes is the conversion of algae into fuels. The United States Military is looking into algae as a potential source to produce jet fuel and diesel as it looks to improve the security of fuel supply for its fight jets and vehicles.[2] Several projects supported by the Defense Advanced Research Projects Agency (DARPA), jet engine manufactures, and airlines have demonstrated that jet fuel can be produced from algae and other crops and that this product meets the specifications of military and civilian jet fuels.[3]

The idea of using algae as an alternative fuel source has been around for over thirty years. Due to limitations in algae cultivation and conventional lipid extraction, the development of the algae-to-fuel process has been slow compared to other renewable sources of fuel. However, with recent developments in algae cultivation and lipid extraction techniques, there is renewed interest in an algae-to-fuel process. Algae can yield 30 times more energy per acre than other crops. This is because algae are grown in suspension, giving it better access to water, CO_2 and other nutrients.[4]

Of the various alternative fuel technologies, the conversion of algae has the most promise as a fuel source as it provides a wide variety of fuels. The lipids in algae can be converted to FAME biodiesel via a transesterfication process, or converted to diesel, jet fuel, gasoline and other transportation fuels through a catalytic hydrotreating process and other processes commonly used in petroleum refineries. Furthermore, unlike current biofuels derived from corn or soybeans, the use of algae does not encroach on the food supply.

C. BARRIERS FOR ALGAE CONVERSION INTO FUEL

Although algae have many distinct advantages over other crops and sources of fuel, there are many hurdles to producing transportation fuels. In terms of algal cultivation, some of the hurdles are maintaining temperature control in the cultivation system, having a source of makeup water, resistance of algae strain to invasion from other species, environment impact, and most importantly, containing capital and operating costs. Some of the challenges in terms of oil (lipid) recovery from the algae include dewatering methods, lipid purification, energy costs, and value from residual biomass. In terms of fuel production, challenges facing algae cultivation include process optimization, cost of processing, and producing a fuel product that meets ASTM standards and specifications. Cost-wise, algae-based fuels historically have not been able to compete with petroleum-based fuels and would have needed government support in the form of subsidies or a mandate for the use of algae-based fuels in order to be competitive with petroleum.[5]

D. PROJECT SUMMARY: CONVERTING ALGAE INTO FUEL

The production of fuel from algae is done through the extraction of lipids from within the algae cell and the conversion of this product into a desired fuel. Alkanes, or saturated carbon chains, are the makeup of transportation fuels. The main petroleum-derived transportation fuels include gasoline, jet fuel and diesel. These fuels are a mixture of different hydrocarbons, including linear and branched alkanes, cycloparaffins (naphthenes), and aromatics. Gasoline is a mixture with hydrocarbons with carbon numbers ranging from C4 to C9, jet fuel is a mixture of hydrocarbons with a general carbon range from C8 to C14, and diesel is a mixture of hydrocarbons ranging from C12 to C22. Based on the triglyceride composition of algae, the n-alkane product produced in this hydrotreating process will have carbon numbers ranging from C13 to C20. While this product meets diesel specifications, it can be further upgraded into jet fuel or naphtha by hydrocracking, isomerization, and catalytic reforming.

The complete process has been broken down into three modules: algae cultivation, lipid extraction, and lipid processing. Each process is described below.

> **Module I: Algae Cultivation. Module I** describes the process at which algae are grown. This can be performed in many different ways including open raceway ponds, closed photo-bioreactors, or a hybrid version of the two. A hybrid version, Simgae™ technology, is an agricultural-based cultivation process that focuses on its simplicity to efficiently produce algae in a cost effective and competitive manner. Important factors to consider include a stable source of CO_2, proper amount of sunlight, nutrients, pH control, and temperature control. Therefore, the location of the cultivation system is vital to algae growth.
>
> **Module II: Lipid Extraction. Module II** describes the process at which the oils (lipids) are separated from the algae cells. The lipid, inside algae consists mostly of triglyceride molecules. Conventional processes of extracting the lipids consist of liquid-liquid extraction techniques using solvents such as hexane. Instead of using solvents, an innovative technology from OriginOil, Inc. called Single-Step Extraction™ focuses on a mechanical separation in which the cell wall is ruptured using microbubbles and ultrasonic waves to release the oils. Gravitation is then used to separate the components.[6]
>
> **Module III: Lipid Processing. Module III** describes the process at which the triglycerides are converted into n-alkanes. This is done through catalytic hydrotreating in which hydrogen is used to saturate the carbon chains, break apart the triglyceride molecule, and completely remove the oxygen to form n-alkanes. The n-alkane product meets diesel specifications and can be blended directly into the refinery diesel pool. Although not included in the scope of this project, the n-alkanes can be further upgraded in a hydrocracking/isomerization unit in which the molecules are broken into smaller chains and separated into jet fuel and naphtha. The naphtha can be upgraded into gasoline through catalytic reforming.

The economic analysis of this project will discuss whether the proposed algae-to-fuel process is commercially viable based on a calculation of the Net Present Value (NPV) and Investor's Rate of Return (IRR).

E. INNOVATION MAP

The process of cultivating algae and converting it into fuel is a market driven process in which the current market price for algae fuel in comparison to other fuels determines the demand. The following innovation map (**Figure 1**) relates the market and customer needs to the material technology which is, in this case, the conversion of algae into fuel.

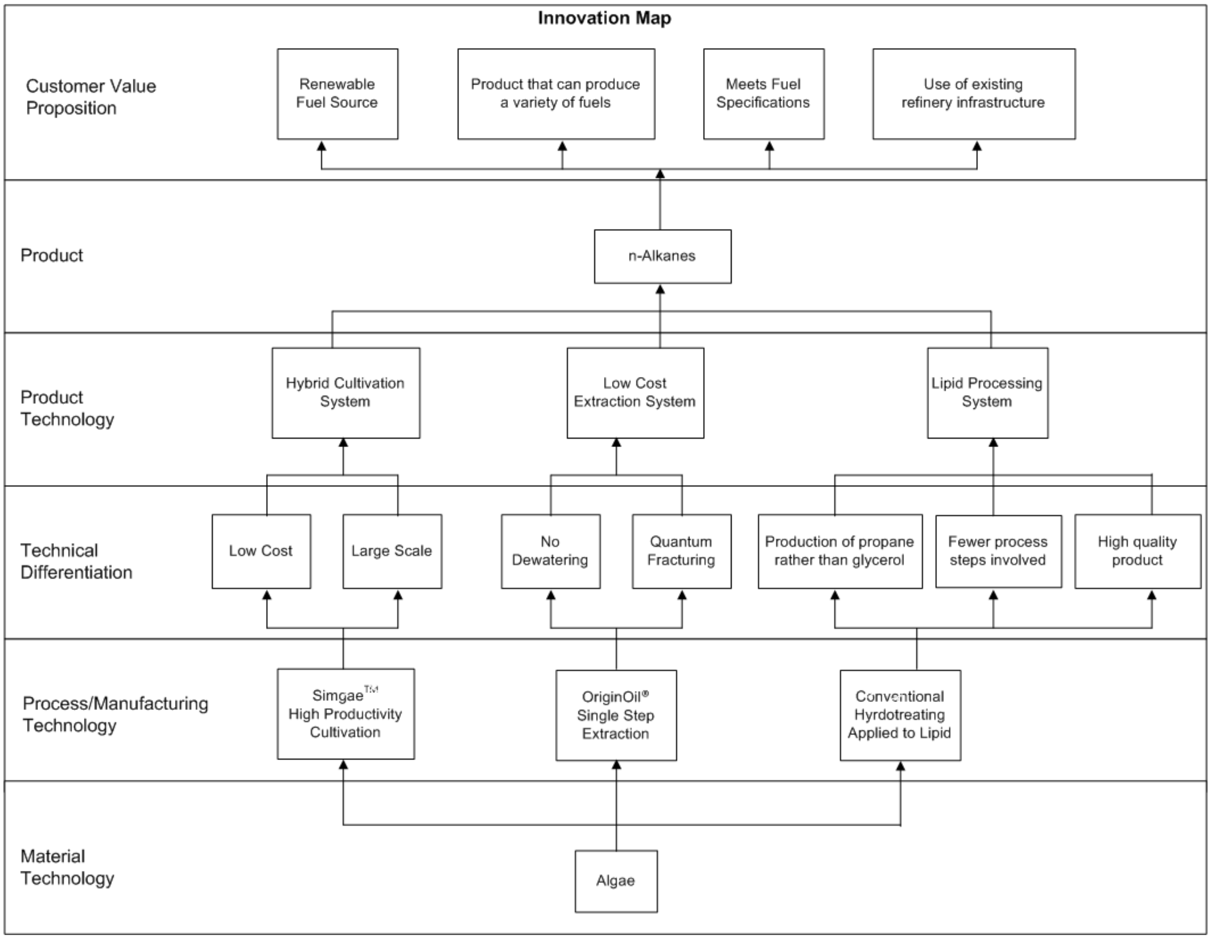


FIGURE 1: INNOVATION MAP.

Algae are the material technologies that enable the production of fuel. Genetically altered algae are the newest of these technologies, but are not considered in this analysis and are therefore excluded from the above diagram. The processing technologies associated with algae are first, the Simgae^{TM} Algal Biomass Production System which differentiates itself from other processes due to its combined low cost, large scale, and high productivity to form a hybrid cultivation system. Second is the OriginOil® Single Step Extraction which does not require a dewatering stage and extracts lipid through newly developed Quantum Fracturing^{TM} technology to form a low cost extraction system. The third processing technology is the catalytic hydrotreating process, which allows for the production of n-alkanes through fewer process steps and a byproduct of propane rather than glycerol. The final product from these three processes is a high quality n-alkane product, produced in an existing petroleum refinery, which meets diesel specifications.

II. OVERALL CONCEPT STAGE

A. OVERALL FLOWSHEET

Figure 2 shows the overall flowsheet of the Algae to Alkanes project. The Simgae™ cultivation system is located in Thompsons, TX. Algae is continuously grown, doubling in concentration every 48 hours. Half of the exiting stream is recycled back into **Module I** for another growth cycle while the other half continues to **Module II** for lipid extraction. In **Module II**, the lipids are extracted from the algal cells using OriginOil's Single-Step Extraction process. The trigylcerides are shipped by rail to a Houston area refinery location. In **Module III**, a catalytic hydtrotreating process converts the triglycerides into n-alkanes.

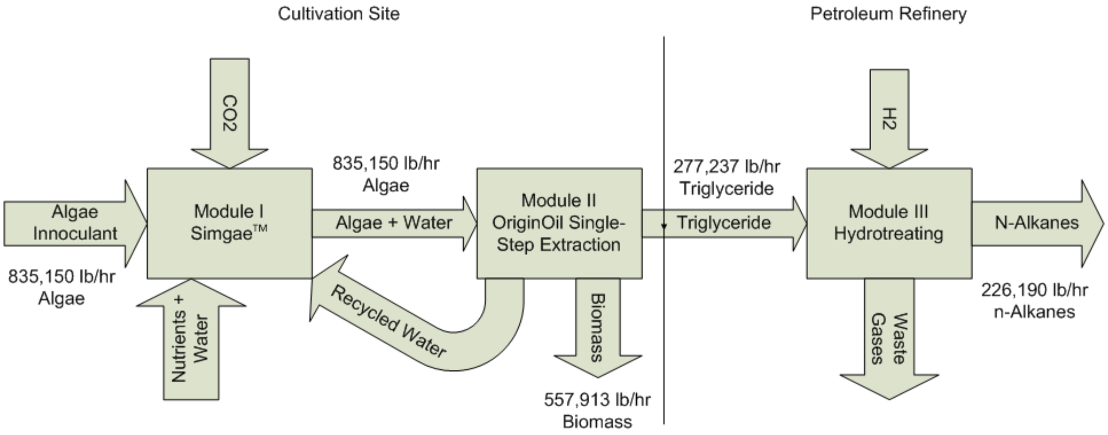


FIGURE 2: OVERALL FLOWSHEET.

B. MARKET AND COMPETITIVE ANALYSIS

In the US market for transportation fuels, there is a need for an alternative to fossil fuel that will address concerns of climate change and political instability around the world. Of the competing alternatives fuel sources, algae holds the most promise for its high productivity and because it does not compete with the food supply.

Currently, fatty acid methyl ester (FAME) biodiesel is the leader in commercialized alternative fuel. It is produced by transesterification of lipids from a variety of vegetable oil feedstock, ranging from corn, soybean, palm oil, and others. Consumption of biodiesel in US was 320 million gallons in 2008, a 7% increase from 2007. Through government tax incentives, biodiesel is priced a few cents below petroleum diesel at the pump. Unlike FAME biodiesel, the n-alkanes produced from algae are not restricted to the diesel market. They can be blended into the refinery diesel pool for distribution or it can be further upgraded into gasoline or jet fuel if there is stronger demand.

The total US refining capacity is 17.7 million barrels per day as of 2009, with over half of the crude oil supplied from overseas. For most of 2010, crude has traded around \$80-\$90. In the short term, the demand for oil is restrained due to a weak economic recovery.

However, in the long term, EIA projects world-wide consumption of crude oil to grow 1.4% annually from 2003 to 2030, mostly driven by demand from developing countries. The price of WTI (West Texas Intermediate) crude oil is expected to exceed $110/bbl (in 2008 dollar-terms) by early 2020. The algae-derived fuel may become competitive if its price can be reduced or if the price of crude oil continues to increase.

C. CUSTOMER REQUIREMENTS

Transportation Fuel Properties

The main petroleum derived transportation fuels include gasoline, jet fuel, and diesel. These fuels are a mixture of different hydrocarbons, including linear and branched alkanes, cycloparaffins (naphthenes), and aromatics. Gasoline is a mixture of hydrocarbons with carbon numbers ranging from C4 to C9, jet fuel is a mixture of hydrocarbons with general range from C8 to C14, and diesel is a mixture of hydrocarbons of n-alkanes ranging from C12 to C22. Based on the composition on the triglycerides in the selected, the n-alkane product produced in this hydrotreating process will have carbon numbers ranging from C13 to C20, and depending on the quality, the product could be directly blended into the diesel pool produced from other units in the refinery.

If the refinery instead wants to produce jet fuel or gasoline from the n-alkane product, the n-alkanes can be further processed in hydrocracking/isomerization steps and catalytic reforming as outlined in **Module III**.

Fuel Specifications

To ensure that the n-alkane produced in this process is comparable to the products produced from crude oil, the n-alkane produced from algae must meet certain specification standards before it can be blended into diesel pool. **Table 1** lists some specifications listed in ASTM D975 (Standard Specification for Diesel Fuel Oils) for standard No. 2 Diesel.[7]

TABLE 1: ASTM D975 DIESEL SPECIFICATIONS.

Property	Specification
Flash Point, °C (°F), min	52 (125)
Water and Sediment, % volume, max	0.05
Kinematic Viscosity, mm^2/sec at 40°C (104°F):	
min	1.9
max	4.1
Ash, % mass, max	0.01
Sulfur, ppm, max	15
Cetane Number, min	40
Cloud Point, °C (°F), max	Varies
Lubricity, 60°C, WSD, microns, max	520

D. TRANSPORTATION BETWEEN MODULES AND STORAGE

The proposed process involves the development of an algae cultivation system at a location in Thompsons, Texas. The lipid extraction system will also be located at the same location, while the lipid processing unit will be located at a refinery location in the Houston area. While the specific locations will be further discussed, the shipment of triglyceride product from the lipid extraction facility to the lipid processing facility will also be addressed.

In general, possible methods of lipid transportation include truck, rail, or barge. While shipment by barge is ideal for large volumes, it would be infeasible for our process due to the inland location of our algae cultivation and lipid extraction facility. Transportation by truck is highly uneconomical due to the large amount of triglycerides to be transported. Consequently, the ideal method of lipid transportation is by rail. When shipping by rail, the triglyceride product would be stored in specialized tank cars which are designed to handle liquids.

Since railway shipments are not continuous processes, storage tanks are required at lipid extraction and lipid processing locations to store the triglyceride product in between railway shipments. These storage tanks must have enough capacity to handle seven days of production to account of the frequency of railway shipments and to provide adequate capacity in case of a temporary unit shutdown. Another set of storage tank capacity with two days of storage capacity is added to store the n-alkane product for further use in the refinery.

MODULE I: ALGAE CULTIVATION

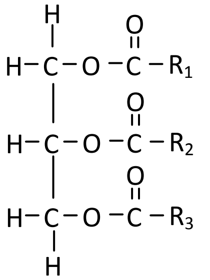
III. CONCEPT STAGE

A. PICKING AN ALGAE STRAIN

There are a large variety of algae strains from which to choose from, not all of them optimal for producing fuel. To maximize fuel production, it is desirable to pick an algae strain with high lipid content as well as high production values.

Lipid Content and Production Rate

The lipid content of algae varies depending on the particular strain of algae. It is composed mostly of triglycerides (TAG) but also consists of other molecules such as polar lipids and free fatty acids.[8] This is the product that will eventually be processed into fuel. A triglyceride molecule is shown below and is made up of a single molecule of glycerol esterified with three fatty acids.



Triglyceride (TAG) Molecule

R = hydrocarbon chain of the fatty acid

Algae can be as much as 85 dry wt. % lipid, but it is equally important to find an algae strain that has a high production rate. Growth rates of the algae are specific to the cultivation process used to grow the algae as well as environmental factors such as pH, temperature, and sunlight. High daily production values are known to be around 50 grams of algae per square meter.[4]

Saltwater vs. Freshwater

Algae can grow in saltwater or freshwater depending on the particular strain. This is considered when evaluating strains to be used at a particular location.

B. INCREASING LIPID CONTENT

Genetically Altered

Some algae strains have been genetically altered to enhance specific targets concerning growth and harvesting. Among these targets are increased lipid content and productivity.[9]

Nitrogen Deprivation

Nitrogen is a vital nutrient for algae growth. When under the stressful condition of nitrogen starvation, many algae appear to produce higher amounts of TAG in comparison to the production of other cell components in an attempt to store energy within the cell. This leads to higher oil content within the algae. However, a study done on certain *Nannochloropsis* strains has shown that nitrogen deprivation acts as a block to cell division, decreasing overall productivity while lipid production continues normally. This increases the lipid content per cell, but does not lead to a net accumulation of lipid within the culture.[1]

C. LOCATION SCREENING

Screening Guidelines

Location is very important when designing a cultivation system. There are many parameters vital to algae growth that must be evaluated to optimize production. The following screening guidelines were created to provide criteria with which to base these location selection decisions.

1. Constant Source of Sunlight
2. Flat Land Requirement
3. Nearby Water Source
4. Nearby CO_2 Source
5. Transportation
6. Overall Climate
7. Other Costs

To properly select a location, it is important to evaluate the availability of the resources required to grow algae, including sunlight, land, water, and CO_2. It is important to find a reliable source of nutrients as well as nearby transportation to both optimize algae cultivation and minimize cost.

Constant Source of Sunlight

Algae require a constant source of sunlight to provide energy for growth. The presence of sufficient sunlight during the entire calendar year is important as production is greatly inhibited during seasons when sunlight is limited. It is important to have daily sunlight at intensities high enough to support algae growth. Requirements are specific to the particular algae strain. Direct sunlight, with an illuminance as high as 130,000 lumens/m^2 (195 watts/m^2), can be harmful to algae. Only about a tenth of this amount is needed for algae growth, although such a value may not provide the optimum amount of sunlight for a particular strain.[10] It is desirable to maximize the number of days during a year where the sunlight intensity is at the optimal level.

Sunlight intensity levels vary across the United States. Places most likely able to support algae growth are located on the West Coast, Southwest, and Gulf Coast regions.

Flat Land Requirement

One of the main requirements for large scale algae cultivation systems is flat land. Any incline will affect the flow and pressure throughout the reactor tubes and may interfere with the installation of the process. Land that is flat, far from urbanized regions, is ideal for cultivating algae.

Western, Southwestern, and Gulf Coast regions of the Unites States have more land available than Mid-Atlantic or New England regions. The amount of required land will depend on the amount of algae to be produced.

Land permits will also be required to allow for use of the land for an algae cultivation system.

Nearby Water Resource

The cultivation system also requires a large amount of water for the algae to grow. Whether it is salt water or fresh water depends on the requirement of the particular strain. Water is used to cultivate the algae and will be continuously replenished by this source. Therefore, it is most convenient and cost effective to have a water source located nearby.

In the United States, the availability of fresh water is greater in the Atlantic and New England regions as opposed to Southwestern regions. The Gulf Coast is a viable location for an algae cultivation system because there are many power plants and refineries in the region that can provide processed water. Saline aquifers can be utilized, provided that they contain enough water and salinity high enough to produce the amount of algae needed. These saline sources can be found beneath certain regions of the United States, such as Texas.

Water permits will also be required to allow for use of the water.

Nearby CO_2 Resource

CO_2 is vital for algae growth as it is the source of carbon that algae use to grow. Because atmospheric carbon dioxide is not enough for the cultivation of algae in a small period of time, the gas has to be drawn from sources such as coal-fired plants, refineries or other plants that emit copious amounts of CO_2. In many industrial processes, carbon dioxide is released along with particulates, NO_x and SO_x into the atmosphere. After surveying the various types of plants, coal-fired power plants were chosen based on carbon emissions from that type of plant. Coal has high carbon content and releases a lot of carbon when undergoing combustion.

Coal-fired power plants are located throughout the United States. When selecting a viable coal-fired power plant for the algae cultivation process, the amount of CO_2 released from the plant will be considered.

It is important to note that flue gas also contain other gases such as SO_X and NO_X. These components do not inhibit algae growth but can instead be used by the algae as nutrients.[11]

Transportation

Transportation is an important factor to consider when evaluating a certain location. As large amounts of water, nutrients, and CO_2 are required, transportation of these materials to the cultivation plant should be minimized. Transportation of the product is also important to consider, as algae must be transported to the lipid extraction site. It is most efficient to have the lipid extraction unit located at the cultivation site.

To keep costs low, the cultivation and extraction site should be located close to a freight railway so that the lipid product can be easily transported by rail to a petroleum refinery for lipid processing.

Overall Climate

Climate is an important factor to consider. Temperature highs and lows will affect the efficiency of a cultivation system. Intense weather conditions such as hurricanes, tropical storms, and tornadoes could destroy cultivation systems and disrupt entire batches of algae. Certain locations within the United States, such as Kansas or Oklahoma, encounter many tornadoes, while the Gulf Coast region from Texas to Florida faces tropical storms and hurricanes during the summer months.

Other Costs

The cost of utilities and property tax rates will vary from place to place. Electricity is required to run certain processes, such as the pump for flow in the cultivation process and to run many of the units required for lipid extraction and lipid processing. The cost of utilizing resources, which include water, CO_2 and electricity, will play an important role in determining where the cultivation system will be located.

Although utilities are not the most significant parameter when evaluating a particular location, it is still desired to minimize costs in as many ways as possible.

D. PICKING A CULTIVATION PROCESS

There are many ways to cultivate algae. They can be open or closed to the atmosphere and have processes that regulate nutrients, sunlight, CO_2, temperature, pH, and other factors. Production values are specific to a process and to the algae strain. Many companies today are maximizing algae production by optimizing growth conditions, although conditions vary depending on the algae strain.

Open-Air Raceway Ponds

Raceway ponds are the most simplistic of all algae cultivation processes. In this particular set up, the inoculants of algae are placed in a natural or artificial pond, fed nutrients (including CO_2), and allowed to grow for a period of time. This method has the advantage of being relatively economical as open bodies of water can be made use of for growing algae and expensive cultivation processes do not need to be installed. Raceway ponds are good for mass cultivation of algae because they are easy to construct and are clean.[12]

However, there are many limitations to open air ponds because it is impossible to control the environmental conditions. Open ponds are highly susceptible to evaporative loses, diffusion of

CO_2 to the atmosphere, and contamination from other species of algae. The lack of a stirring mechanism to agitate the algae lowers mass transfer rates with nutrients, limiting productivity.[12]

Compact Photo-Bioreactor

Photo-bioreactors are typically closed systems that provide more structured and controlled processes of cultivating algae. Either artificial or natural light can be used, and different parameters for algae growth (such as temperature) can be monitored. Production rates of algae are optimized over time and are particular to the location, its climate, and availability of resources. Photo-bioreactors have large illumination areas of the reactor to optimize the amount of solar radiation received by algae. Effective mixing in the tanks, with low shear stress, increases mass transfer rates between the algae, water, and nutrients. This helps to increase total productivity. It is also possible to decrease photo-inhibition, which occurs when algae receive a very high concentration of solar radiation, resulting in a decrease in productivity.[12]

Photo-bioreactors also have many limitations. In general, sophisticated materials and multiple components are required for the installation of a system. This greatly increases the cost to produce large scale cultivation processes when compared to the simplicity of an open raceway pond. Algae growth on surfaces of the reactor will decrease the amount of sunlight received by algae, lowering overall output. Large pH gradients could also develop due to high concentrations of oxygen and CO_2 dissolved in water.

The Algae Tree

Currently, new and revolutionary cultivation systems are being designed and tested to improve the illumination area and optimize the amount of sunlight algae receives. This research led to the design of the algae tree, a type of photo-bioreactor whose design maximizes the sunlight received by algae.[13] It is a batch system where algae remain within the shaft of a system in the shape of a tree. The branches and leaves of the algae tree are made from optical materials that help distribute light and also direct sunlight into the shaft of the algae tree.

While the technology seems promising, its design is complicated and scale-up of the design will lead to higher costs compared to scale up of conventional photo-bioreactor systems. Because of the design, the system is highly susceptible to evaporative loses which will increase the salinity of the reactor over time and may lead to conditions that inhibit algae growth.[13]

NASA OMEGA System

The Ames Research Center of the National Aeronautics and Space Administration (NASA) has been developing a non-terrestrial cultivation system that will produce algae and treat waste water. The system is known as the Offshore Membrane Enclosure for Growing Algae (OMEGA) system and uses porous plastic bags to enclose the algae and sewage which is then placed into the ocean or another large body of water. Water from the ocean and CO_2 from the air enter the system through osmosis and, with natural sunlight, facilitate the photosynthetic process in algae. The movement of the waves in the ocean mixes the contents of the bag to improve mass transfer and algae productivity.[14]

There are many advantages of this system over the conventional algae ponds and photo-bioreactors. The chief advantage is that there are no land requirements for producing algae. No water irrigation is needed as the OMEGA system uses an open body of water as its source. Temperature and pH are maintained by the ocean.

Shortcomings include the relatively short lives of the plastic bags. Although the material is relatively inexpensive, the bag is not expected to last longer than two years requiring many bags to be replaced in a short period of time.

E. OPTIMAL CONDITIONS FOR CULTIVATION

Optimal conditions for cultivation are specific to a particular strain and greatly affect growth rates. These parameters vary for each alga species:

- **Temperature** regulation is important, as values too low can slow growth, while temperatures too high can cause death. Optimal temperatures for algae growth have been found to be between 16 and 27°C, although some species have been found to grow well at 30°C.[15]
- Cultures are of slightly basic **pH levels** of 7-9 with the optimum around 8.2-8.7.[15] As algae grow, pH levels gradually increase and can be lowered with CO_2 injections. Therefore, pH control will be done primarily with CO_2 aeration techniques that also replenish the carbon source as it is depleted.
- The **oxygen** generated from photosynthesis should not exceed 400% of air saturation values. If values exceed this concentration, it could inhibit photosynthesis or, combined with sunlight, produce photo-oxidative damage to the algae.[16]
- A sufficient source of **sunlight** is needed. Either natural or artificial light can be used. Direct sunlight has an illuminance of as high as 130,000 lumens/m^2 (195 watts/m^2) and is harmful to algae. Only about one tenth of this value is required for growth.[17]
- For marine strains, the **salinity** of the medium must also be monitored. Values of 20-24 g/L have been found to be optimal salinities.[15]

F. PROPOSED MODULE I PARAMETERS

Proposed Algae, *Nannochloropsis sp.*

Nannochloropsis is a genus of marine algae under the algal class Eustigmatophyceae. It consists of about six species of algae, five of which are marine and one is freshwater. This project focused on the marine species, *Nannochloropsis sp.*[18] In selecting a marine strain, the competitive market for fresh water is avoided as there is a wide availability of salt water sources relative to fresh water sources.

Nannochloropsis sp. lipid contents range from 31 to 68 dry weight %.[4] The lipid composition is 79% TAG, 9% polar lipids, 2.5% hydrocarbons, and the rest being pigments, free fatty acids, and other various molecules.[8]

TAG molecules produced by *Nannochloropsis sp.* have carbon chains containing anywhere from 14 to 20 carbons. The fatty acid content is shown in **Table 2** and makeup the hydrocarbon chains of the TAG molecules.[19]

Fatty Acid	% of Total Fatty Acid
C14:0	6.9
C16:0	19.9
C16:1	27.4
C18:1	1.7
C18:2	3.5
C18:3	0.7
C18:4	4.2
C20:5	34.9

TABLE 2: FATTY ACID COMPOSITION OF *NANNOCHLOROPSIS SP.*
Values listed are the percents and wt fractions of the fatty acids that make up the triglyceride molecules.

In order to accurately and conservatively model *Nannochloropsis sp.* growth, the selected strain is not genetically altered and is grown under optimal conditions with sufficient resources (no nitrogen deprivation).

Proposed Location

Based on the criteria for land selection, we have decided to base the Simgae™ cultivation system at the W.A. Parish Electric Generating Station, operated by NRG Texas LLC., in Thompsons, Texas.

Constant Source of Sunlight

Thompsons receives as low as 2.7 kWh/m²/day (112 W/m^2) during the month of January and as high as 6.0 kWh/m²/day (250 W/m^2) during the month of June.[20] Algae can be cultivated year round.

Flat Land Requirement

Land surrounding the W.A. Parish Electric Generating Station is ideal for placing the fields of reactor beds as it is both flat and is situated right beside the generating station. This allows for easy use of the stack gas without transportation across long distances. The land can easily be prepared for the installation of the fields.

Nearby Water Source

The proposed field will be situated in a location that sits atop a saline aquifer. The aquifer is very large and can supply the needs of multiple Simgae^{TM} fields. According to a study done by the National Renewable Energy Laboratory (NREL), the state of Texas sits over many saline aquifers that could potentially be used.

Nearby CO_2 Source

The W.A. Parish Electric Generating Station is a coal-fired and natural gas-fired power plant that is made up of 8 generating units. Units 1 through 4 burn natural gas to produce a total of 1190 MW of power. Units 5 through 8 burn coal to generate 2475 MW of power.[21] The emissions from these units would contain enough carbon dioxide to cultivate large quantities of algae.

Transportation

There are many refineries located in the Houston area and the distance between Thompsons and these refineries is relatively short, ranging from 30-60 miles. As a result, transporting algae to a Houston area refinery for lipid processing would be cheaper than transporting algae from a cultivation plant in Arizona to a West Coast or Gulf Coast refinery.

Overall Climate

Thompsons is a city in Fort Bend County, in the southeastern part of Texas, near Houston and the Gulf Coast. Temperatures can range anywhere from 50°F to 60°F between the months of November and March and 60°F to 82°F between the months of April and October.[20] The average yearly temperature is about 67°F. It is susceptible to flash floods and hurricanes.

Other Costs

The surrounding area has high property tax rates and would make the purchase of the land relatively expensive. However, the potentially high cost of land purchase is offset by the relatively lower costs of preparing the land, pumping saline water and transporting algae.

Alternative Locations

Alternatively, other locations were screened based on the established criteria. While these sites showed potential, they faced certain obstacles that made it difficult to select them for as a suitable location. The Springerville Generating Station is a coal-fired power plant, operated by the Salt River Project (SRP), Tri-State Generation and Transmission (TSGT), and the Tucson Electric Power Company (TEP), and is situated near the Arizona-New Mexico border.[22]

Constant Source of Sunlight

Springerville receives an annual insolation average of about 5.7 kWh/m²/day (235 W/m^2). Insolation can be as high as 7.6 kWh/m²/day (317 W/m^2) and as low as 3 kWh/m²/day (125 W/m^2).[23] The amount of sunlight that Springerville receives is above the national year round average and will provide more than enough sunlight for algae to photosynthesize during the months of December and January.

Flat Land Requirement

The land surrounding the Springerville Generating Station is ideal for placing the fields of reactor beds since it is both flat and in very close proximity to the power generating station, which will allow it to make use of the plant's stack gases without long distance pumping.

Nearby Water Source

While there are no open bodies of saline water near the generating station, there is a saline aquifer situated to the north in Apache County. The aquifer stretches through Coconino, Navajo and Apache counties, with the center being located in Navajo county. The concentration of salts and other dissolved solids range from 1,000 to over 10,000 mg/L.[10] However, this aquifer is located about 60 miles away from the station, with the most saline part located 70 miles away. Though a viable source, pumping and transporting the water over that distance would prove too costly to undertake.

Nearby CO_2 Source

The Springerville Generating Station is made up of 4 units, two of which are operated by TEP and the last two by SRP and TSGT. Units 1 and 2 each generate 340 MW of power from burning low-sulfur coal. Units 3 and 4 both generate 400 MW of power.[22] Typical emissions from these units supply more than enough carbon from the combustion of coal for algal growth in the reactors.

Overall Climate

Throughout the year, Springerville receives a lot of sunlight and experiences temperatures that range from 48°F to 55°F between the months of November and February and from 55°F to 82°F between the months of March and October.[23]

IV. FEASIBILITY AND DEVELOPMENT STAGES

A. PROPOSED CULTIVATION PROCESS - Simgae^{TM}

The cultivation process used in this project, Simgae^{TM}, is developed by XL Renewables, Inc. and currently licensed by Diversified Technology, Inc. The framework of the cultivation process is taken from the XL Renewable Patent for the Simgae^{TM} technology. For this design, certain values are adjusted to optimize land use:[24]

> The reactor area relative to the total field area is increased by doubling the number of reactor tubes per reactor bed from 8 to 16, while keeping the overall reactor bed area constant. This decreases the field acreage from 40 to 33 acres per field. It is assumed that Simgae^{TM} technology can handle marine strains of algae with salt water nutrient sources.

This system consists of a series of clear polyethylene tubes through which an algae inoculant and nutrients circulate over a 48 hour time period. The concentration of the algae doubles during this period. The process is continuous with an inlet and outlet control valve.[25]

Simgae^{TM} Technology

Field. Simgae^{TM} cultivation processes are broken up into blocks called fields. Each field is almost 33 acres and contains the reactor beds, algae inoculation and nutrient source, CO_2 source and injection sites, gas relief valves, circulation pumps, and harvest sumps. Each field contains 100 reactor beds.

Reactor Bed. Each reactor bed contains 16 tubes and a 1.5 foot path on each side forming a net reactor bed area of 27.5 acres and an effective reactor area of 23 acres.

Tubes. Algae circulate in clear polyethylene tubes with UV inhibitors to protect against direct sunlight. They are 6 inches in diameter, 1250 feet in length, 0.01 inches thick, inflate when under pressure, and deflate when not under pressure. This forms a net reactor area of 23 acres. Plastic mulch is distributed above and below the tubing to regulate the temperature and sun exposure of the tubes. Please refer to **Figure 3** for a cross sectional view of the reactor tubing.

CO_2 Source. Carbon dioxide is taken from a coal fired power plant as stated in the location selection and diluted to a concentration of 6% CO_2 with dry air.

CO_2 Injections are used to replenish the source of CO_2 as it is consumed. An injection occurs every 300 feet of reactor tubing.

Gas Relief Valves are used to release produced oxygen and provide gas relief within the algae slurry every 300 feet.

Pump. The pump is used to regulate flow along the tubing and to agitate the algae. It is used to keep the system pressurized at an operating pressure of 5 to 20 psi.

Dwelling Time. It takes two days to double the amount of algae in the system, meaning the residence time of an algae molecule is a 48 hour period in which the algae travels a single length of tubing and the total density is doubled. The process has a recirculation line in case dwell time or flow rate is increased.

Maintenance. The cultivation system is shut down for approximately a month each year for maintenance purposes. The tubing may require replacement as it will lose clarity over time, although it is predicted long tubing will last 5 years. A tractor roller is used to agitate the tubing to remove biofilm that may build up along the walls and to agitate the algae during growth, as discussed on page 25.

Harvesting takes place after the algae has made a single pass through the reactor tubing. It is pumped and collected at a harvest sump location and continuously pumped into **Module II**, where the lipid extraction process takes place.

Figure 4 (page 22) shows a diagram of the cultivation process. This diagram shows a total of 30 reactor beds, while in full scale, the entire system will contain 100 beds. The algae enter the system from the algae inoculation and nutrient site to the common inlet line where it enters a tube. It travels through the tubing system in a 48 hour period where it passes through four different gas relief valves and CO_2 injection sites. Here, the CO_2 source is replenished and built up O_2 is released. At the end of the tubing, the algae then enter the common outlet line where it is transported to the harvest sump for collection. From here, the algae are continuously fed through a pipeline system to **Module II** where lipid extraction takes place. It is possible for the algae to enter the recirculation line where dwell time can be increased and the algae are given more time to grow.[24] Otherwise, the recirculation line is used to recycle half the algae for the next circulation throughout the system.

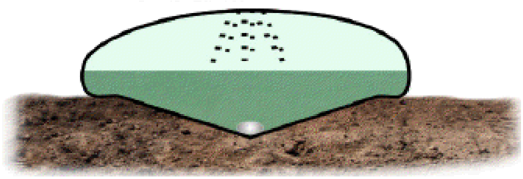


FIGURE 3: CROSS SECTIONAL AREA OF TUBING.[25]

B. GENERAL MATERIAL BALANCES

Algae Material Balance

A material balance is conducted to determine the amount of algae to be eventually processed into fuel and the amount of CO_2 required to sufficiently support algae growth. When calculating the algal material balance, the following assumptions were made:

- Algae concentration is doubled within a 48 hour dwell time.[25] The amount of algae produced was determined and taken as the incoming algae density. The incoming density was then doubled and taken as the exiting density.
- Concentrations were determined through productivity values taken from Diversified Energy: an annual production of 100 dry tons of algae per acre, equivalent to 90,720 kg algae per acre.[26] This value is dry weight, meaning that it is independent of water content within an algae cell. It is interpreted that this value is per total field acreage (33 acres) and not solely acreage of reactor area within a single field (23 acres).
- The entire tubing is filled with fluid, resulting in a volume of 245 ft^3 per tube.
- Density of the streams was constant throughout the process. From the calculated production value, algae density increases by approximately 1.5 g algae/L and has a negligible effect on the overall density of the nutrient stream.

    Because the production value is given in dry tons, the density value is also assumed to be in grams of dry weight algae per liter of fluid.
- A single pass through the tubing was assumed to take 48 hours leading to a flow velocity of 26.03 ft/hr and the resulting flow rates listed in **Table 1**.[25]
- *Nannochloropsis sp.* has a lipid content of 46 dry wt%. As stated above, it is assumed that 80 % lipid content is composed of TAG.
- The total flow rate of CO_2 enriched air injected into the system is increased from 3.2 lb/s to 9.0 to allow for a lower overall CO2 concentration to create optimal growth conditions.

Table 3 displays many of the important parameters and calculations relevant to a tube, reactor bed, or field. When calculating the mass balance, an amount of algae produced was first determined. Because the amount of algae doubles throughout the system, this value was doubled to give an exiting concentration of 2.93 g algae/L. **Figure 4** shows a detailed view of a single reactor bed with 16 tubes.

Flow rates were determined using parameters taken from both the XL Renewables™ patent and Diversified Energy presentation detailing Simgae™ technology. More specifically, a 48 hour doubling time throughout a system of tubing 6 inches in diameter and 1,300 feet in length was used to determine a flow velocity and volumetric flow rate. Field flow rates are detailed in **Table 4**.

SINGLE FIELD				
Gross	33	acres	1080 ft X 1320 ft	
Reactor Beds	28	acres	960 ft X 1250 ft	
Reactor Area	23	acres	800 ft X 1250 ft	
Space for Paths	151.5	ft	1 1/2 feet per pathway	
Reactor Beds	100	beds/field		
Excess Space	8.5	ft		
Total Volume	393000	ft^3	11100000	L
Common Inlet/Outlet	2.23	ft^3/s	64.3	L/s
REACTOR BED				
Number of Tubes	16	tubes		
Flow Rate to Bed	0.023	ft^3/s	0.643	L/s
Total Volume	3930	ft^3	111000	L
TUBES				
Tube Diameter	0.5	ft		
Tube Length	1250	ft		
Flow Velocity	0.00723	ft/s		
Flow Rate	0.00142	ft^3/s	0.04	L/s
Total Volume	245	ft^3	6950	L
Dwell Time	48	hours	2	days

TABLE 3: SINGLE FIELD, BED, AND TUBE DESCRIPTIONS. Certain descriptions for a field, bed, and tube are described. More specifically, the dimensions and total volume capacity of each. The flow velocity (0.00723 ft/s) within a tube is determined from the specified 48 hour dwell time and tube dimensions.

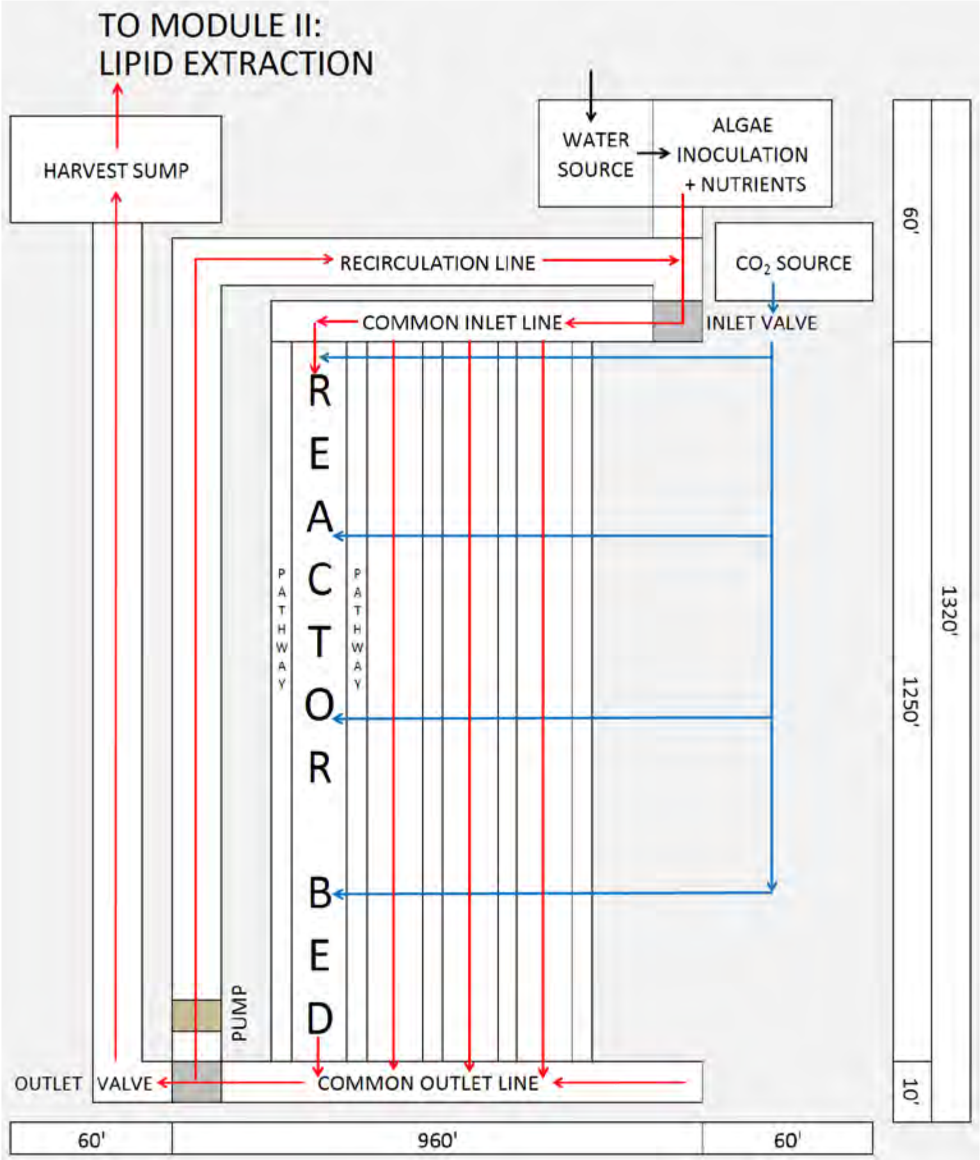


FIGURE 4: CULTIVATION FIELD. Modeled after Diversified Energy Inc.'s Simgae^{TM} and totaling almost 33 acres with 28 acres of reactor bed and an effective reactor area of 23 acres. Black arrows represent the flow of the salt water source. Red arrows model the flow path of algae. The recirculation line is used to recycle half the algae stream for the next growth circulation. Blue arrows model the flow of 10 wt. % CO_2 where it is injected into the field at four different locations. Just before the CO_2 injection site is a gas relief valve where produced O_2 is released. A single reactor bed is labeled in the system and shown in detail in **Figure 5**. A complete cultivation field has a total of 100 reactor beds. Only 33 are shown here.

Stream	Volumetric Flow Rate		Algae Flow Rate
	ft^3/s	L/s	kg/hr
Common Inlet	2.23	64.3	339
Common Outlet	2.23	64.3	678
Recirculation Line	1.12	32.2	339
To **Module II**	1.12	32.2	339
Nutrients	1.12	32.2	0

TABLE 4: FIELD STREAM FLOW RATES. The volumetric and mass flow rates relevant to **Figure 4** are shown.

Summary of Important Statistics:

Algae Production	100 dry tons/acre*yr	Tube Flow Velocity	26.03 ft/hr
Initial Algae Concentration	1.46 g/L	Dwell Time	48.03 hours
Exiting algae concentration	2.93 g/L	Lipid Content	46 dry wt. %

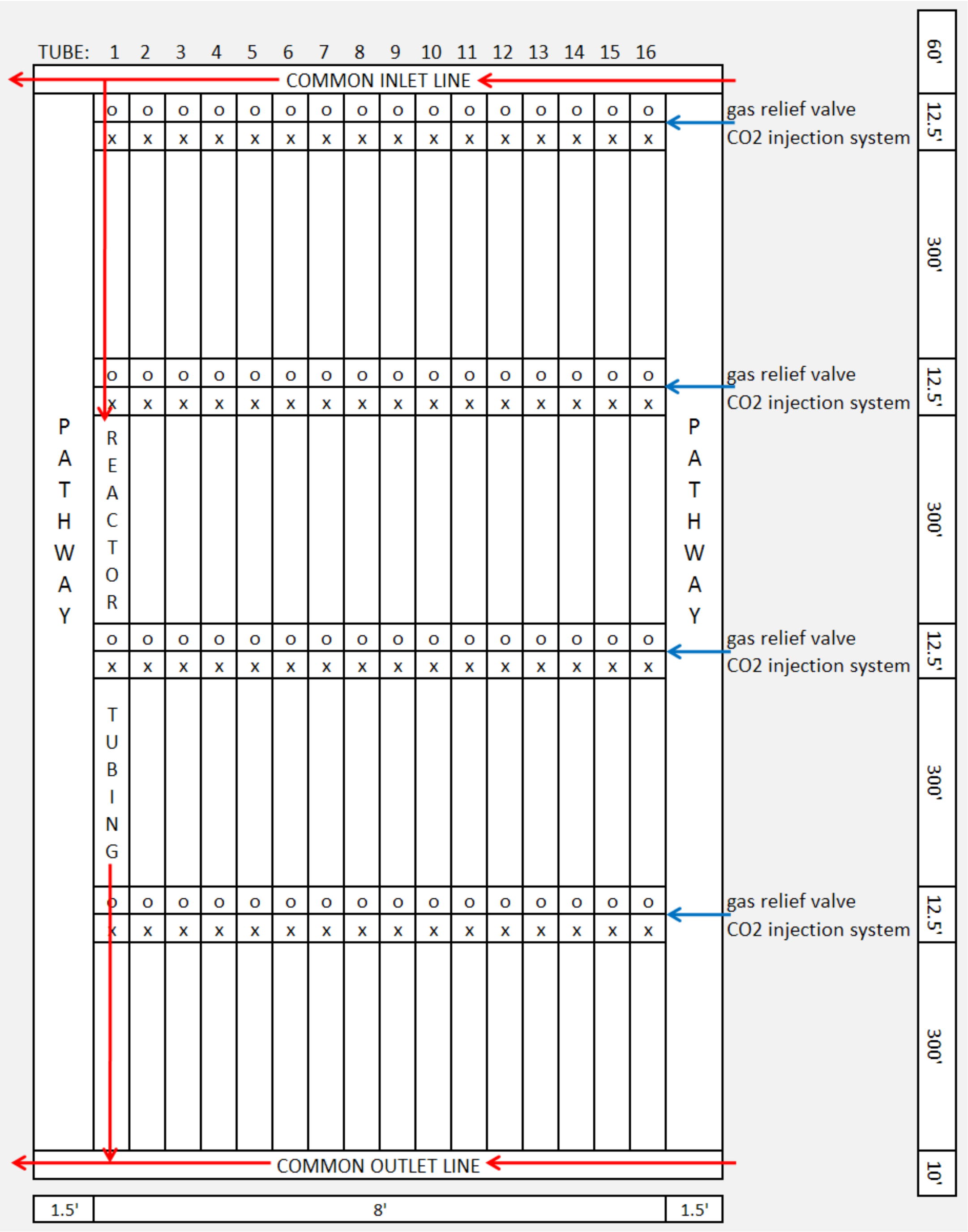


FIGURE 5: REACTOR BED. A reactor bed contains 16 tubes, 6 inches diameter and 1250 feet long. The red arrows show the flow of algae throughout the system.

Table 5 summarizes the volumetric and algal flow rates of the different streams throughout the cultivation process.

	FIELD	REACTOR BED	SINGLE TUBE
Total V (ft^3)	393000	3930	245
Volumetric Flow (ft^3/hr)	8180	81.8	5.1
Incoming Algae Flow (kg algae/hr)	339	3.39	0.21
Outgoing Algae Flow (kg algae/hr)	678	6.78	0.42
Outgoing Lipid Flow (kg lipid/hr)	156	1.56	0.10

TABLE 5: VOLUMETRIC AND MASS FLOW RATES. The total fluid within a field, reactor bed, and single tube is listed. The volumetric flow rates in and out of a field, reactor bed, and tube are shown in cubic feet per hour. The volumetric flow in and out remains constant due to the constant density assumption. The outgoing algae flow and its corresponding lipid flow rate is also shown.

Multiple Fields

The scope of this project is to produce 20,000 bpd of n-alkane product. In order to accomplish this, multiple fields will be needed. **Figure 6** is a schematic showing how multiple fields will be placed within a single location.[24] The number of fields will depend on the capacity of a specific location which is determined by both the available land and amount of CO_2 released in emissions and available as a resource.

Optimal Conditions for *Nannochloropsis sp.* Cultivation

The following values represent optimal conditions for the cultivation of *Nannochloropsis sp.* It is recommended to run the cultivation process at the following parameters:

- Optimum *temperatures* were found to be at around 25°C.[4] For temperature control, inject nutrients at a low temperature. The land should provide temperature control.
- *pH Levels* will be maintained at a slightly basic level of around 7.8 and will be regulated with the injected CO_2.[27]
- As previously stated, only about one tenth of direct sunlight, or 19.5 W/m^2 is required to grow algae. UV inhibitors within the reactor tubing are used to prevent harm from direct sunlight.
- *Salinity* ranges from seawater to brackish water with one tenth the salinity of seawater.[4] This means that one liter of seawater can contain anywhere from 35 g dissolved salts to 3.5 g dissolved salts.
- *O_2 level* will also be regulated to stay below 400% of air saturation values.[17] Oxygen saturation occurs at 9 mg/L, meaning O_2 levels within the culture should not surpass 36 mg/L.[28]
- *Nutrients.* An F/2 media with sea water will be used as the algae nutrient source. The make-up of the nutrient source is shown in **Appendix II** on page 119. About 2 mL of media is required per L of algae produced.[29]

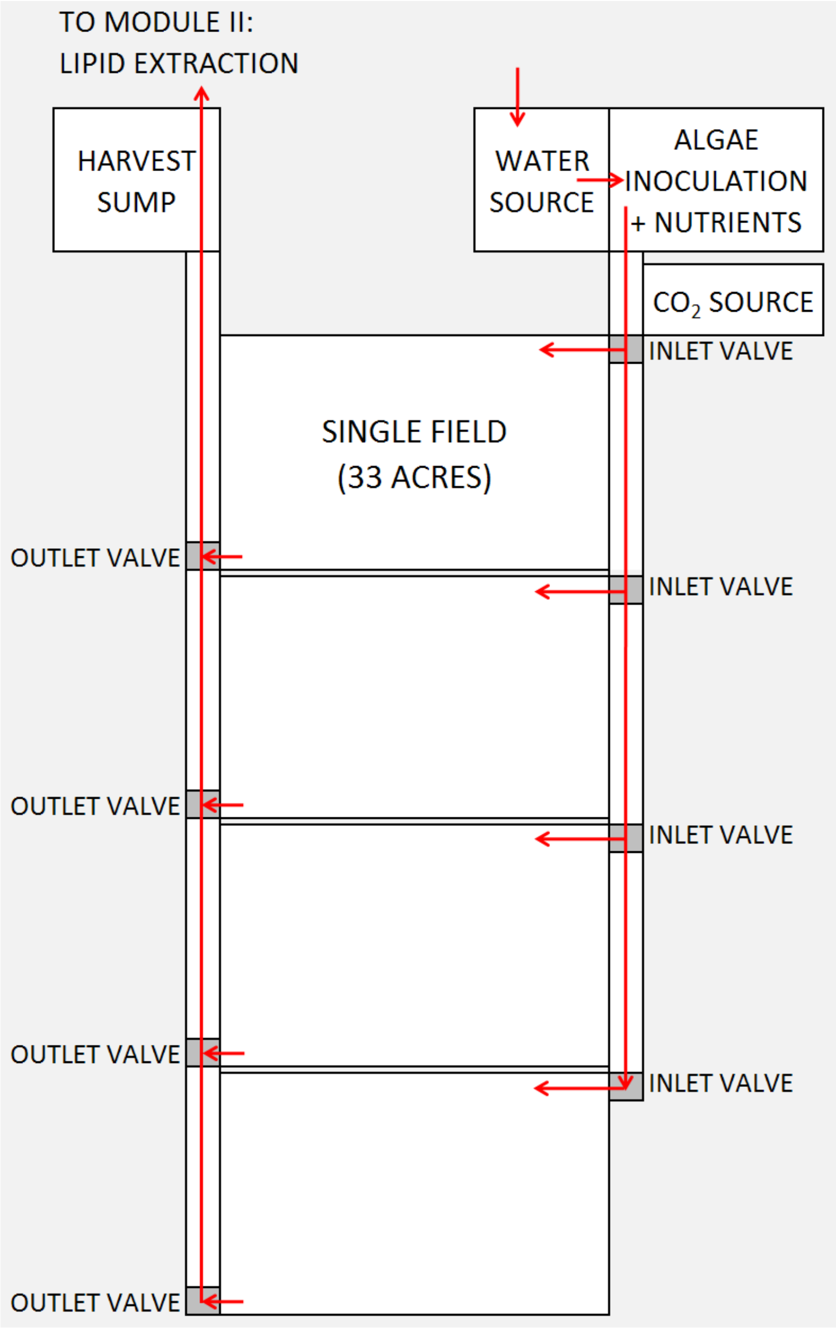


FIGURE 6: MULTIPLE FIELDS. Red arrows represent the flow of algae, water and nutrients. CO_2 is supplied to each field as shown in **Figure 4**. A common inlet and outlet flow stream runs alongside multiple fields. Separate inlet and outlet valves lead into and out of individual fields.

Cleaning the System – Accumulation of Biofilm

As the algae grow, there may be accumulation of biofilm build up on the reactor tubing. As stated above, the maintenance tractor can be used to remove this. The system is a continuous process run under pressure. With no pressure, the tubing collapses, and with pressure, it inflates. To remove biofilm buildup, the tractor applies slight pressure on the reactor tubing as the system is pressurized. The natural flow of the system should then remove the biofilm.

Production Comparisons

The following section compares the use of 100 dry tons of algae/acre-year as the production rate of *Nannochloropsis sp.* within the Simgae^{TM} cultivation process to production values of outside sources.

Diversified Energy, Inc. released a production value for Simgae^{TM} technology as a value from 100-200 dry tons of algae/acre-year. To remain conservative, it is assumed that *Nannochloropsis sp.* growth is the lower value of this range. In order to justify this value used to model growth, rates were compared with those of outside sources. **Table 6** lists values of production assumed for the Simgae^{TM} process compared to production values taken from outside sources. The conversions are shown in **Appendix II**. The factor listed describes the how much larger or smaller the assumed production rate is than the compared rate:

Factor = Model Production Rate/Reference Production Rate

Model Production Rate		Reference Production Rate		Factor
27200	kg TAG/acre*yr	33300	kg TAG/acre*yr	1.23
8000	gallons TAG/acre*yr	9560	gallons TAG/acre*yr	1.19

TABLE 6: PRODUCTION COMPARISONS. Model production rate is the assumed value used to model *Nannochloropsis sp.* within the Simgae^{TM} system. Reference production rates are taken from National Renewable Energy Laboratory and US Department of Energy sources.[4]

As seen, the assumed production rate is close to the values specified by outside sources. It is greater than referenced sources by about 20%.

CO_2 Source and Consumption

Consumption Rate

Algae use CO_2 as its source of carbon, so a reliable and sufficient source is needed to provide nutrients for a field. To calculate the consumption rate of CO_2, a general molecular formula for algae was used. To determine this, multiple sources were gathered and compared. For a determination of algae molecular composition, please refer to **Appendix II**. Algae are approximately 50 wt.% carbon resulting in a consumption rate of 1.83 grams of CO_2 needed to produce a gram of algae:[30]

$$\frac{44\ g\ CO_2/mol}{12\ g\ C/mol}\ \frac{.5\ g\ C}{g\ algae} = 1.83\ \frac{gCO_2}{g\ algae}$$

Algae enter a field at a flow rate of 339 kg algae/hour and exit at 678 kg algae/hour. A total of 339 kg algae/hour is produced. A consumption rate of CO_2 per field is calculated:

$$339\ \frac{kg\ algae}{hour}\frac{hr}{3600s}\frac{1000g\ algae}{kg\ algae} = 94.17\ \frac{g\ algae}{s}\cdot 1.83\ \frac{gCO_2}{g\ algae} = 172.3\ \frac{g\ CO_2}{s} = .381\frac{lb\ CO_2}{s}$$

CO_2 Enriched Air Flow Rates and Concentrations

Using this consumption rate, a balance on CO_2 was calculated to determine the flow of CO_2 enriched air to be injected into a single field. The composition of the flue gas from the coal fired power plant is 31.57 wt.% CO_2.[31] A dilution with dry air is needed to reduce the concentration to a desirable value of 6 wt.% CO_2 which will then be injected into a field at four different locations. To do so, 1.8 lb/s of flue gas is mixed with 7.2 lb/s of dry air. Calculations for this dilution can be found in **Appendix II**. This leads to a total injection rate of 9 lb/s for the entire field, or 2.25 lb/s at each of the four injection locations. The composition and flow data is shown below in **Table 7**.

Component	Flow (lb/s)	wt %
CO_2	0.58	6.35
H_2O	0.11	1.23
O_2	1.73	19.25
N_2	6.47	71.92
SO_2	0.01	0.10
NO_x	0.01	0.11
Ar	0.09	1.0
SUM	9.0	100

TABLE 7: CO_2 ENRICHED AIR INLET FLOW DATA. Details the flow rate and composition to be injected into an *entire field*. In reality, flow will be divided into four streams, each 2.4 lb/s and injected at four locations 300 feet apart along a field. Also contains trace amounts of mercury from the flue gas.

Using the consumption rate of .380 lb CO_2/s, the amount of leftover CO_2 and composition of the flow stream coming out of an entire field is calculated and shown in **Table 8**.

Component	Flow (lb/s)	wt %
CO_2	0.19	2.21
H_2O	0.11	1.29
O_2	1.73	20.10
N_2	6.47	75.10
SO_2	0.01	0.10
NO_x	0.01	0.12
Ar	0.09	1.07
SUM	8.62	100.00

TABLE 8: CO_2 ENRICHED AIR OUTLET FLOW DATA. Details the flow rate and composition exiting an *entire field*. It contains trace amounts of mercury from the flue gas.

As shown, an overall starting concentration of about 6 wt% CO_2 will be injected with a total flow rate of 9 lb/s, to be reduced to about 2 wt.% CO_2 and an overall mass flow of 8.62 lb/s of CO_2 enriched air out of a single field. The optimal CO_2 concentration for *Nannochloropsis sp.* has been found to be 2 wt% CO_2 which is the basis for the resulting exit concentration.[32]

Location Carbon Capacity

The W.A. Parish Electric Generating Station generates 2,475 MW of electricity through the use of coal and 1,190 MW with natural gas.[21] It is desirable to calculate the number of fields this location can provide CO_2 for. Emissions data collected in 1999 states that the average CO_2 output was 2.095 lbs CO_2/KWh for coal fired electricity generation and 1.321 lbs CO_2/KWh for natural gas fired plants.[33] The rate of CO_2 produced from this power plant was calculated:

$$\text{Coal Fired Plant: } 2475000\ KW\,\frac{2.095\ lbs\ CO_2}{KWh} = \frac{248886000\ \ lbs\ CO_2}{3600s} = 1440\ \frac{lbs\ CO_2}{s}$$

$$\text{Natural Gas Fired Plant: } 1190000\ KW\,\frac{1.321\ lbs\ CO_2}{KWh} = \frac{75455520\ \ lbs\ CO_2}{3600s} = 437\ \frac{lbs\ CO_2}{s}$$

This value was compared to the amount of CO_2 injected per field to determine the capacity of this location. Emissions will only be taken from the coal fired power plants. Thompsons, TX has the carbon capacity to support almost 3780 fields.

$$\frac{1440\ \dfrac{lbs\ CO_2}{s}}{0.381\,\dfrac{lb\ CO_2}{s\cdot field}} = \ 3779.53\ fields$$

Nutrient Consumption

The media used to nourish the algae is Guillard's F/2 formula for marine algae. The recipe for the nutrient stream can be found in **Appendix II**. Consumption of nutrients is based off a value taken from an outside source of 2mL of medium required per L of algae.[29] No concentration of algae is coupled with this value. In order to calculate nutrient consumption, it is postulated that this value can be used with the exiting algae concentration of a field.

$$\frac{.002\ L\ nutrients}{L\ algae}\cdot\frac{L\ algae}{.00293\ kg\ algae} = .6826\,\frac{L\ nutrients}{kg\ algae}$$

Therefore, for an entire field, consumed nutrients per time is determined:

$$.6826\,\frac{L\ nutrients}{kg\ algae}\cdot\frac{(678-339)\ kg\ algae}{hr}\cdot\frac{hr}{3600\ s} = .0642\,\frac{L\ nutrients}{s}$$

Overall, in an entire field of flow rate 64.3 L/s loses .0642 L nutrients/s as algae is grown. From this, the excess amount of nutrients is determined and can be used as recycle.

$$64.3\,\frac{L}{s} - .0964\,\frac{L\ nutrients}{s} = 64.2\,\frac{L}{s}$$

$$1 - \frac{.0642\frac{L\ nutrients}{s}}{64.3\ \frac{L}{s}} = .99 = 99\%\ \text{recycle}$$

99.9% of the fluid within the system can be recycled. This will save also save a large cost when the economics are evaluated. Since only half of the exiting algae stream (32.15 L/s) goes to processing in **Module II**, the recycle stream returning to **Module I** from **Module II** will be 99% of the 32.15 L/s fluid.

Oxygen Production

The rate at which oxygen is produced is also calculated. The process of photosynthesis shows that for every mole of carbon dioxide consumed, a mole of oxygen is produced:

$$12H_2O + 6CO_2 + light\ \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

However, a 1:1 ratio does not account for all of the oxygen produced. Oxygen is also produced from splitting molecules of water to provide energy for metabolic processes within the algae. In order to accurately account for all the oxygen, it is known that it takes 8 photons of light to produce a molecule of O_2 and 8-12 photons to assimilate a CO_2 molecule into the system. Therefore the amount of energy needed to assimilate a CO_2 molecule for algae growth, is provided by an amount of energy that is created in the splitting of water molecules, releasing a certain number of O_2 molecules. An average of 10 photons to assimilate a CO_2 molecule is used in the following calculation of amount of O_2 produced:[30]

$$\frac{8\ mol\ O_2}{10\ mol\ CO_2} \cdot \frac{32\ \frac{g\ O_2}{mol\ O_2}}{44\frac{g\ CO_2}{mol\ CO_2}} 1.83\ \frac{g\ CO_2}{g\ algae} = 1.07\ \frac{g\ O_2}{g\ algae}$$

$$1.07\ \frac{g\ O_2}{g\ algae} \cdot \frac{(678 - 339)\ kg\ algae}{hr} \cdot \frac{hr}{3600\ s} \cdot \frac{1000\ g}{kg} = 100.76 \frac{g\ O_2}{s} = 0.222 \frac{lb\ O_2}{s}$$

C. LAND REQUIREMENT

To produce the desirable amount of 20,000 bpd of n-alkane product, a certain amount of land is required to cultivate the algae. The flow rate of algae to be processed is half the total exiting algae flow, .0941 kg algae/s. This is because half of the exiting flow will be recycled and used as the algae inoculant for the next cultivation cycle. *Nannochloropsis sp.* has a water content of 0.8 wt% and is 46 dry wt% lipid with 80 % of total lipid as TAG. The land requirement calculation is done assuming a 90% lipid extraction efficiency in **Module II** and a value of 3,018,062.3 kg TAG/day needed to produce 20,000 bpd of n-alkane taken from **Module III**:

$$\frac{678}{2}\ \frac{kg\ algae}{hr} = 339\ \frac{kg\ algae}{hr} \frac{hr}{3600s} = .0941\ \frac{kg\ algae}{s}$$

$$.0941\ \frac{kg\ algae}{s} \frac{86400\ s}{day} (.46)(0.8) = \ 2993.38 \frac{kg\ TAG}{day \cdot field}$$

$$\frac{3018062.3\ \frac{kg\,TAG}{day}}{0.9\cdot 2993.38\frac{kg\,TAG}{day\cdot field}} = 1120.27\,fields \approx 1120\,fields$$

A total of 1,120 fields are required. The number of locations required for the full scale process is dependent upon the capacity of fields at Thompsons, TX. Based on aerial imagery of the proposed location, it is evident that our location has enough open land for much more than 1,120 fields. In this case, only the location of Thompsons, TX is needed to produce the total 20,000 bpd of n-alkane product. In reality, the capacity will depend on the amount of available land and property laws in the area.

D. ENERGY CALCULATIONS

The energy input into the system includes energy taken from the sunlight and converted into energy to power algae growth and a pump used to move the algae slurry throughout the system. A centrifugal pump will be used with an assumed pump head of 150 feet.

> Algae convert sunlight into energy through the process of photosynthesis. For *Nannochloropsis sp.* a minimum of 19.5 W/m^2 is required for growth. An entire field of 33 acres requires at least 2580 KW from sunlight. All 1120 fields require at least 2,900,000 KW of sunlight to produce 20,000 bpd of n-alkanes.
>
> The power calculation of the circulation pump, a centrifugal pump with a pump head of 150 feet (45.72 meters) is shown below. The pump head was assumed based on the recommendation of two industrial consultants, Mr. Gary Sawyer of Lyondell Chemical Co. and Mr. Wayne Robbins. A density between that of pure water and sea water (1015 kg/m^3) is assumed throughout the system, as the amount of algae is minimal relative to the media and the salinity of the media can be between that of sea water (35 g dissolved salts/L) and 1/10 (3.5 g/L) the value of seawater.[4] In the following equation, Q is the volumetric flow rate in m^3/s, ρ is the density in kg/m^3, H the pump head in m, and a gravitational acceleration of 9.81 m/s^2.[34]

$$Power = Q\cdot\rho\cdot H\cdot 9.81 = 1015\frac{kg}{m^3}\cdot 9.81\frac{m}{s^2}\cdot 45.72\,m\cdot .0643\ \frac{m^3}{s} = 32524.43\,W = 32.5KW$$

E. ECONOMICS

Capital Costs

According to Diversified Energy, the capital costs for installation including estimates for the cost of land, harvesting, and product storage for the Simgae^{TM} cultivation system is within the range of \$45k to \$60k per acre. This cost is significantly less than costs of conventional cultivation processes of this scale which can range anywhere from \$100k to \$1M per acre.[26] For a conservative estimate, a value of \$60k per acre was used to calculate capital costs for a single field and for the full scale project of producing 20,000 bpd of n-alkane. A contingency fee of 15% and a contractors fee of 3% is added to the capital cost. For a single field:

$$\frac{\$60{,}000}{acre}\cdot 32.72\,acres\cdot 1.18 = \$2.32\,MM$$

Operations and Maintenance

Operations are negligible as they are minimal in comparison to other continuous process costs and capital costs.

Maintenance will be taken as 4.5% of the total capital costs. This amounts to

$$1{,}963{,}636\ dollars \cdot .045 = 88{,}364\,\frac{dollars}{field}$$

Continuous Costs

Nutrients. Guillard's F/2 medium will be used to nourish the algae. There is great uncertainty in the calculation of the F/2 medium cost for the Simgae cultivation system. As a reference, F/2 medium is sold by Sigma-Aldrich, a company that provides chemical and biochemical products and kits, at a price of \$18.50 for 10 liters (\$1.85/L) of nutrients. The cost of buying nutrients directly from Sigma-Aldrich is calculated below.

$$.0643\,\frac{L\ nutrients}{s} \cdot 1.85\,\frac{dollars}{L\ nutrients} = 0.119\,\frac{dollars}{s}$$

However, it is infeasible to use this price when estimating nutrient cost because the f/2 medium sold by Sigma-Aldrich is such a small quantity (10L) and such a price quote cannot be extrapolated for the large amount of nutrients required for an industrial-scale cultivation system.

Instead, the cost of f/2 medium can be estimated by individually purchasing components of the f/2 medium from an industrial chemical supplier and preparing the f/2 medium independently. The recipe of the f/2 medium and calculations for preparing the medium is shown in **Appendix II** to give a value of \$.0098 per liter of medium, approximately 200 times less than the extrapolated laboratory-scale cost estimate. While this value is highly variable, the nutrient cost estimate based on purchasing nutrient components individually is more reasonable that extrapolating laboratory-scale price quotes for a large-scale process. For the purposes of this analysis, the nutrient cost is estimated to be \$0.0098/L, resulting in a continuous cost of nutrients of \$0.0006/s.

$$.0643\,\frac{L\ nutrients}{s} \cdot .0098\,\frac{dollars}{L\ nutrients} = 0.0006\,\frac{dollars}{s}$$

Sea water. The cost of seawater was taken as the cost to purchase process water, \$0.75/1000 gallons. It is assumed that 99% of the water is recycled.

$$\frac{\$0.75}{1000\ gallons} \cdot 0.264\frac{gallons}{L} \cdot 0.01 \cdot 64.3\frac{L}{s} = .000127\frac{dollars}{s}$$

CO_2 Costs are negligible. The source of CO_2 is taken from power plants located near the cultivation plant and assumed to be of no cost.

Pump. The pump used to run a field is a centrifugal pump generating 32.5 KW, or an annual value of 257,400 KWh. Using a cost of electricity of \$.07 per KWh, the pump cost is calculated:

$$257400\ KWh \cdot \frac{0.07\ dollars}{kWh} = 18018\frac{dollars}{year}$$

The above costs quantify the continuous costs to produce algae. The following **Economic Summary** summarizes the total economics for both a single field, and the entire process to produce 20,000 bpd of n-alkane.

Economic Summary

	FOR A SINGLE FIELD		FOR ALL FIELDS	
FIXED COSTS				
Capital Costs	$60,000	per acre		
	32.70	acre/field		
	$1,960,000	per field	1120	fields
15% Contingency	$295,000	per field	$2,199,273,000	
3% Contractors Fee	$59,000	per field	$329,891,000	
4.5% Maintenance Cost	$88,000	per field	$98,967,000	
TOTAL	**$2,405,000**	**per field**	**$2,694,110,000**	**all fields**
CONTINUOUS COSTS				
Materials Cost				
F/2 Media	$0.0098	per liter	$0.01	per liter
	$0.0006	per second	$0.71	per second
Sea Water	$0.0002	per liter	$0.00	per liter
Flow (with 99% recycle)	0.643	L/s	720	L/s
	$0.00013	per second	$0.14	per second
CO_2	$0	per liter	$0	per liter
	$0	per second	$0	per second
Pump Cost				
Required Power				
Annually	257000	KWh	288,000,000	KWh
Electricity Cost	$0.07	per KWh	$0.07	per KWh
	$18,000	per year	$20,200,000	per year
	$0.0006	per second	$0.64	per second
TOTAL	$0.0013	per second	$1.49	per second
	$42,000	**per year**	**$46,983,000**	**per year**
Cost for the Production of Algae				
Total Continuous Cost	$42,000	per year	$46,983,000	per year
Algae Produced	2,684,000	kg /year	3,006,394,000	kg /year
	$0.014	**per kg algae**	**$0.014**	**per kg algae**

Capital costs to install cultivation systems are very high, at $2.4MM per field. This calculation is calculated from a base cost of $60k per acre of land, each field being 33 acres in surface area and includes a cost for installation, land, harvesting, and product storage. According to the above economic analysis, it costs about $0.014 to produce a kg of algae. It is important to note that the above economic analysis does not include the continuous cost of running a CO_2 injection system, which could be fairly energy intensive.

A GLANCE AT ECONOMICS: Diversified Energy Algal Biofuels Modeling and Analysis

"Over a two-year period, an exhaustive technical, engineering, cost, and economic model was constructed, reviewed, and matured [by Diversified Energy, Inc.] to provide a realistic baseline assessment of algal biofuel economics and the cost drivers associated with commercial-scale algae production."[35]

In order to determine inaccuracies within the economic analysis of **Module I**, relative values are compared to an article documenting the economic assessment performed by Diversified Energy. The model is not specific to any particular cultivation system, so it is independent of technology and comparable to the Simgae^{TM} cultivation system.[35]

Table 9 lists the continuous costs taken from the previous economic analysis of the Simgae^{TM} system. As can be seen, the nutrient cost composes 47% of the total continuous costs.

Component	Continuous Cost		Percentage
Nutrients	0.00063	\$/s	47%
Sea Water	0.00013	\$/s	10%
CO_2	0	\$/s	0
Pump	0.00057	\$/s	43%

TABLE 9: CONTINUOUS COSTS. A summary of the continuous costs shows that the medium composes 47% of the total.

Figure 7 shows the breakdown of costs for cultivation processes according to the analysis done by Diversified Energy. As shown by the two pie charts, there are operations and maintenance costs as well as capital costs. Each is broken down into their respective compositions. As seen under the operations and maintenance pie chart, nutrients only compose 9% of the total cost, while utilities make up the largest piece of 36%.[35] This is much different from the analysis of the Simgae^{TM} system that was previously done. This is due to many factors:

- No cost for CO_2
- Utilities are only composed of by the pump cost. Missing utilities include electricity to operate the CO_2 injection system and aeration valves. Other utility costs include energy required to run the maintenance tractor which removes biofilm buildup along the reactor tubing.
- Management and labor costs were assumed negligible when compared to the cost of nutrients.
- As will be seen in **Module II**, dewatering is not required for lipid extraction through the OriginOil^{TM} process.

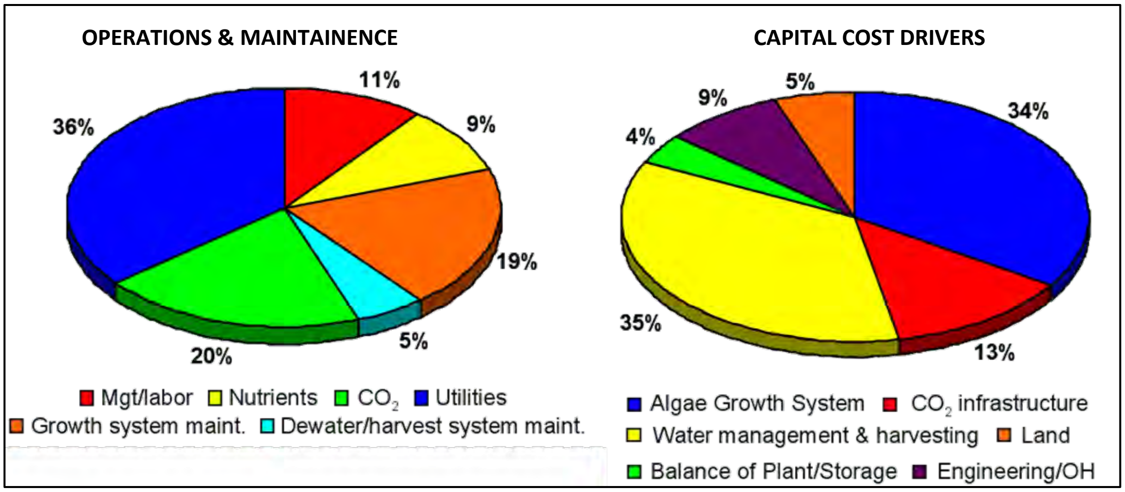


FIGURE 7: OPERATIONS/MAINTENANCE AND CAPITAL COST COMPONENTS. The pie chart located on the left side details the operations and maintenance costs while the pie chart on the right details capital cost drivers. Both charts show a breakdown of costs into its different components. Courtesy of Diversified Energy, Inc.

As seen by the pie chart detailing the capital cost breakdown, most of the capital costs are contributed to the water management and harvesting of the algae as well as the installation of the algae growth system. When calculating capital costs, a direct number was taken from Diversified Energy, Inc. ($60k per acre) and is seen as accurately modeling the Simgae™ process.[35]

F. Concern with the Simgae^{TM} Analysis: Dilute Exiting Algae Stream

The exiting algae stream from the Simgae^{TM} cultivation system modeling our algae has a density of just 2.93 g dry weight algae/L. This value is significantly lower than the exiting densities of other cultivation processes which can contain around 10 g of algae per L. Therefore, the exiting stream is extremely dilute when sent to **Module II**.

The Diversified Energy presentation detailing Simgae^{TM} also has a low exiting concentration, a value of 2 g algae dry weight/L. Therefore, a very dilute exiting stream is taken as a parameter of the cultivation system. This is seen as an inefficiency as it results in very large quantities of fluid relative to algae flowing into **Module II** for lipid extraction.

When optimizing the system in the future, it will be more beneficial to increase the dwell time within the system, and therefore the total time spent within the cultivation system. This would result in an increase in the exiting concentration of algae. Less excess fluid will be sent to **Module II** and recycled back to **Module I**, increasing the efficiency of the process.

G. Other Important Considerations

One possible concern with the Simgae^{TM} process is the idea of temperature control. Most algae strains grow well in temperatures ranging from 20-27°C. However, temperatures well above 30°C and below 17°C could result in harm to the algae strain. The Simgae^{TM} process relies on the land to provide both structure and temperature control. In extreme temperatures, where water temperatures rise outside of this range, it may be important to employ other temperature controlling techniques.

For high temperature relief, it is possible to inject the nutrient stream at a cooled temperature at the CO_2 injection sites spaced apart every 300 feet. During colder months of the year, it is possible to inject CO_2 at a higher temperature to keep the system warm.

The system has a flow velocity of 0.007 ft/s, a very low rate. As mentioned previously, maintenance tractors are used to remove biofilm buildup along the reactor tubing. This is done through the application of pressure on a focused portion of the tubing while the system is pressurized, so that the algae flow by this area knocking off the biofilm. It is a concern that the flow velocity is not large enough to do this. Although the entire system can be flushed out and cleaned every year, biofilm buildup occurs within a short time. It is important to be able to remove this biofilm so that sunlight isn't prevented from reaching the algae in circulation.

One possible way to remove the biofilm is through increasing the flow velocity temporarily as the maintenance tractor passes over the tubing. Another method would be to chemically dissolve the biofilm buildup periodically.

MODULE II: LIPID EXTRACTION

V. CONCEPT STAGE

A. LIPID EXTRACTION

A significant obstacle to commercializing algae fuel is the high energy costs of dewatering required to extract the lipid from algae. Conventional processes rely on hexane solvent extraction, which use several steps of mechanical and evaporative dewatering. For this stage, we choose to assess a new process under development by OriginOil^{TM}. The new process promises significant energy savings by avoiding the need to dewater. The following is a technology overview of conventional lipid extraction process and OriginOil's extraction process.

B. CONVENTIONAL LIPID EXTRACTION

Hexane extraction takes advantage of the high solubility of lipid in hexane and hexane's low boiling point (67°C). The process brings raw material feed (mechanically lysed cells usually in cake form) in contact with a hexane stream. Lipids in the feed will migrate into the hexane stream to until the interface reaches equilibrium, producing an oil-hexane solution called miscella. Distillation of the miscella will then yield the lipid in the bottoms, while the hexane is recovered and reused.

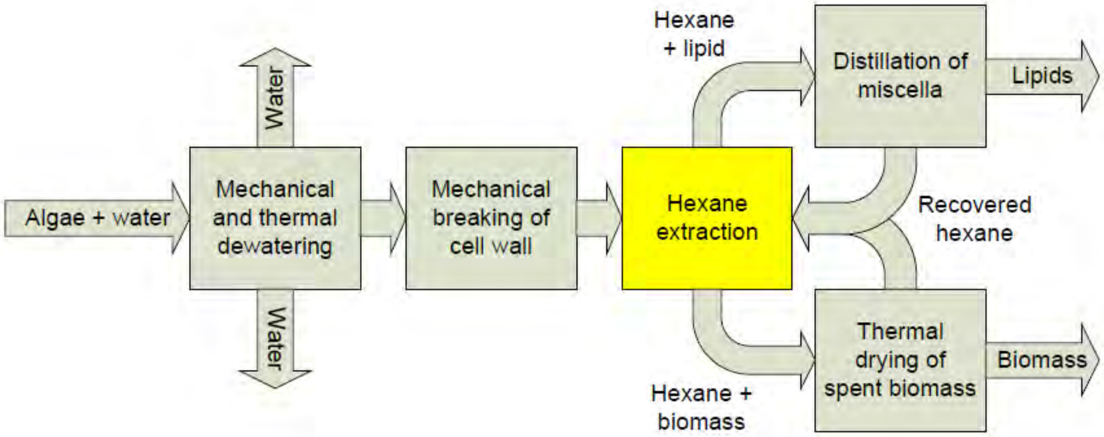


FIGURE 8: CONVENTIONAL LIPID EXTRACTION USING HEXANE EXTRACTION.

Multiple stages of mechanical and thermal dewatering are required for hexane extraction. The following is an example of the processes that may be involved:

1. Mechanical dewatering of the algae slurry to produce dewatered algae containing 70% moisture. The separated water is returned to algae cultivation.
2. Thermal drying of the dewatered algae to produce dry algae of 10% moisture and water vapor.
3. Mechanical lysing of the dry algae.

4. Treat lysed cells with hexane solvent to produce miscella (solvent with 10-25% oil) and spent biomass (solids with 30% solvent).
5. Distillation of miscella to separate solvent from lipids.
6. Removal of solvent from spent biomass with heat.
7. Recovery and treating of solvent from vapors and waste water.

C. ORIGINOIL^{TM} EXTRACTION PROCESS

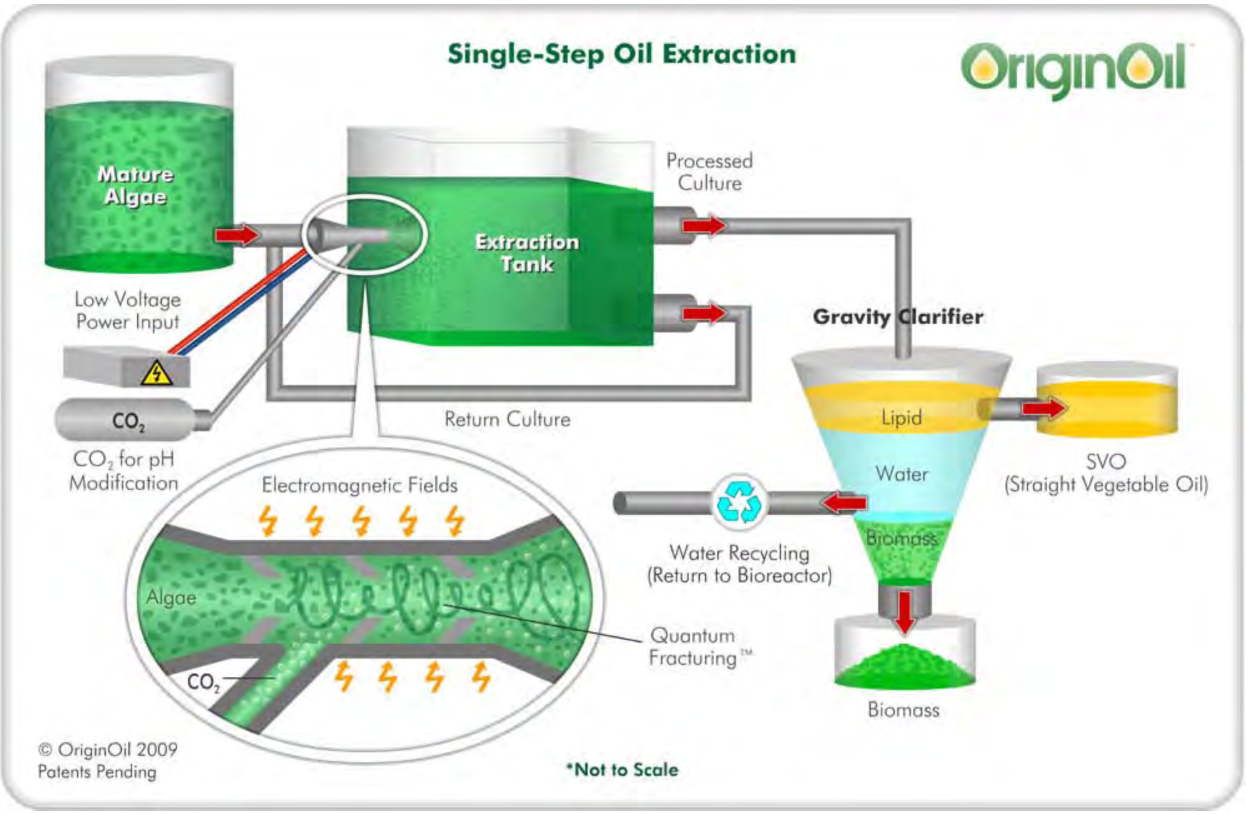


FIGURE 9: ORIGINOIL'S SINGLE-STEP OIL EXTRACTION.

The key technology in the OriginOil^{TM} process is Quantum Fracturing^{TM}, which lyse the algae cell while it is still in the slurry. This process uses high pressure injection of CO_2 microbubbles in combination with electromagnetic radiation to rupture the algae cells. The broken cells then separate into lipid, water, and biomass layers in a gravity clarifier. This eschews much of the mechanical and thermal dewatering required for conventional extraction. The company claims energy savings of up to 90% as well as drastic reductions in capital expenditure. OriginOil^{TM} is currently developing a pilot scale plant.

VI. FEASIBILITY AND DEVELOPMENT STAGES

The following sections will introduce and explain the OriginOil Single-Step Extraction^{TM} process to extraction lipids from algae. **Section A** provides the process flow diagram (PFD) and associated mass balances. The detailed process description is listed in **Section B**. **Sections C, D,** and **E** list the associated utility requirements, equipment summaries, and specification sheets. **Section F** explains the operating costs and economic analysis of the OriginOil^{TM} process.

A. Process Design and Material Balances

PROCESS FLOW DIAGRAM

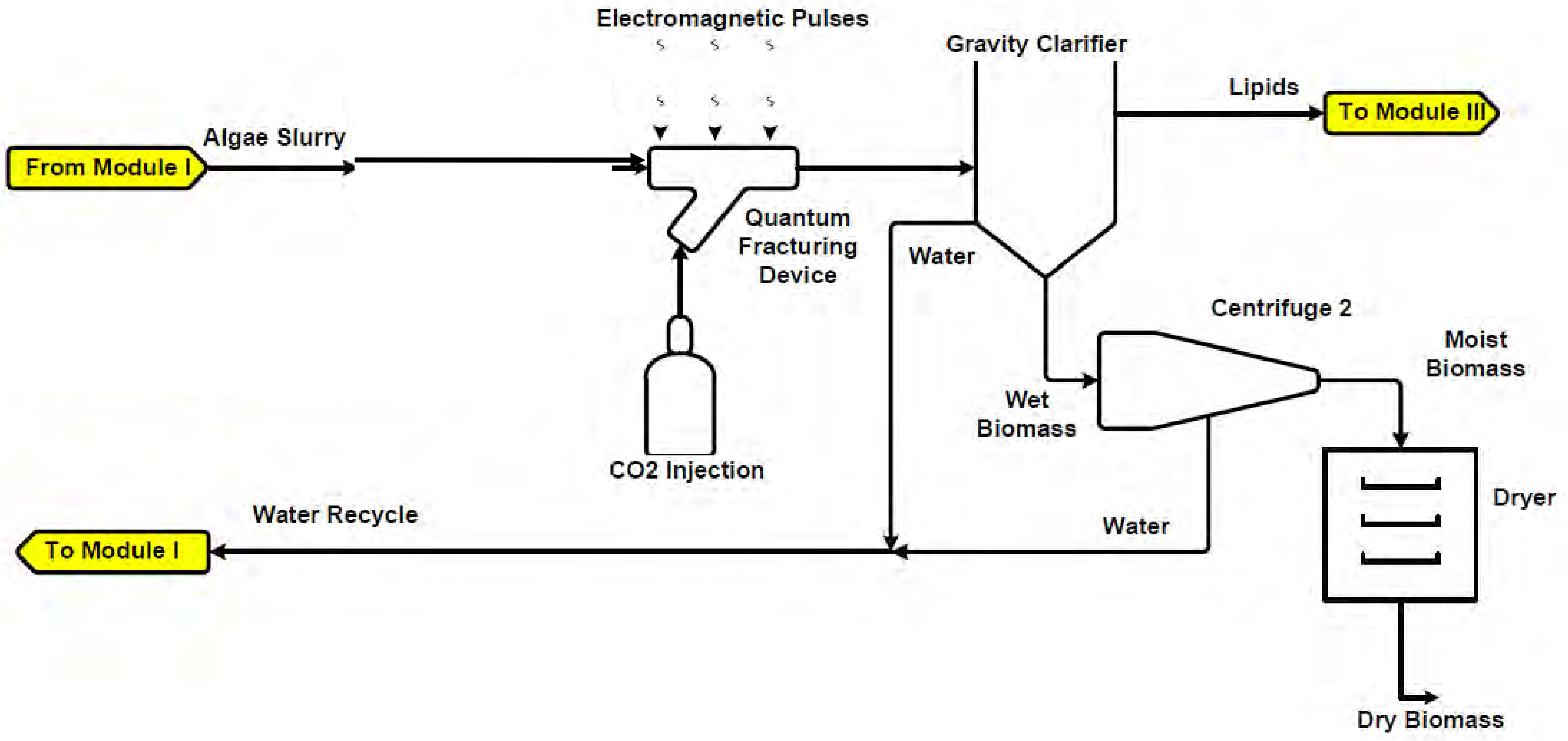


FIGURE 10. PROCESS FLOW DIAGRAM FOR MODULE II.

MATERIAL BALANCE

TABLE 10: MATERIAL BALANCES FOR ORIGINOIL PROCESS.

Stream	Algae Slurry	Lipids	Wet Biomass	Moist Biomass	Dry Biomass	Water Recycle
Mass flow (kg/hr)	130,054,471	157,191	2,224,970	278,121	247,219	129,650,061
Component mass flow (kg/hr)						
H2O	129,674,783	Trace	2,002,473	55,624	24,722	129,650,061
Lipid	174,656	157,191	17,466	17,466	17,466	Trace
Biomass	205,031	0	205,031	205,031	205,031	Trace
H2O fraction (wt%)	99.71%	0.00%	90.00%	20.00%	10.00%	100.00%
Mass flow (lb/hr)	286,721,029	346,546	4,905,220	613,152	545,024	285,829,458
Component mass flow (lb/hr)						
H2O	285,883,961	Trace	4,414,698	122,630	54,502	285,829,458
Lipid	385,051	346,546	38,505	38,505	38,505	Trace
Biomass	452,017	0	452,017	452,017	452,017	Trace

B. PROCESS DESCRIPTION

Given the scope of this project, and the limited public information available on the OriginOil^{TM} process, the proprietary technology is treated as a black-box and postulates are used to estimate the material and energy balances.

The following postulates have been made for the calculation of the material balance:

- The concentration of algae is 2.928 grams dry weight per liter.
- The algae cell contains 46% lipid on a dry weight basis, and 80% of this lipid are triglycerides.
- The water content of the wet biomass, moist biomass, and dry biomass are 90%, 20%, and 10% respectively.
- 90% of the lipids contained in the algae leaves in the lipid stream. The remaining 10% are trapped in the biomass.[36]

Breaking the Cell Wall

The raw material feed into the OriginOil^{TM} process is algae slurry from the cultivation farm at a flow rate of 130 million liters per hour. The slurry contains approximately 2.93 grams of algae per liter and first enters the Quantum Fracturing^{TM} Device, where it is subject to electromagnetic radiation and CO_2 microbubble injection.[36] The CO_2 is injected at high pressure to ultrasonically agitate the cell as well as modify the pH. The Quantum Fracturing^{TM} Device induces the algae cell wall to rupture. From there, the broken cell is carried in slurry to the gravity clarifier.

Gravity Separation

For simplicity, the Process Flow Diagram (**Figure 10**) shows a single clarifier. However, for a flow rate of 130 million L/hr (34 million gal/hr), it is estimated that three clarifiers, each of 12 million gallon capacity, are required in parallel. The combined capacity of these clarifiers provide a residence time of one hour, during which the broken cells will separate into layers of lipid, water, and biomass.

From the clarifier, the lipid layer is siphoned off as the lipid stream. A lipid yield of 90% is assumed, which is within the range of 85% to 97% that OriginOil^{TM} reported achievable with this technology in bench-scale testing.[37] The mass flow rate of lipid is around 346,000 lb/hr. In terms of lipid composition it is assumed that 80% of the lipid composition is triglyceride, so further purification is required before the lipid can be processed into fuel. The details of lipid purification procedures are beyond the scope of this study. Instead, it is assumed that there are purification steps **Module II** and **III** and they will require additional cost. These purification steps produce a nearly pure triglyceride that is the feed to **Module III**.

Dewatering

The remaining water and biomass mixture is partially separated in the clarifier as well. It is assumed that the wet biomass stream leaving the clarifier is 90% water by weight, and contains residual lipids trapped in the biomass. To prevent spoiling, the biomass must be dried to less than 10% water content through a series of dewatering steps. The first step is the centrifuge, where the wet biomass stream is dewatered to 20% water by weight (moist biomass cake). The water separated by the centrifuge, as well as the water from the clarifier, are recycled for algae cultivation. Nearly all of the water from the slurry feed (99.7%) is recycled.

Drying

The moist biomass cake enters the dryer, where water is boiled off until a dry biomass solid of 10% or less water content is left. This dry biomass can then be sold as livestock feed. Please refer to the Dryer discussion in the **Unit Descriptions** section on page 47 for more detail.

Other Considerations

Carbon Dioxide

One component so far ignored in the discussion is CO_2. OriginOil does not provide any data on the amount of CO_2 needed for Quantum Fracturing. The CO_2 is likely purchased in liquid form and expanded prior to injection. The quoted price of liquefied CO_2 refill of ASME code cylinder is $0.233/lb from Continental Carbonic, a vendor based in Illinois. However, since the quantity of CO_2 injection in the OriginOil process is unknown, the cost of CO_2 is not included in the economic analysis going forward. We postulate its cost is small compared to other variable costs. Also, the CO_2 does not interact with the rest of the materials in any other way, and bubbles off in the gravity clarifier.

C. ENERGY BALANCE AND UTILITY REQUIREMENTS

TABLE 11. UTILITY REQUIREMENTS FOR ORIGINOIL^{TM} PROCESS.

Energy Consumption		**Units**
Extraction		
Electromagnetic waves, CO_2 injection	213,574	kWh
Dewatering		
Centrifuge	38,566	kWh
Drying	20,416	kWh
Total energy use	272,556	kWh

Electricity cost	0.07	$/kWh
Total energy cost	**19,079**	**$/hr**

Total energy use for lipid extraction is 273,000 kWhs per hour. With the cost for electricity at $0.07 per kWh, the energy cost come out to $19,000 per hour.[38] This analysis shows the energy requirement for extraction is 0.79 kWh/lb lipid, or a cost of $0.055/lb.

The assumptions used to calculate this energy consumption are explained below. Note this analysis does not include the energy needed to pump the streams or to purify the lipid to pure triglyceride. However, these costs should be trivial compared to the energy costs of extraction and dewatering.

EXTRACTION

Extraction Energy Requirements

The most energy intensive step of the lipid extraction process is OriginOil's Quantum Fracturing^{TM} technology. The process involves generation of electromagnetic waves and injection of microbubbles of CO_2. Our estimate of energy consumption is based on information provided in OriginOil^{TM}'s presentation at the World Biofuels Conference on March 15-17, 2010.[36]

TABLE 12. EXTRACTION ENERGY REQUIREMENTS FOR ORIGINOIL^{TM} PROCESS.

From OriginOil presentation		**Units**
Slurry flow rate	10,000,000	L/hr
Algae conc.	1	g/L
Algae mass flow	10,000,000	g/hr
Extraction		
Electromagnetic waves, CO_2 injection	5625	kWh
Energy consumption per gram algae	0.0005625	kWh/g

To use this information, we assume the energy consumption is directly proportional to the mass flow rate of algae. This relationship is probable since much of the energy goes into breaking the cell walls. The energy of extraction at the mass flow rate of our design is:

$$130 * 10^6 \frac{L}{hr} * 2.93 \frac{g}{L} * 0.0005625 \frac{kWh}{g} = 2.13 * 10^5 \; kWh$$

DEWATERING

Centrifuge

The centrifuge processes 205,000 kg/hr of solids from 90% water content to 20% water content. An article published by the Water Environment Federation in 1994 estimates that the energy consumption of centrifuge is 171 kWh/dry ton.[39] The energy use of the centrifuge is:

$$205{,}000 \; \frac{kg}{hr} * \frac{1 \; ton}{907.18 \; kg} * 171 \frac{kWh}{ton} = 39{,}000 \; kWh$$

Thermal Dryer

Biomass leaving the centrifuge with 20% water content must be dried to 10% water content. The amount of water removed is:

$$(205{,}000 + 17{,}500) \frac{kg \; solid}{hr} * \left(\frac{0.20 \; kg \; H2O}{0.80 \; kg \; solid} - \frac{0.10 \; kg \; H2O}{0.90 \; kg \; solid} \right) = 31{,}000 \text{ kg H2O}$$

For a heat of vaporization of 0.627 kWh / kg water, this would require:

$$31{,}000 \; kg \; H_2O * 0.627 \frac{kWh}{kg} = 20{,}000 \; kWh$$

D. EQUIPMENT LIST AND UNIT DESCRIPTIONS

Quantum Fracturing^{TM} Device

Quantum Fracturing^{TM} is a proprietary process developed by OriginOil^{TM}. The technology uses a combination of pH modification, electromagnetic field, and CO_2 microbubbles to break the cell wall of the algae as it flows past.

Gravity Clarifier

The gravity clarifier enhances separation of the lipid, water, and biomass layers coming from the Quantum Fracturing^{TM} device. The stream containing ruptured algae cells flows into the unit, where it separates into three layers. The lipids rise to form a top layer for skimming and further processing. The remaining biomass sinks to the bottom layer, and is sent to centrifuge. The intermediate water layer is recycled. It operates at ambient temperature and atmospheric pressure. A total of three clarifiers of 12 million gallon each are used in this process. The clarifiers are built of concrete and have a combined settling area of 225,000 square feet, which is enough to handle the expected 5.4 thousand tons of solids per day. The bare-module cost of each clarifier is $3 million.

Centrifuge

Six similar centrifuges are needed to dewater the biomass coming out of the clarifier. The units are continuous scroll solid bowl centrifuges designed for processing 40 tons solids per hour. Each centrifuge is made of stainless steel and has a bare-module cost of $0.77 million. The utility need of the centrifuges together is 38,566 kWh.

Dryer

The dryers continue the dewatering process by reducing the moisture content of biomass from 20% to 10%, the level necessary to avoid spoiling as livestock feed. A total of 24 drum dryers are needed to evaporate 68,000 lb of H_2O. Each stainless steel dryer has a diameter of 480 square feet and, operating at an evaporation rate of 6 lb/hr/ft^2, can evaporate 2880 lb/hr. The total utility required for all of the dryers is 20,416 kWh. The bare-module cost of each unit is $0.7 million.

E. SPECIFICATION SHEETS

Gravity Clarifier

Identification:	Item:	Gravity Clarifier	Date:	April, 5, 2010
	Item No:		By:	AX
	No. Required:	3		

Function: Separate slurry into lipid, biomass, and water streams

Operation: Continuous

Materials Handled:

Inlet Stream ID:	Algae Slurry	
Quantity (lb/hr):	286,721,029	
Composition:	H_2O	99.70%
	Lipid	0.13%
	Biomass	0.16%
	CO_2	Trace

Design Data: **Notes:**

Type:	Gravity Clarifier		
Material:	Concrete		
Pressure:	14.7	psia	
Capacity:	12,000,000	gallons	
Settling Area (A):	75,000	square feet	
Purchase Cost (Cp):	1,452,076		Cp = 2160*A^0.58
Bare-module Factor:	2.06		Seider Tbl. 22.11
Bare-module Cost:	2,991,276		

Utilities: None

Comments:

Centrifuge

Identification:	Item:	Centrifuge	Date:	April, 5, 2010
	Item No:		By:	AX
	No. Required:	6		

Function: Dewater biomass from 90% moisture to 20% moisture

Operation: Continuous

Materials Handled:

		Inlet	Outlet	Outlet
Stream ID:		Wet Biomass	Moist Biomass	Water
Quantity (lb/hr):		4,905,220	613,152	4,292,067
Composition:				
	H_2O	90.00%	20.00%	100%
	Lipid	0.78%	6.28%	
	Biomass	9.22%	73.72%	

Design Data:			**Notes:**
Type:	Continuous Scroll Solid Bowl		
Material:	Stainless Steel		
Sizing Factor (S)	40	tons/hr	
Purchase Cost (Cp):	379,473		Cp = 60000*S^0.5
Bare-module Factor:	2.03		Seider Tbl. 22.11
Bare-module Cost:	770,331		

Utilities: 38,566 kW

Comments: Assume utility requirements of 171 kWh / dry ton based on article published by Water Environment Federation, June 1994

Dryer

Identification:	Item:	Dryer	Date:	April, 5, 2010
	Item No:		By:	AX
	No. Required:	24		

Function: Dewater biomass from 20% moisture to 10% moisture

Operation: Continuous

Materials Handled:		Inlet	Outlet	Outlet
Stream ID:		Moist Biomass	Dry Biomass	Water
Quantity (lb/hr):		613,152	545,024	68,128
Composition:				
	H_2O	20.00%	10.00%	100%
	Lipid	6.28%	7.10%	
	Biomass	73.72%	82.90%	

Design Data:			**Notes:**
Type:	Drum Dryer		
Material:	Stainless Steel		
Evaporation rate	6	lb/hr-ft^2	Seider Pg. 581
Heat-transfer Area	480	ft^2	
Purchase Cost (Cp):	334,212	$	Cp = 32000*A^0.38
Bare-module Factor:	2.06		Seider Tbl. 22.11
Bare-module Cost:	688,476	$	

Utilities: 20,416 kW

Comments: Energy required to evaporate 68128 lb water/hr

F. OPERATING COSTS AND ECONOMIC ANALYSIS

Since publically available information on the OriginOil process is limited, especially with regard to costs, we conducted a simplified economic analysis based on postulates.

The annual total cost for lipid extraction is approximately \$2.1 billion. This includes raw material cost, energy cost, depreciation, and debt service.

OriginOil does not provide expected capital expenditure for its technology. Thus to establish a floor on capital investment, the cost of each major piece of equipment was estimated. Summing the bare module costs of each unit, the total capital investment in the facility is approximately \$30 million. This does not include the cost of the Quantum Fracturing^{TM} technology, which is difficult to estimate due to its novelty. Thus the actual fixed investment may be much higher.

TABLE 13. OPERATING COSTS FOR ORIGINOIL^{TM} PROCESS.

COSTS		Units	Notes
EQUIPMENT			
Gravity Clarifier	2,991,000	$	See equipment spec sheet for sizing calc.
Number of clarifiers	3		Total settle area = 225000 ft^2
Centrifuge	770,000	$	See spec sheet for details
Number of centrifuge	6		6 needed to handle throughput
Dryer	688,000	$	See spec sheet for details
Number of dryers	24		Evaporation rate = 6 lb/ft^2 hr
Quantum Fracturing equipment	N/A	$	
Purification equipment	N/A	$	
Total Equipment	30,119,000	$	Floor estimate
Annual Depreciation	4,303,000	$	Assume straight-line over 10 years
RAW MATERIAL			
Algae Cost	0.014	$/kg	From **Module I**, profitable if < $0.4
Daily Algae Cost	129,000	$	
ENERGY			
Daily Electricity Cost	458,000	$	Quantum fracturing and dewatering, 7 cents/kWh
ANNUAL OPERATING COST	197,903,000	$	Operating cost and depreciation

In terms of revenue, the selling price of algae lipids is approximated from May futures of soybean oil on the CME exchange, as is the price of livestock feed. It is unlikely for the products to sell much higher than these comparable commodities.

TABLE 14: REVENUE FROM ORIGINOIL PROCESS.

PRODUCTION		Units	Notes
Daily Lipid Harvest (mass)	3,773,000	kg	24 hour days
Lipid Density	0.92	kg/L	
Daily Lipid Harvest (vol)	4,092,000	L	
Daily Biomass Harvest	5,911,000	kg	After extraction process, 10% moisture
PRICES			
Lipid	0.85	$/L	Approx from vegetable oils, May futures
Livestock Feed (Biomass)	0.29	$/kg	Chicago Mercantile Exchange May 2010 futures
REVENUE:			
Daily Lipid Sales	3,478,000	$	
Daily Livestock Feed Sales	1,714,000	$	
ANNUAL REVENUE	1,713,414,000	$	Total Sales, 330 days of operation per year

As seen in Table 14, the livestock feed sales (from biomass) are an important source of revenue. Besides animal feedstock, there are other potential uses for algae materials in chemicals, pharmaceuticals, and biomass power generation. For example, algae produce omega-3 fatty acids, an essential fat with many health benefits.[40] With the advent of federally mandated renewable power generation, there is also potential for the use of biomass as a source of renewable power generation. These byproducts are more valuable than livestock feed and may bring in additional revenue. For every 10 cents increase in biomass selling price, the annual revenue increases by $200 million.

This analysis concludes that the process cost of lipids extraction is $0.05/kg lipid, irrespective of the cost of algae. Actual energy cost of extraction is likely to be higher, as this estimate relies on a single data point provided by OriginOil^{TM}. However, the potential energy savings of this new process remains significant. The cost is much lower than the $1.24/kg lipid cost of conventional lipid extraction estimated by OriginOil^{TM}.[36] For a detailed breakdown of the costs, please see **Appendix III** on page 123.

MODULE III: LIPID PROCESSING

VII. CONCEPT STAGE

A. PRELIMINARY PROCESS SYNTHESIS

The purpose of the lipid processing module is to produce a high-quality transportation fuel. There are several approaches for this process, including the conversion of lipids to FAME biodiesel via transesterfication or the conversion of lipids to n-alkanes through either thermocracking or catalytic hydrotreating. FAME Biodiesel generally consists of long chain alkyl esters while conventional diesel consists of a mixture of alkanes, naphthenes, and aromatics.

FAME Biodiesel

Most of the existing technologies to produce fuel from vegetable oils and lipids involve the production of fatty acid methyl esters (FAME). This product has high cetane (a measurement of the combustion quality) but has poor stability and high solvency, resulting in storage problems.[41] In addition, for a constant volume basis, biodiesel has approximately 9% lower energy content than regular diesel, due to its high oxygen content. The process of converting lipids to biodiesel involves the following reaction:

Triglyceride + Methanol → FAME + Glycerol (1)

As seen in **Equation 1**, one of the byproducts of this reaction is glycerol, which in an unrefined state has limited value. The high concentration of free fatty acids in the lipid feedstock can also cause problems due to the saponification reactions with the catalyst which form alcohols and the salts of carboxylic acids.

Thermal Hydrolysis

A patent by Professors Roberts, Lamb, and Stikeleather of North Carolina State University introduces a proposal for the conversion of biomass to fuel.[42] Their patent features three major processes:

1. Thermal hydrolysis on lipidic biomass
2. Catalytic deoxygenation of the free fatty acid stream
3. Reforming of a n-alkane stream

The hydrolytic conversion of triglycerides in the first step would break the fatty acid chains from the glycerol backbone, forming the product as described in **Equation 2**.

Triglyceride + 3 H_2O -> 3 Free Fatty Acids + Glycerol (2)

The free fatty acids are then catalytically deoxygenated through one of the following processes:

$RCOOH \rightarrow RH + CO_2$ (3a)

$RCOOH \rightarrow RH + CO_2 + H_2O$ (3b)

The n-alkane stream is then reformed to produce various grades of transportation fuels such as diesel, jet fuel, and gasoline. One of the limitations of this method is that the reaction must occur at high pressure (210 bars) due to the stability of the water molecule.[43] In addition, there are more processing steps required in this method compared to the catalytic hydrotreating process described below.

Catalytic Hydrotreating

The hydrotreating process, a conventional petroleum refining process employed in petroleum refineries, can convert the triglycerides derived from the algae into n-alkanes in a more efficient and economical way. In our hydrotreater, the triglyceride reacts with hydrogen at high temperature and pressure over a catalyst in one processing step. The products include the straight chain alkanes, CO, CO_2, water, methane, and propane. After a series of separations, the primary product is a mixture of straight chain alkanes with carbon numbers ranging from C13 to C20 ($C_{13}H_{28}$ to $C_{20}H_{42}$). These n-alkanes are suitable for direct blending into a diesel pool or for further upgrading/reforming into gasoline, jet fuel, or gasoline. A more thorough description of the hydrotreating process is found in the **Process Description** section on page 64.

B. FACILITY DESIGN

In order to optimize the efficiency and productivity of the lipid processing module, it was determined that the hydroprocessing unit will be located at the site of an existing petroleum refinery instead of building a single standalone unit. Since the proposed location for the Simgae™ cultivation field is located in Thompsons, Texas, oil refineries in the Houston area would be ideal candidates for locations for our lipid processing unit. These include oil refineries owned by ConocoPhillips, BP, ExxonMobil, and others.

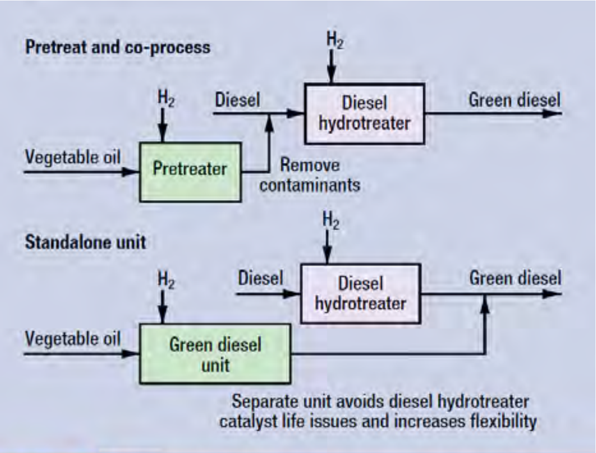


FIG. 3 Alternative vegetable-oil hydroprocessing routes to transportation fuels.

FIGURE 11. ALTERNATIVE VEGETABLE-OIL HYDROPROCESSING ROUTES TO TRANSPORTATION FUELS.[41]

There are two options to implement the lipid hydrotreating process, as seen in **Figure 11**. With the co-processing option, the triglyceride feedstock is co-fed with the diesel feed and hydrotreated triglyceride feedstock into a diesel hydrotreating unit. The alternative option is to build a standalone hydrotreating unit specifically designed to handle triglyceride feedstock. Although the co-processing option might have a lower implementation cost due to the use of existing equipment, there are significant technical challenges with this approach. Depending on the specific refinery site, these challenges may include the large amount of hydrogen required to hydrotreat the algae lipid, the large amount of water produced from the algae, the large amount of CO and CO_2 produced from the lipid, and the hydraulic capacity constraints of the existing equipment.[41] These factors would limit the amount of algae lipid that could be co-processed in the existing unit. In addition, the lipid feedstock may contain trace metals which may deactivate the catalyst over a short period of time. To accommodate co-processing a large amount of lipid, significant modifications to and an expensive revamp of the existing equipment is required. The standalone hydrotreating unit, specifically designed to deal with algae lipid, would minimize some of these challenges and provide a more efficient process.

C. ASSEMBLY OF DATABASE

The ASPEN PLUS simulation of the hydrotreating process will use the Refinery process type and the RK-SOAVE property method. A list of the reactions modeled in the hydrotreating process is listed in **Table 15**.

TABLE 15. LIST OF REACTIONS IN THE HYDROTREATING PROCESS.

Reaction Number	Fractional Conversion	Stoichiometry	Notes
1	0.32 of C14FFA	C14FFA --> C13ALKANE + CO_2	Decarboxylation
2	0.32 of C14FFA	C14FFA + H_2 --> C13ALKANE + CO + WATER	Decarbonylation
3	0.36 of C14FFA	C14FFA + $3H_2$ --> C14ALKANE + 2 WATER	Hydrogenation
4	0.32 of C16FFA	C16FFA --> C15ALKANE + CO_2	Decarboxylation
5	0.32 of C16FFA	H2 + C16FFA --> C15ALKANE + CO + WATER	Decarbonylation
6	0.36 of C16FFA	3 H_2 + C16FFA --> C16ALKANE + 2 WATER	Hydrogenation
7	0.32 of C18FFA	C18FFA --> C17ALKANE + CO2	Decarboxylation
8	0.32 of C18FFA	H_2 + C18FFA --> C17ALKANE + CO + WATER	Decarbonylation
9	0.36 of C18FFA	3 H_2 + C18FFA --> C18ALKANE + 2 WATER	Hydrogenation
10	0.32 of C20FFA	C20FFA --> C19ALKANE + CO2	Decarboxylation
11	0.32 of C20FFA	H2 + C20FFA --> C19ALKANE + CO + WATER	Decarbonylation
12	0.36 of C20FFA	3 H_2 + C20FFA --> C20ALKANE + 2 WATER	Hydrogenation
13	0.90 of CO	CO + 3 H2 --> CH_4 + WATER	Methanation
14	0.50 of CO_2	CO_2 + H_2 --> CO + WATER	Water-Gas Shift

The determination and development of the reactions listed in **Table 15** will be described in the **Process Description**. The principal chemicals required for the hydrotreating process include the triglyceride feedstock, monoethanolamine (MEA) fluid used in the amine scrubber, NiMo catalyst, and hydrogen. The price of MEA solution is \$1.20/lb, as quoted by Univar, a distributor for the Dow Chemical Company.[31] Triglyceride feedstock is priced at \$0.16/kg (\$0.07/lb), an approximation based on the cost of lipids in **Module II** and hydrogen feed is priced at \$1.00/lb as listed in Process and Product Design Principles.[44]

Catalyst

The proposed reactions carried out in the hydrotreating process occur in the presence of a catalyst. In the hydrotreating reactor, the catalyst operates with a bifunctional purpose: the metal function of the catalyst, with high hydrogen pressure, contributes to the saturation of the double bonds of the side chains of the triglycerides, while the acid function of the catalyst contributes to the cracking of the C-O bonds. The selection of the catalyst is crucial and can affect the composition of the product outputs since the distribution of the TAG reactions via the three various reaction pathways (hydrodeoxygenation, decarboxlyation, and decarbonylation) depends on catalyst selected. Typical catalysts used in conventional hydrotreating processes include NiMo/γ-alumina, CoMo/γ-alumina and Pt-Zeolitic-based catalysts. Based on a study by Sotelo-Boyas, Liu, and Minowa, the NiMo/γ-alumina catalyst is a good choice for the hydrotreating process due to its hydrogenation activity and mild acidity as well as its low cost relative to Pt-zeolitic based catalysts.[45]

D. BENCH-SCALE LABORATORY WORK

The hydrotreating of triglycerides has been discussed in various literature and reports. Most of the literature discusses the hydrotreating of vegetable oils such as canola, jatropha, soybean oils. A paper by Donnis, Egeberg, Blom, and Knudsen of Haldor Topsoe proposes a process for hydrotreating vegetable oils using conventional hydrotreating processes based on model compound tests and real feed tests.[46] Likewise, Huber, O'Connor, and Corma discuss the proposed reaction mechanisms based on three studies they performed: hydrotreating of pure vegetable oils, hydrotreating of heavy vacuum oil (HVO), and hydrotreating of HVO-vegetable oil mixtures.[47] Other studies have been performed to demonstrate the performance of the fuels produced from triglyceride feedstocks. A report from the Boeing Company, Evaluation of Bio-Derived Synthetic Paraffinic Kerosene (Bio-SPK), summarizes results from test flights using bio-derived oils such as algae and jatropha hydrotreated using UOP's Renewable Jet Process.[3]

VIII. FEASIBILITY AND DEVELOPMENT STAGES

The following sections will introduce and explain the catalytic hydrotreating process used to convert the triglyceride feedstock into n-alkanes. **Section A** provides the process flow diagram (PFD) and associated mass balances. The detailed process description is listed in **Section B**. **Sections C, D,** and **E** list the associated utility requirements, equipment summaries, and specification sheets. **Sections F, G ,** and **H** list and explain the fixed investment summary, other important considerations, and the operating costs for the hydrotreating process.

A. PROCESS FLOW DIAGRAM AND MATERIAL BALANCES

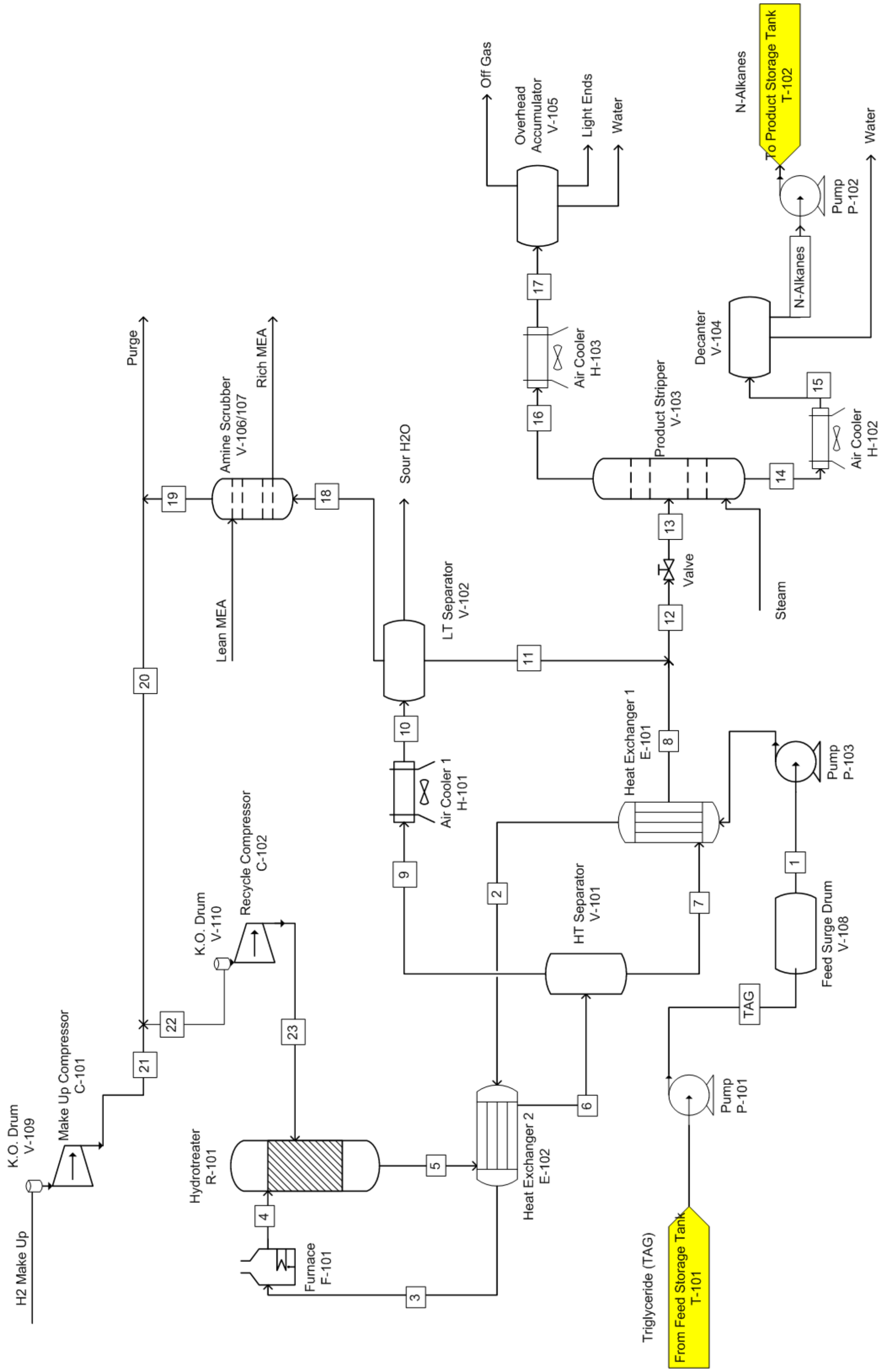


FIGURE 12: PROCESS FLOW DIAGRAM OF THE HYDROTREATING PROCESS.

TABLE 16: STREAM SUMMARY OF HYDROTREATING PROCESS.

		TAG	1	2	3	4	5	6	7	8
From			PUMP	HX-1	HX-2	FURNACE	REACTOR	HX-2	HTSEP	HX-1
To		PUMP	HX-1	HX-2	FURNACE	REACTOR	HX-2	HTSEP	HX-1	MIXER-2
Substream: MIXED										
Phase:		Liquid	Liquid	Liquid	Liquid	Liquid	Vapor	Mixed	Liquid	Mixed
Component Mass Flow										
C13ALKAN	LB/HR	0	0	0	0	0	7920.1	7920.1	6020.3	6020.3
C14ALKAN	LB/HR	0	0	0	0	0	4794	4794	3962.59	3962.59
C15ALKAN	LB/HR	0	0	0	0	0	62298.33	62298.33	54632.48	54632.48
C16ALKAN	LB/HR	0	0	0	0	0	37356.83	37356.83	34124.31	34124.31
C17ALKAN	LB/HR	0	0	0	0	0	14840.35	14840.35	13965.85	13965.85
C18ALKAN	LB/HR	0	0	0	0	0	8834.62	8834.62	8469.89	8469.89
C19ALKAN	LB/HR	0	0	0	0	0	56525.71	56525.71	54913.79	54913.79
C20ALKAN	LB/HR	0	0	0	0	0	33456.6	33456.6	32818.69	32818.69
H2	LB/HR	0	0	0	0	0	19732.5	19732.5	106.5	106.5
CO	LB/HR	0	0	0	0	0	9628.65	9628.65	76.46	76.46
CO2	LB/HR	0	0	0	0	0	13929.14	13929.14	273.25	273.25
WATER	LB/HR	0	0	0	0	0	22452.08	22452.08	1517.58	1517.58
CH4	LB/HR	0	0	0	0	0	18489.35	18489.35	241.5	241.5
C14FFA	LB/HR	15329.22	15329.22	15329.22	15329.22	15329.22	0	0	0	0
C16FFA	LB/HR	117508.7	117508.7	117508.7	117508.7	117508.7	0	0	0	0
C18FFA	LB/HR	27431.78	27431.78	27431.78	27431.78	27431.78	0	0	0	0
C20FFA	LB/HR	102796.7	102796.7	102796.7	102796.7	102796.7	0	0	0	0
MEA	LB/HR	0	0	0	0	0	0	0	0	0
PROPANE	LB/HR	14170.64	14170.64	14170.64	14170.64	14170.64	52185.58	52185.58	2069.27	2069.27
Mole Flow	LBMOL/HR	1272.07	1272.07	1272.07	1272.07	1272.07	14981.72	14981.72	1080.51	1080.51
Mass Flow	LB/HR	277237	277237	277237	277237	277237	362443.8	362443.8	213192.4	213192.4
Volume Flow	CUFT/HR	5665.93	5669.05	6292.74	7742.42	8071.33	254088.1	213269.5	5773.97	5110.8
Temperature	F	77	78.33	303.33	617	662	662	519	437	186.77
Pressure	PSIA	33.35	797.71	797.71	797.71	754.2	725.19	725.19	681.68	681.68
Vapor Fraction		0	0	0	0	0	1	0.94	0	0.02
Liquid Fraction		1	1	1	1	1	0	0.06	1	0.98
Molar Enthalpy	BTU/LBMOL	-291569.2	-290721.6	-264212.5	-218701.5	-211417.5	-20278.04	-24142.28	-134709.8	-165918.4
Mass Enthalpy	BTU/LB	-1337.83	-1333.94	-1212.31	-1003.48	-970.06	-838.2	-997.93	-682.74	-840.91
Enthalpy Flow	BTU/HR	-370895500	-369817200	-336095900	-278202900	-268937100	-303799900	-361692900	-145555200	-179276500
Molar Entropy	BTU/LBMOL-R	-357.05	-356.96	-316.03	-266.36	-259.68	-24.45	-28.13	-286.63	-327.2
Mass Entropy	BTU/LB-R	-1.64	-1.64	-1.45	-1.22	-1.19	-1.01	-1.16	-1.45	-1.66
Molar Density	LBMOL/CUFT	0.22	0.22	0.2	0.16	0.16	0.06	0.07	0.19	0.21
Mass Density	LB/CUFT	48.93	48.9	44.06	35.81	34.35	1.43	1.7	36.92	41.71
Average Molecular Weight		217.94	217.94	217.94	217.94	217.94	24.19	24.19	197.31	197.31

		9	10	SOURH2O	11	12	13	STEAM	14	15
From		HTSEP	COOLER-1	LTSEP	LTSEP	MIXER-2	VALVE		STRIPPER	COOLER-2
To		COOLER-1	LTSEP		MIXER-2	VALVE	STRIPPER	STRIPPER	COOLER-2	DECANTER
Substream: MIXED										
Phase:		Vapor	Mixed	Liquid	Liquid	Mixed	Mixed	Vapor	Liquid	Liquid
Component Mass Flow										
C13ALKAN	LB/HR	1899.81	1899.81	0	1899.4	7919.69	7919.69	0	7900.02	7900.02
C14ALKAN	LB/HR	831.42	831.42	0	831.35	4793.94	4793.94	0	4788.34	4788.34
C15ALKAN	LB/HR	7665.9	7665.9	0	7665.67	62298.15	62298.15	0	62265.41	62265.41
C16ALKAN	LB/HR	3232.54	3232.54	0	3232.5	37356.81	37356.81	0	37347.51	37347.51
C17ALKAN	LB/HR	874.51	874.51	0	874.51	14840.35	14840.35	0	14838.79	14838.79
C18ALKAN	LB/HR	364.74	364.74	0	364.74	8834.63	8834.63	0	8834.19	8834.19
C19ALKAN	LB/HR	1611.93	1611.93	0	1611.92	56525.71	56525.71	0	56524.41	56524.41
C20ALKAN	LB/HR	637.92	637.92	0	637.91	33456.61	33456.61	0	33456.28	33456.28
H2	LB/HR	19626	19626	0	7.44	113.94	113.94	0	0	0
CO	LB/HR	9552.19	9552.19	0	10.5	86.97	86.97	0	0	0
CO2	LB/HR	13655.9	13655.9	0	152.41	425.65	425.65	0	0	0
WATER	LB/HR	20934.51	20934.51	20766.2	36.84	1554.43	1554.43	20000	5171.52	5171.52
CH4	LB/HR	18247.87	18247.87	0	54.64	296.14	296.14	0	0	0
C14FFA	LB/HR	0	0	0	0	0	0	0	0	0
C16FFA	LB/HR	0	0	0	0	0	0	0	0	0
C18FFA	LB/HR	0	0	0	0	0	0	0	0	0
C20FFA	LB/HR	0	0	0	0	0	0	0	0	0
MEA	LB/HR	0	0	0	0	0	0	0	0	0
PROPANE	LB/HR	50116.31	50116.31	0	2597.62	4666.89	4666.89	0	0	0
Mole Flow	LBMOL/HR	13901.21	13901.21	1152.7	150.07	1230.59	1230.59	1110.17	1237.43	1237.43
Mass Flow	LB/HR	149251.5	149251.5	20766.2	19977.46	233169.9	233169.9	20000	231126.5	231126.5
Volume Flow	CUFT/HR	199741.7	109793.3	332.54	485.32	5658.47	49485.09	309136.2	5147.64	4851.24
Temperature	F	437	68	68	68	177.23	176.23	302	198.69	77
Pressure	PSIA	681.68	667.17	652.67	652.67	652.67	29.01	29.01	29.01	29.01
Vapor Fraction		1	0.92	0	0	0.02	0.15	1	0	0
Liquid Fraction		0	0.08	1	1	0.98	0.85	0	1	1
Molar Enthalpy	BTU/LBMOL	-17521.87	-22650.39	-123011.4	-125491.5	-160988.2	-160988.2	-102187.1	-170426.6	-182651.4
Mass Enthalpy	BTU/LB	-1631.98	-2109.65	-6828.17	-942.72	-849.64	-849.64	-5672.24	-912.45	-977.9
Enthalpy Flow	BTU/HR	-243575300	-314867900	-141795100	-18833110	-198109600	-198109600	-113444900	-210890500	-226017700
Molar Entropy	BTU/LBMOL-R	-10.01	-17.36	-39.28	-234.45	-315.54	-314.04	-9.15	-307.42	-327.91
Mass Entropy	BTU/LB-R	-0.93	-1.62	-2.18	-1.76	-1.67	-1.66	-0.51	-1.65	-1.76
Molar Density	LBMOL/CUFT	0.07	0.13	3.47	0.31	0.22	0.02	0	0.24	0.26
Mass Density	LB/CUFT	0.75	1.36	62.45	41.16	41.21	4.71	0.06	44.9	47.64
Average Molecular Weight		10.74	10.74	18.02	133.12	189.48	189.48	18.02	186.78	186.78

		N-ALKANE	DECWATER	16	17	LIGHTALK	OFFGAS	OHDWATER	18	LEANMEA
From		DECANTER	DECANTER	STRIPPER	COOLER-3	OHDACC	OHDACC	OHDACC	LTSEP	
To				COOLER-3	OHDACC				SCRUBBER	SCRUBBER
Substream: MIXED										
Phase:		Liquid	Liquid	Vapor	Mixed	Liquid	Vapor	Liquid	Vapor	Liquid
Component Mass Flow										
C13ALKAN	LB/HR	7900.03	0	19.67	19.67	19.34	0.33	0	0.41	0
C14ALKAN	LB/HR	4788.34	0	5.6	5.6	5.57	0.03	0	0.07	0
C15ALKAN	LB/HR	62265.41	0	32.74	32.74	32.68	0.07	0	0.21	0
C16ALKAN	LB/HR	37347.51	0	9.3	9.3	9.29	0.01	0	0.03	0
C17ALKAN	LB/HR	14838.79	0	1.56	1.56	1.56	0	0	0	0
C18ALKAN	LB/HR	8834.19	0	0.44	0.44	0.44	0	0	0	0
C19ALKAN	LB/HR	56524.41	0	1.3	1.3	1.3	0	0	0	0
C20ALKAN	LB/HR	33456.29	0	0.32	0.32	0.32	0	0	0	0
H2	LB/HR	0	0	113.94	113.94	0	113.94	0	19618.56	0
CO	LB/HR	0	0	86.97	86.97	0	86.97	0	9541.68	0
CO2	LB/HR	0	0	425.65	425.65	0.04	425.53	0.08	13503.49	0
WATER	LB/HR	234.93	4936.58	16382.91	16382.91	0.1	41.34	16341.47	131.46	0
CH4	LB/HR	0	0	296.14	296.14	0.01	296.13	0	18193.23	0
C14FFA	LB/HR	0	0	0	0	0	0	0	0	0
C16FFA	LB/HR	0	0	0	0	0	0	0	0	0
C18FFA	LB/HR	0	0	0	0	0	0	0	0	0
C20FFA	LB/HR	0	0	0	0	0	0	0	0	0
MEA	LB/HR	0	0	0	0	0	0	0	0	1.17
PROPANE	LB/HR	0	0	4666.89	4666.89	2.28	4664.62	0	47518.68	0
Mole Flow	LBMOL/HR	963.4	274.02	1103.33	1103.33	0.4	195.83	907.09	12598.44	0.01
Mass Flow	LB/HR	226189.9	4936.58	22043.45	22043.45	72.93	5628.97	16341.55	108507.8	1.17
Volume Flow	CUFT/HR	4709.53	79.56	260739.3	38795.32	1.6	38463.86	263.36	111096.6	0.02
Temperature	F	77	77	189.42	77	77	77	77	68	77
Pressure	PSIA	29.01	29.01	29.01	29.01	29.01	29.01	29.01	652.67	14.5
Vapor Fraction		0	0	1	0.18	0	1	0	1	0
Liquid Fraction		1	1	0	0.82	1	0	1	0	1
Molar Enthalpy	BTU/LBMOL	-202135.7	-124265.1	-91236.91	-108902.7	-161276.5	-37693.05	-124265.2	-12318.6	-205561.6
Mass Enthalpy	BTU/LB	-860.95	-6897.76	-4566.62	-5450.84	-886.55	-1311.36	-6897.74	-1430.27	-1725.03
Enthalpy Flow	BTU/HR	-194738500	-34051360	-100664100	-120155300	-64655.81	-7381603	-112719800	-155195100	-2024.94
Molar Entropy	BTU/LBMOL-R	-413.74	-40.89	-13.62	-40	-320.81	-35.37	-40.89	-12.81	-219.23
Mass Entropy	BTU/LB-R	-1.76	-2.27	-0.68	-2	-1.76	-1.23	-2.27	-1.49	-1.84
Molar Density	LBMOL/CUFT	0.2	3.44	0	0.03	0.25	0.01	3.44	0.11	0.54
Mass Density	LB/CUFT	48.03	62.05	0.08	0.57	45.59	0.15	62.05	0.98	64.52
Average Molecular Weight		234.78	18.02	19.98	19.98	181.92	28.74	18.02	8.61	119.16

		RICHMEA	19	PURGE	20	H2MAKEUP	21	22	23
From		SCRUBBER	SCRUBBER	SPLIT	SPLIT		MKCOMP	MIXER-1	RYCCOMP
To			SPLIT		MIXER-1	MKCOMP	MIXER-1	RYCCOMP	REACTOR
Substream: MIXED									
Phase:		Mixed	Vapor	Vapor	Vapor	Vapor	Vapor	Vapor	Vapor
Component Mass Flow									
C13ALKAN	LB/HR	0.41	0	0	0	0	0	0	0
C14ALKAN	LB/HR	0.07	0	0	0	0	0	0	0
C15ALKAN	LB/HR	0.21	0	0	0	0	0	0	0
C16ALKAN	LB/HR	0.03	0	0	0	0	0	0	0
C17ALKAN	LB/HR	0	0	0	0	0	0	0	0
C18ALKAN	LB/HR	0	0	0	0	0	0	0	0
C19ALKAN	LB/HR	0	0	0	0	0	0	0	0
C20ALKAN	LB/HR	0	0	0	0	0	0	0	0
H2	LB/HR	0	19618.56	3923.71	15694.85	8228.81	8228.81	23923.66	23923.66
CO	LB/HR	0	9541.68	1908.34	7633.35	0	0	7633.35	7633.35
CO2	LB/HR	12153.14	1350.35	270.07	1080.28	0	0	1080.28	1080.28
WATER	LB/HR	131.46	0	0	0	0	0	0	0
CH4	LB/HR	0	18193.23	3638.65	14554.59	0	0	14554.59	14554.59
C14FFA	LB/HR	0	0	0	0	0	0	0	0
C16FFA	LB/HR	0	0	0	0	0	0	0	0
C18FFA	LB/HR	0	0	0	0	0	0	0	0
C20FFA	LB/HR	0	0	0	0	0	0	0	0
MEA	LB/HR	1.17	0	0	0	0	0	0	0
PROPANE	LB/HR	0	47518.68	9503.74	38014.95	0	0	38014.95	38014.95
Mole Flow	LBMOL/HR	283.46	12314.99	2463	9851.99	4081.99	4081.99	13933.99	13933.99
Mass Flow	LB/HR	12286.5	96222.51	19244.5	76978.01	8228.81	8228.81	85206.82	85206.82
Volume Flow	CUFT/HR	1685.22	108814.2	21762.85	87051.39	82015.36	50129.34	136040	127433.5
Temperature	F	68	68	68	68	77	272.27	120.11	142.12
Pressure	PSIA	652.67	652.67	652.67	652.67	290.08	652.67	652.67	725.19
Vapor Fraction		0.97	1	1	1	1	1	1	1
Liquid Fraction		0.03	0	0	0	0	0	0	0
Molar Enthalpy	BTU/LBMOL	-169127	-8736.02	-8736.02	-8736.02	9.76	1383.92	-5771.36	-5596.22
Mass Enthalpy	BTU/LB	-3901.86	-1118.08	-1118.08	-1118.08	4.84	686.51	-943.8	-915.16
Enthalpy Flow	BTU/HR	-47940230	-107584000	-21516800	-86067190	39820	5649163	-80418030	-77977590
Molar Entropy	BTU/LBMOL-R	-9.32	-13.13	-13.13	-13.13	-5.93	-5.38	-10.67	-10.59
Mass Entropy	BTU/LB-R	-0.22	-1.68	-1.68	-1.68	-2.94	-2.67	-1.74	-1.73
Molar Density	LBMOL/CUFT	0.17	0.11	0.11	0.11	0.05	0.08	0.1	0.11
Mass Density	LB/CUFT	7.29	0.88	0.88	0.88	0.1	0.16	0.63	0.67
Average Molecular Weight		43.35	7.81	7.81	7.81	2.02	2.02	6.12	6.12

B. PROCESS DESCRIPTION

This section discusses the operation and background of the catalytic hydrotreating process. The hydrotreating process can be divided into the following components: 1) preparation of triglyceride and hydrogen feed, 2) hydrotreating reactor, 3) stream separations, 4) product separations, and 5) gas scrubbing and recycle. This process is modeled after various vegetable oil hydrotreating processes such as the UOP/Eni Green Diesel™ Process.[48] The hydrotreating process is widely used in petroleum refineries around the world and licensed by a range of vendors such as UOP, Haldor Topsoe, and others. While the hydrotreating technology is an established and mature technology used in petroleum refineries to improve the properties of petroleum products, the innovative aspect of this process is the use of a triglyceride feedstock in replacement of crude oil. While triglyceride feedstock can be run through existing hydrotreating units, some adjustments in the design are made to account for the properties of lipid feedstock. These adjustments include additional quench zones in the hydrotreating reactor to account for the exothermic reactions and modifications to the makeup gas and recycle gas streams.

A simulation of this hydotreating process is developed using the ASPEN PLUS process modeling software. Please see **Appendix IV** on page 124 for ASPEN PLUS simulation results. In order to accurately calculate the cost of hydrotreating, this hydrotreating process is designed for a throughout of 20,000 barrels/day of n-alkanes, which is equivalent to the output of small diesel hydrotreater.

Preparation of triglyceride stream

The triglyceride product from **Module II** is stored in a large storage tank (T-101) and pumped (P-101) into a feed surge drum (V-108), which ensures that the flow into the hydrotreating process is steady with a mass flow rate of 277,237 lb/hr at ambient temperature (25^{o}C). For the purposes of the simulation, it is assumed that the triglyceride feedstock is pure without significant amounts of trace metals (phosphorous, sodium, potassium, or calcium) because such contaminants can denature the catalyst. It is difficult to model triglycerides in ASPEN since a triglyceride is composed of three fatty acids (FFAs) and a glycerol backbone. Since there are eight different FFAs in *Nannochloropsis sp.*, there is no single triglyceride that can model the product distribution. Therefore, to accurately model the product distribution, the feed stream is represented as a combination of saturated FFAs of various length (based on their weight percents as listed in **Table 15**) and propane. This feed stream (Stream 1) is pumped to 50 bars (P-103) and the temperature of the feed stream (Stream 2) increases when passed through two heat exchangers (E-101 and E-102). A fired heater (F-101) heats the feed stream (Stream 3) to a target reaction temperature of 350^{o}C (662°F).

Hydrogen feed

Makeup hydrogen (produced by a hydrogen plant in the refinery) enters the battery limit of the hydrotreating unit at 20 bars and ambient temperature (77^{o}F). A makeup compressor (C -101) increases the makeup H_2 to the pressure of the recycle gas stream (45 bars). The makeup hydrogen stream (Stream 21) is mixed with the recycle gas stream (Stream 20) and compressed to 50 bars (Stream 23) before entering the hydrotreating reactor (R-101).

Hydrotreating Reactor

In the hydrotreating reactor (R-101), the feed stream (Stream 4) reacts with hydrogen at high temperature (350^0C) and high pressure (50 bars) over a NiMo catalyst. In the first step of the reaction pathway, the triglyceride is hydrogenated and broken down into free fatty acid (FFA) and propane components. These FFA reaction intermediates are then converted into straight chain alkanes through one of three different reaction pathways: decarboxylation, decarbonylation, and hydrogenation.[47]

Decarboxylation: in this reaction pathway, the carboxyl group is split off from the free fatty acid, forming an n-alkane chain with one less carbon than the FFA.

$$\text{R-CH}_2\text{-COOH} \rightarrow \text{RH-CH}_3 + \text{CO}_2 \qquad (4)$$

Decarbonylation: in this reaction pathway, the carbonyl group is split off from the free fatty acid, forming an n-alkane chain with one less carbon than the FFA.

$$\text{R-CH}_2\text{-COOH} + \text{H}_2 \rightarrow \text{R-CH}_3 + \text{CO} + \text{H}_2\text{O} \qquad (5)$$

Hydrogenation: in this reaction pathway, hydrogen is added to the free fatty acid, resulting in an n-alkane chain the same length as the FFA.

$$\text{R-CH}_2\text{-COOH} + 3\text{H}_2 \rightarrow \text{R-CH}_2\text{-CH}_3 + 2\text{H}_2\text{O} \qquad (6)$$

In addition to the above reaction mechanism, there are two additional reactions that occur simultaneously in the hydrotreating reactor.

$$\text{Water gas shift: } \text{CO}_2 + \text{H}_2 \leftrightarrow \text{CO} + \text{H}_2\text{O} \qquad (7)$$

$$\text{Methanation: } \text{CO} + 3\text{H}_2 \leftrightarrow \text{CH}_4 + \text{H}_2\text{O}$$

The hydrogenation, decarboxylation, and decarbonylation pathways are modeled using a RSTOIC block in ASPEN PLUS. The feed stream is composed of free fatty acids, and the three reactions occur simultaneously in the reactor. A paper from Haldor Topsoe estimates the reaction pathways to occur in the following distribution: 32% of FFA proceed by decarboxylation, 32% by decarbonylation, and 36% by hydrogenation (HDO).[46]

The water gas shift and methanation reactions are also modeled in the reactor. The extent of these side reactions can be inferred by the hydrogen consumption in excess of the three pathways. Studies from Haldor Topsoe suggest that 50% of CO_2 shifts to CO[46] and industrial consultants have suggested that the extent of the methanation reaction is approximately 90%.

Stream Separation

To recover the heat contained in the reactor effluent (Stream 5), the effluent passes through heat exchangers E-102, where some of its heat is transferred to the feed stream (Stream 2), before reaching the High Temperature Separator (V-101). This is a flash drum that separates the liquid n-alkanes (Stream 7) from the gases (Stream 9). The liquid stream passes through another heat exchanger (E-101) before going to the Product Stripper (V-103).

The vapor stream (Stream 9) from the High Temperature Separator is cooled by an air finned cooler (H-101) and passes through the Low Temperature Separator (V-102), which is a three phase separator that separates the vapor (Stream 18) from any entrained n-alkanes (Stream 11, which are returned to the main n-alkane stream, and water (Stream SOURH2O), which is separated and sent to a sour water treatment facility. The vapor (Stream 18) is treated in an Amine Scrubber unit (V-106/V-107) and recycled back to the Hydrotreater (R-101), as described below.

Product Stripper

The pressure of the n-alkane product stream (Stream 12) is reduced before it is sent to the Product Stripper (V-104). Steam is used as stripping fluid in the Product Stripper to remove dissolved gases from the liquid product. The product stripper removes any dissolved H_2, H_2O, CO, CO_2 and light hydrocarbon gases from the hydrotreater product streams. The overhead product (Stream 16) is then cooled by an air cooler (H-103) before passing through an accumulator (V-105), where the vapor (offgas) is separated from the water and light end streams.

The Product Stripper bottom (Stream 14), containing n-alkanes and some dissolved water, is further cooled in an air-cooler (H-102) and then pass though a Decanter (V-104), where residual water is separated from the n-alkane product, which is pumped (P-102) to Product Storage Tank (T-102). The n-alkane product, containing mainly straight chain paraffins ($C_{13}H_{28}$ to $C_{20}H_{42}$), can be used for direct blending into the refinery diesel pool or it can be further upgraded through a hydrocracking/isomerization or reforming process to produce high quality diesel, jet fuel, and gasoline, as described in the **Other Important Considerations** section.

Gas Scrubbing and Recycle

The gases (Stream 18) from the Low Temperature Separator (V-102) include H_2, CO, CO_2, methane, and propane and pass through an Amine Scrubbing system (V-106/107) to remove CO_2 and other particulates. The treated gas from the amine scrubber is recycled back to the hydrotreater with about 20% purge to reduce the accumulation of CO, methane, and propane in the recycle gas stream (Stream 20). The potential use of this purge gas will be described in the **Other Important Considerations** section. A recycle compressor (C-102) increases the pressure of the recycle stream back to 50 bars.

C. ENERGY BALANCE AND UTILITY REQUIREMENTS

The energy requirements for the hydrotreating process can be determined using the ASPEN PLUS simulation. **Table 17** lists the utility requirements and annual expenditure for the various utilities.

TABLE 17. UTILITY REQUIREMENTS AND ANNUAL EXPENDITURE BY UTILITY.

Low Pressure Steam					
Equipment	**Unit**	**Flowrate (lb/hr)**	**Annual Consumption**	**Price**	**Annual Cost**
Product Stripper	V-103	20,000	158,400,000 lb	$3.00/1000 lb	$ 388,000

Fuel Gas					
Equipment	**Unit**	**Heat Duty (MM Btu/hr)**	**Annual Consumption**	**Price**	**Annual Cost**
Fired Heater	F-101	9.27	73,385 MM Btu	$2.60/MM Btu	$ 191,000

Electricity					
Equipment	**Unit**	**Power (kW)**	**Annual Consumption**	**Price**	**Annual Cost**
Feed Storage Pump	P-101	10.2	81,126 kWh	$0.05/kWh	$ 6,000
Product Storage Pump	P-102	8.5	67,432 kWh	$0.05/kWh	$ 5,000
Centrifugal Pump	P-103	316	2,502,922 kWh	$0.05/kWh	$ 175,000
Makeup Compressor	C-101	2205	17,460,072 kWh	$0.05/kWh	$ 1,222,000
Recycle Compressor	C-102	961	7,608,780 kWh	$0.05/kWh	$ 533,000
Total Electricity		3500	27,720,333 kWh	$0.05/kWh	$ 1,940,000

Total Utility Cost	$ 2,519,000

The major utilities required in the hydrotreating process include low pressure stream, fuel gas, and electricity. Since the hydrotreating process is located at a refinery environment, these utilities will be readily available without building new utility plants.

Low Pressure Steam is used as a stripping fluid for the Product Stripper (V-103) to separate the n-alkanes from the offgas. The steam requirement for the Product Stripper is generally 5-10% of the feed flow rate; based on a 233,170 lb/hr feed flow rate into the Product Stripper, the steam requirement was specified as 20,000 lb/hr of steam at 2 bars and 150°C. The price of Low Pressure Steam is based on Table 23.1 of Product and Process Design Principles.[44]

Fuel Gas is combusted in the Fired Heater (F-101) to heat the triglyceride feedstock (Stream 3) in preparation of the reactor. The fired heater has a heat duty of 9.27MM Btu/hr in order to heat Stream 3 to 350°C. Although the source of this fuel gas can be offgas from the vapor purge stream or from the Product Stripper overhead, in this analysis the purchase price of fuel gas and the selling price of offgas will be calculated independently of each other. The price of fuel gas is listed in Product and Process Design Principles.[44]

Electricity is required for various pumps and compressors in the hydrotreating process, such as the Feed Storage Pump (P-101), Product Storage Pump (P-102), Centrifugal Pump (P-103), Makeup Compressor (C-101), and Recycle Compressor (C-102). The electricity requirements for the Makeup Compressor (C-101) are especially high because of the compression of hydrogen gas from 20 bars to 45 bars. The electricity requirements for the hydrotreating process were assessed at a price of $0.07/kWh.

D. EQUIPMENT LIST AND UNIT DESCRIPTIONS

TABLE 18. EQUIPMENT LIST FOR THE HYDROTREATING PROCESS.

Unit No.	Unit Type	Function	Size	Mat'l Construction	Oper. T	Oper. P
C-101	Makeup Compressor	Increase the pressure of the makeup H_2 stream	Pc = 2204.5 hp	Cast Iron	134 C	45 bar
C-102	Recycle Compressor	Increase the pressure of the recycle stream to reactor pressure	Pc = 960.7 hp	Cast Iron	61 C	50 bar
E-101	Shell and Tube Heat Exchanger	Heat the feed stream from ambient to higher temperature	A = 1867.6 ft^2 Q = 3372185.2 btu/hr	Stainless Steel	49 C	55 bar
E-102	Shell and Tube Heat Exchanger	Heat the feed stream to the furnace inlet temperature	A = 108.9 ft^2 Q = 57893017.3 btu/hr	Stainless Steel	43 C	55 bar
F-101	Furnace	Heat the feed up the reactor inlet temperature	Q = 9265792.3 btu/hr	Steel	350 C	52 bar
H-101	Air Cooler	Cool the vapor stream from the HT separator overhead	A = 6847.4 ft^2 Q = 71292563 btu/hr	Stainless Steel	20 C	42 bar
H-102	Air Cooler	Cool the bottom stream leaving the stripper	A = 2356.7 ft^2 Q = 15127226 btu/hr	Stainless Steel	25 C	42 bar
H-103	Air Cooler	Cool the overhead stream leaving the stripper	A = 3121.4 ft^2 Q = 19491178 btu/hr	Stainless Steel	25 C	2 bar
P-101	Centrifugal Pump	Increase the pressure of the feed stream	V = 5665.9 ft^3/hr Pc = 423.8 hp H = 73.6 ft	Cast Iron	25 C	54 bar
P-102	Centrifugal Pump	Increase the pressure of the product stream	V = 4709.5 ft3/hr Pc = 11.4 hp H = 2249.5 ft	Cast Iron	25 C	2 bar
P-103	Centrifugal Pump	Increase the pressure of the feed stream	V = 5665.9 ft^3/hr Pc = 13.7 hp H = 74.9 ft	Cast Iron	25 C	55 bar

R-101	Reactor	Convert the triglycerides into alkanes	D = 9.13 ft H = 49.6 ft Ncb = 3 catalyst beds	Stainless Steel 316	350 C	50 bar
T-101	Feed Storage Tank	Holds TAG stream from the lipid extraction step	V = 5665.9 ft^3/hr	Carbon Steel	25 C	2 bar
T-102	Product Storage Tank	Holds the n-alkane product stream from hydrotreating	V = 4709.5 ft^3/hr	Carbon Steel	25 C	2 bar
V-101	HT Separator	Separate light gases from liquid product stream	D = 5.86 ft H = 29.3 ft	Stainless Steel 316	225 C	45 bar
V-102	LT Separator	Separate light gases and water from liquid product stream	D = 4 ft H = 22.8 ft	Stainless Steel 316	20 C	42 bar
V-103	Product Stripper	Removes water vapor and light gases from the product stream	D = 6.59 ft H = 50 ft	Stainless Steel 316		2 bar
V-104	Decanter	Remove residual water from the product n-alkane stream	D = 11.7 ft L = 35.2 ft	Carbon Steel	25 C	2 bar
V-105	Overhead Accumulator	Separate the offgas gas from light gases and water	D = 9.37 ft L = 18.7 ft	Stainless Steel 316	25 C	2 bar
V-106 V-107	Amine Scrubber	Removes CO2 and other impurities before recycling it to reactor	D = 1.4 ft H = 25.9 ft	Stainless Steel 316	20 C	45 bar
V-108	Feed Surge Drum	Holds the TAG stream to provide a steady feed to the process	D = 10.6 ft L = 21.3 ft V = 5665.9 ft^3/hr	Stainless Steel 316	25 C	1 bar
V-109	Make Up KO Pot	Removes any liquid present in the H2 inlet stream	D = 4.25 ft L = 12.8 ft	Stainless Steel 316	25 C	20 bar
V-110	Recycle KO Pot	Removes any liquid present in the recycle inlet stream	D = 4.74 ft L = 14.2 ft	Stainless Steel 316	49 C	45 bar

Reactor (R-101)

The hydrotreating reactor (hydrotreater) is a fixed-bed reactor filled with NiMo catalyst on alumina. The temperature inside the reactor varies and increases due to the heat released by the reactions **(Equations 4** to **7)** described above. Therefore, the reactor is divided into three catalyst beds with two quench zones to control the temperature of the catalyst beds and the reaction rates. The feed stream enters the reactor at the top with most of the hydrogen feed while the remaining hydrogen feed enters the reactor at the two quench zones. In addition, the operating temperature of the reactor has to be raised over time because of the efficiency of the catalyst decreases over time and a higher temperature is required to maintain the same level of conversion. However, simplifying assumptions were made in ASPEN PLUS and the reactor was modeled to operate at a constant temperature of 350°C (662°F) without quenching. The reactor was modeled as a vertical pressure vessel in the equipment sizing and costing calculations with a liquid hourly space velocity (LHSV) of 1.5hr^{-1} as specified in the Haldor Topsoe report.[46] The total bare-module cost of this unit is $2,859,000. Please refer to the Reactor Specification Sheet on page 76 and the Sample Calculations on page 148.

High Temperature Separator (V-101)

The High Temperature Separator is a flash vessel that separates the n-alkane product from the light products (H_2, CO, CO_2, methane, propane, and water). The vapor stream is cooled and sent to the Low Temperature Separator for further separation. The liquid stream is sent to the product stripper to separate any residual non n-alkane components. The HT Separator operates at 225°C (437°F) and 47 bars. The ASPEN simulation shows that the vapor-liquid separation is not 100%, a sizable amount of n-alkane product exits in the vapor stream instead of the liquid stream and will be recovered in the LT Separator. The High Temperature Separator is designed as a vertical vapor-liquid flash drum where the vessel diameter can be calculated using the Souders-Brown equation. The total bare-module cost of this unit is $ 991,275. Please refer to the HT Separator Specification Sheet on page 77 and the Sample Calculations on page 149.

Low Temperature Separator (V-102)

The Low Temperature Separator is a three-phase flash vessel that separates the vapor stream from the high temperature separator into gasses (H_2, CO, CO_2, methane, propane), liquid (any n-alkanes carried over in the vapor stream), and water. The gasses are sent to the Amine Scrubber while the liquid n-alkanes are combined with the main n-alkane stream and sent to the product stripper. Water is separated and sent to a sour water treatment facility. The Low Temperature Separator operates at 20°C and 45 bars. The vessel is sized as a horizontal vapor-liquid separator based on a procedure outlined by Monnery and Svrcek.[49] The total bare-module cost of this unit is $352,000. Please refer to the LT Separator Specification Sheet on page 79 and the Sample Calculations on page 150.

Product Stripper (V-103)

The Product Stripper removes any dissolved H_2, H_2O, CO, CO_2 and light hydrocarbon gases from the hydrotreater liquid product stream. The reactor effluent enters near the top of the column and flows downwards while steam enters at the bottom of the product stripper as stripping fluid to remove light gases from liquid alkane product. Based on feedback from industrial consultants, a typical product stripper has a total of 25 stages spaced 18 inches apart. The Product Stripper is modeled in ASPEN Plus using the RADFRAC subroutine operating at 2 bars. The total bare-module cost of this unit is $981,000. Please refer to the Product Stripper Specification Sheet on page 79 and the Sample Calculations on page 151.

Decanter (V-104)

The Decanter is a liquid-liquid separation unit that will remove water from the alkane stream by cooling down the stream from 245°F to 100°F and lowering the pressure from 29 psia to 20 psia. The decanter removes almost 88% of the water in the n-alkanes stream. The n-alkane stream exiting the Decanter contains about 10 ppm of water, which is less than the maximum 500ppm allowed in diesel fuel specifications. The decanter is modeled as a horizontal pressure vessel with a residence time of 5 minutes as suggested by industrial consultants. The total bare-module cost of this unit is $191,000. Please refer to the Specification Sheet on page 80 and the Sample Calculations on page 152.

Overhead Accumulator (V-105)

The Overhead Accumulator separates the Product Stripper offgas from the light alkane and water streams. The unit is modeled as a horizontal pressure vessel constructed with stainless steel 316. The size of the unit is estimated based on the volumetric flow rate and a residence time of 2 minutes. The total bare-module cost of this unit is $275,700. Please refer to the Specification Sheet on page 81 and the Sample Calculations on page 153.

Amine Scrubber (V-106/V-107)

The Amine Scrubber is a unit that removes CO_2 and other impurities/particulates from the vapor stream before it is recycled back to the hydrotreater. Although not modeled in our simulation, one of the key impurities that can be removed with the amine scrubber is H_2S. In the Absorber (V-106), monoethanolamine flows countercurrent against the vapor stream and uptakes 90% of the carbon dioxide in the vapor stream. The bottom stream (rich amine) of the scrubber passes through the Regenerator (V-107), where CO_2 is released from the MEA solution and the MEA solution is then recycled back into the absorber. The design for this system is based on a University of Pennsylvania Senior Design project by Czarnick, Lau, and McLeod.[31] Based on the throughput CO_2 in this hydrotreating process compared to the CO_2 flow through the MEA process listed in the Czarnick, et. al. report, the total bare-module cost of this unit is approximately $5,754,000. Please refer to the Sample Calculations on page 154.

Feed Surge Drum (V-108)

The feed surge drum holds the triglyceride feedstock to even out flow swings and to provide a steady feed into the hydrotreating process. The surge drum is sized as a horizontal pressure vessel using stainless steel 316 to with a residence time of 20 minutes. The total bare-module cost of this unit is $402,000. Please refer to the Specification Sheet on page 82 and the Sample Calculations on page 155.

Makeup Compressor (C-101) and K.O. Drum (V-109)

The Makeup Compressor increases the pressure of the makeup H_2 stream from 20 bars to 45 bars before it is mixed with the recycle vapor stream. There is a knock-out drum (V-109) associated with the makeup compressor; the purpose of this drum is to remove any liquid that might exist in the makeup gas stream. The compressor is an electric centrifugal compressor made with cast iron, while its knock out drum is modeled as a horizontal flash drum constructed with stainless steel 316. The total bare-module cost of the makeup compressor is $1,991,000 and the total bare-module cost of its associated knock out drum is $199,000. Please refer to the Makeup Compressor Specification Sheet on page 85 and the Sample Calculations on page 158 and the Makeup Compressor K.O. Drum Specification Sheet on page 83 and the Sample Calculations on page 156.

Recycle Compressor (C-102) and K.O. Drum (V-110)

The Recycle Compressor increases the pressure of the recycle vapor stream going into the reactor. The stream, containing the recycled gases mixed with a makeup hydrogen stream, enters the compressor at a pressure of 45 bars and leaves at 50 bars. There is a knock-out drum (V-110) associated with the recycle compressor; the purpose of this drum is to remove any liquid that might exist in the recycle stream. The compressor is an electric centrifugal compressor made with cast iron, while its knock out drum is modeled as a horizontal flash drum constructed with stainless steel 316. The total bare-module cost of the recycle compressor is $1,023,000 and the total bare-module cost of its knock out drum is $310,000. Please refer to the Recycle Compressor Specification Sheet on page 86 and the Sample Calculations on page 159 and the Recycle K.O. Drum Specification Sheet on page 84 and the Sample Calculations on page 157.

Feed Tank Pump (P-101)

The Feed Tank Pump is used to pump the triglyceride feedstock from the feed storage tank (T-101) to the feed surge drum (V-108). Assuming a 25 psi pressure loss between the tank and the surge drum, a pressure head of 73.57ft is calculated. This unit is a centrifugal pump made of cast iron. The total bare-module cost of this unit is $310,000. Please refer to the Feed Tank Pump Specification Sheet on page 87 and the Sample Calculations on page 160.

Product Tank Pump (P-102)

The Product Tank Pump is used to pump the n-alkane products from the Decanter (V-104) to the Product Storage Tank (T-102). Assuming a 25 psi pressure loss between the Decanter and the Product Storage Tank, a pressure head of 74.96ft is calculated. The total bare-module cost of this unit is $284,000. Please refer to the Product Tank Pump Specification Sheet on page 88 and the Sample Calculations on page 161.

Centrifugal Pump (P-103)

The Centrifugal Pump increases the pressure of the triglyceride feed stream to 55 bars. The outlet from the pump will go directly to the feed-effluent heat exchangers for heat recovery before entering the feed furnace and the reactor. This unit is a centrifugal pump made of cast iron. The total bare-module cost of this unit is $877,000. Please refer to the Centrifugal Pump Specification Sheet on page 89 and the Sample Calculations on page 162.

Feed Storage Tank (T-101)

The feed storage tank is a floating-roof tank that stores the triglyceride feedstock that arrives from the OriginOil^{TM} lipid extraction facility. The tank has a capacity to store 7,120,500 gallons of triglyceride feedstock, which is adequate storage for seven days of inventory. This accounts for any potential disruptions in feedstock transfer or in the hydrotreating process. Using a carbon steel construction, the total bare-module cost of this unit is $4,527,000. Please refer to the Feed Storage Tank Specification Sheet on page 90 and the Sample Calculations on page 163.

Product Storage Tank (T-102)

The product storage tank is a floating roof tank that stores the n-alkane product before it is sent to other areas of the refinery for additional processing. The tank has a capacity to store 1,710,300 gallons of n-alkane, which is adequate storage for two days of inventory. The residence time is reduced because the n-alkanes product is transferred to other units of the refinery and not an outside location, minimizing potential transportation disruptions. In addition, in case of any unit disruption, there are other storage tanks located at the refinery which could be used. Using a carbon steel construction, the total bare-module cost of this unit is $2,174,000. Please refer to the Product Storage Tank Specification Sheet on page 91 and the Sample Calculations on page 164.

Fired Heater (F-101)

This unit heats the triglyceride feed stream (Stream 4) to 350°C (662°F) in preparation for the hydrotreating reactor. Fuel gas provides the necessary fuel for combustion in the fired heater; the fuel gas used for this process can come from the offgas as described in the **Other Important Considerations** section. The fired heater absorbs heat duty of 9,265,792 BTU/hr and operates at a pressure of 52 bars. Since the fired heater is made of stainless steel, the total bare-module cost of this unit is $1,874,000. Please refer to the Fired Heater Specification Sheet on page 92 and the Sample Calculations on page 165.

Heat Exchanger 1 (E-101)

Heat Exchanger 1 is a shell and tube heat exchanger which uses the heat from the bottom outlet stream of the High Temperature Separator to heat up the feed stream going to the Fired Heater. The feed stream, containing the triglycerides will be heated from 25°C (77^{o}F) to 75°C (168^{o}F). Based on a stainless steel construction for both the shell and tube, the total bare-module cost of this unit is $250,000. Please refer to the Heat Exchanger 1 Specification Sheet on page 93 and the Sample Calculations on page 166.

Heat Exchanger 2 (E-102)

Heat Exchanger 2 is a shell and tube heat exchanger which uses the heat from the reactor effluent to further preheat the feed stream before going to the Fired Heater. The feed stream, containing the triglycerides, will be heated from 75°C (168^{o}F) to 325°C (617^{o}F). Based on a stainless steel construction for both the shell and tube, the total bare-module cost of this unit is \$379,000. Please refer to the Heat Exchanger 2 Specification Sheet on page 94 and the Sample Calculations on page 167.

Air Cooler 1 (H-101)

This Cooling Unit is a fin fan heat exchanger used to cool the vapor outlet stream emerging from the High Temperature Separator. The Cooler lowers the temperature of the stream from 225°C (437°F) to 20°C (68°F). The Cooler has a heat requirement of 266,680,000 Btu/hr of energy. Based on a carbon steel construction, the total bare-module cost of this unit is \$186,000. Please refer to the Cooler 1 Specification Sheet on page 95 and the Sample Calculations on page 168.

Air Cooler 2 (H-102)

The cooling unit is a fin fan heat exchanger used to cool the bottoms stream emerging from the Product Stripper. The cooler lowers the temperature of the stream from 92°C (198°F) to 25°C (77°F). Based on a carbon steel construction, the total bare-module cost of this unit is \$121,000. Please refer to the Cooler 2 Specification Sheet on page 96 and the Sample Calculations on page 169.

Air Cooler 3 (H-103)

The cooling unit is a fin fan heat exchanger used to cool the overhead stream emerging from the Product Stripper. The cooler lowers the temperature of the stream from 92°C (198°F) to 25°C (77°F). Based on a carbon steel construction, the total bare-module cost of this unit is \$136,000. Please refer to the Cooler 3 Specification Sheet on page 97 and the Sample Calculations on page 170.

E. SPECIFICATION SHEETS

The following pages list the specification sheets detailing the different units within the hydrotreating process.

Reactor

Identification:	Item:	Reactor	Date:	April, 5, 2010
	Item No:	R-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Converts the triglycerides into alkanes

Operation: Continuous

Materials Handled:	**Inlet**		**Outlet**
Inlet Stream ID:	4	23	5
Quantity (lb/hr):	277237	85206.82	362444
Composition:			
C14FFA	15329.22		
C16FFA	117508.7		
C18FFA	27431.78		
C20FFA	102796.7		
C13ALKN			7920.1
C14ALKN			4794
C15ALKN			62298.33
C16ALKN			37356.83
C17ALKN			14840.35
C18ALKN			8834.62
C19ALKN			56525.7
C20ALKN			33456.6
Propane	14170.64	38014.95	52185.58
H2		23923.66	19732.5
WATER		7633.35	22452.08
CO		1080.28	9628.65
CO2		14554.59	13929.14
CH4			18489.35
Temperature (°F):	662	142.12	662
Pressure (psig):	710.49	710.49	710.49
Vapor Fraction:	0	1	1

Design Data:

Type:	
Material:	Stainless Steel 316
Height (ft):	50.211
Catalsyt Bed Height (ft):	27.816
Diameter (ft):	9.13
Heat Duty (btu/hr)	43111600

C_P	$	687,144
C_{BM}	$	2,858,518

High Temperature Separator

Identification:	Item:	Separator	Date:	April, 5, 2010
	Item No:	V-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Separate light gases from liquid product stream

Operation: Continuous

Materials Handled:		**Feed**	**Distillate**	**Bottoms**
Inlet Stream ID:		6	9	7
Quantity (lb/hr):		362443.8	149251.5	213192.4
Composition:				
	C13ALKN	7920.1	1899.8	6020.3
	C14ALKN	4794	831.42	3962.59
	C15ALKN	62298.33	7665.87	54632.48
	C16ALKN	37356.83	3232.53	34124.31
	C17ALKN	14840.35	874.51	13965.85
	C18ALKN	8834.62	364.74	8469.89
	C19ALKN	56525.71	1611.92	54913.79
	C20ALKN	33456.6	637.91	32818.69
	Propane	52185.58	50116.31	2069.27
	H2	19732.5	19626	106.5
	WATER	22452.08	20934.51	1517.58
	CO	9628.65	9552.19	76.46
	CO2	13929.14	13655.9	273.25
	CH4	18489.35	18247.87	241.5
Temperature (°F):		519	437	437
Pressure (psig):		710.49	666.9	666.9
Vapor Fraction:		0.94	1	0

Design Data:

Type:	Flash Drum
Material:	Stainless Steel 316
Height (ft):	29.3
Diameter (ft):	5.86

C_P	$	305,163
C_{BM}	$	1,269,477

Low Temperature Separator

Identification:	Item:	Separator	Date:	April, 5, 2010
	Item No:	V-102	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Separate light gases and water from liquid product stream

Operation: Continuous

Materials Handled:	**Feed**	**Distillate**	**Bottoms**	**Water**
Inlet Stream ID:	10	18	11	
Quantity (lb/hr):	149251.5	108507.8	19977.4	20766.2
Composition:				
C13ALKN	1899.8	0.41	1899.39	
C14ALKN	831.42	0.07	831.35	
C15ALKN	7665.87	0.21	7665.65	
C16ALKN	3232.53	0.03	3232.49	
C17ALKN	874.51		874.5	
C18ALKN	364.74		364.73	
C19ALKN	1611.92		1611.91	
C20ALKN	637.91		637.91	
Propane	50116.31	47518.68	2597.62	
H2	19626	19618.56	7.44	
WATER	20934.51	131.46	36.84	20766.2
CO	9552.19	9541.68	10.5	
CO2	13655.9	13503.49	152.41	
CH4	18247.87	18193.23	54.64	
Temperature (°F):	68	68	68	68
Pressure (psig):	608.9	637.9	637.9	637.9
Vapor Fraction:	0.92	1	0	0

Design Data:

Type:	Flash Drum
Material:	Stainless Steel 316
Height (ft):	22.7
Diameter (ft):	4.56

C_P	$	182,577
C_{BM}	$	556,859

Product Stripper

Identification:	Item:	Stripper	Date:	April, 5, 2010
	Item No:	V-103	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Removes water vapor and light gases from the product stream

Operation: Continuous

Materials Handled:		**Feed**		**Outlet**	
Inlet Stream ID:		13	STEAM	14	16
Quantity (lb/hr):		233169.9	20000	231126.5	22043.45
Composition:					
	C13ALKN	7919.69		7900.02	19.67
	C14ALKN	4793.94		4788.34	5.6
	C15ALKN	62298.13		62265.41	32.74
	C16ALKN	37356.8		37347.51	9.3
	C17ALKN	14840.35		14838.79	1.56
	C18ALKN	8834.62		8834.19	0.44
	C19ALKN	56525.7		56524.41	1.3
	C20ALKN	33456.6		33456.28	0.32
	Propane	4666.89			
	H2	113.94			
	WATER	1554.43	20000	5171.52	16382.91
	CO	86.97			86.97
	CO2	425.65			425.65
	CH4	296.14			296.14
Temperature (°F):		176.23	302	198.69	189.42
Pressure (psig):		14.3	14.3	14.3	14.3
Vapor Fraction:		0.15	1	0	1
No. of Stages:		1	17	17	1

Design Data:

Type:	Stripping Column
Material:	Stainless Steel 316
Height (ft):	25.9
Diameter (ft):	6.63

C_P	$	235,897
C_{BM}	$	981,330

Decanter

Identification:	Item:	Flash	Date:	April, 5, 2010
	Item No:	V-104	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Remove residual water from the product n-alkane stream

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**	
Inlet Stream ID:		15	N-ALKANE	DECWATER
Quantity (lb/hr):		231126.5	226189.9	4936.58
Composition:				
	C13ALKN	7900.02	7900.03	
	C14ALKN	4788.34	4788.34	
	C15ALKN	62265.41	62265.41	
	C16ALKN	37347.51	37347.51	
	C17ALKN	14838.79	14838.79	
	C18ALKN	8834.19	8834.19	
	C19ALKN	56524.41	56524.41	
	C20ALKN	33456.28	33456.29	
	WATER	5171.52	234.93	4936.58
Temperature (°F):		198.69	77	77
Pressure (psig):		14.3	14.3	14.3

Design Data:

Type:	Pressure Vessel
Material:	Carbon Steel
Length:	23.5 ft
Diameter:	11.7 ft

C_P	$	61,636
C_{BM}	$	187,991

Overhead Accumulator

Identification:	Item:	Flash	Date:	April, 5, 2010
	Item No:	V-105	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Separate the offgas gas from light gases and water

Operation: Continuous

Materials Handled:

	Inlet		**Outlet**	
Inlet Stream ID:	17	OFFGAS	NALKANE	HWATER
Quantity (lb/hr):	22043.45			16341.55
Composition:				
C13ALKN	19.67	0.33	19.34	
C14ALKN	5.6	0.03	5.57	
C15ALKN	32.74	0.07	32.68	
C16ALKN	9.3	0.01	9.29	
C17ALKN	1.56		1.56	
C18ALKN	0.44		0.44	
C19ALKN	1.3		1.3	
C20ALKN	0.32		0.32	
Propane	4666.89		2.28	
H2	113.94	113.94		
WATER	16382.91	41.34	0.1	16341.47
CO	86.97	86.97		
CO2	425.65	425.53	0.04	0.08
CH4	296.14	296.13	0.01	
Temperature (°F):	189.42	77	77	77
Pressure (psig):	14.3	14.3	14.3	14.3

Design Data:

Type:	Pressure Vessel
Material:	Stainless Steel 316
Length:	32.1 ft
Diameter:	16 ft

C_P	$	179,118
C_{BM}	$	546,311

Feed Surge Drum

Identification:	Item:	Drum	Date:	April, 5, 2010
	Item No:	V-108	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Holds the TAG stream to provide a steady feed to the process

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		TAG	1
Quantity (lb/hr):		277237	277237
Composition:			
	C14FFA	15329.22	15329.22
	C16FFA	117508.7	117508.7
	C18FFA	27431.78	27431.78
	C20FFA	102796.7	102796.7
	Propane	14170.64	14170.64

Design Data:

Type:	Pressure Vessel
Material:	Stainless Steel 316
Length:	21.3 ft
Diameter:	10.6 ft

C_P	$	131,762
C_{BM}	$	401,874

Make Up KO Drum

Identification:	Item:	Drum	Date:	April, 5, 2010
	Item No:	V-109	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Removes any liquid present in the H2 inlet stream

Operation: Continuous

Materials Handled:	**Inlet**	**Outlet**
Inlet Stream ID:	H2FEED	H2FEED
Quantity (lb/hr):	8228.81	8228.81
Composition:		
H2	8228.81	8228.81

Design Data:

Type:	Pressure Vessel
Material:	Stainless Steel 316
Length:	12.8 ft
Diameter:	4.25 ft

C_P	$	65,351
C_{BM}	$	199,319

Recycle KO Drum

Identification:	Item:	Drum	Date:	April, 5, 2010
	Item No:	V-110	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Removes any liquid present in the recycle inlet stream

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		22	22
Quantity (lb/hr):		85206.82	85206.82
Composition:			
	Propane	38014.95	38014.95
	H2	23923.66	23923.66
	CO	7633.35	7633.35
	CO2	1080.28	1080.28
	CH4	14554.59	14554.59

Design Data:

Type:	Pressure Vessel
Material:	Stainless Steel 316
Length:	14.2 ft
Diameter:	4.75 ft

C_P	$	170,821
C_{BM}	$	521,003

Makeup Compressor

Identification:	Item:	Compressor	Date:	April, 5, 2010
	Item No:	C-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Increase the pressure of the make up H2 stream

Operation: Continuous

Materials Handled:	**Inlet**	**Outlet**
Inlet Stream ID:	H2FEED	21
Quantity (lb/hr):	8228.81	8228.81
Composition:		
H2	8228.81	8228.81
	In	Out
Temperature (°F):	77	272.27
Vapor Fraction	1	1

Design Data:

Type:	
Material:	Cast Iron
Net Work Req (HP):	2204.5
Pressure (psig):	637.9
Efficiency:	0.72

C_P	$	925,995
C_{BM}	$	1,990,890

Recycle Compressor

Identification:	Item:	Compressor	Date:	April, 5, 2010
	Item No:	C-102	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Increase the pressure of the recycle stream to reactor pressure

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		22	23
Quantity (lb/hr):		85206.82	85206.82
Composition:			
	Propane	38014.95	38014.95
	H2	23923.66	23923.66
	CO	7633.35	7633.35
	CO2	1080.28	1080.28
	CH4	14554.59	14554.59
		In	Out
Temperature (°F):		120.11	142.12
Vapor Fraction		1	1

Design Data:

Type:	
Material:	Cast Iron
Net Work Req (HP):	959.1
Pressure (psig):	710.5
Efficiency:	0.72

C_P	$	475,833
C_{BM}	$	1,023,040

Centrifugal Pump

Identification:	Item:	Pump	Date:	April, 5, 2010
	Item No:	P-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Increase the pressure of the feed stream

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		TAG	TAG
Quantity (lb/hr):		277237	277237
Composition:			
	C14FFA	15329.22	15329.22
	C16FFA	117508.7	117508.7
	C18FFA	27431.78	27431.78
	C20FFA	102796.7	102796.7
	Propane	14170.64	14170.64

Design Data:

Type:	Centrifugal Pump
Material:	Cast Iron
Net Work Req (HP):	13.7
Pressure (psi):	25
Efficiency:	0.75

C_P	$	86,024
C_{BM}	$	283,879

Centrifugal Pump

Identification:	Item:	Pump	Date:	April, 5, 2010
	Item No:	P-102	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Increase the pressure of the product stream

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		N-ALKANE	N-ALKANE
Quantity (lb/hr):		226189.9	226189.9
Composition:			
	C13ALKN	7900.03	7900.03
	C14ALKN	4788.34	4788.34
	C15ALKN	62265.41	62265.41
	C16ALKN	37347.51	37347.51
	C17ALKN	14838.79	14838.79
	C18ALKN	8834.19	8834.19
	C19ALKN	56524.41	56524.41
	C20ALKN	33456.29	33456.29
	WATER	234.93	234.93

Design Data:

Type:	Centrifugal Pump
Material:	Cast Iron
Net Work Req (HP):	11.4
Pressure (psi):	25
Efficiency:	0.75

C_P	$	265,610
C_{BM}	$	876,514

Centrifugal Pump

Identification:	Item:	Pump	Date:	April, 5, 2010
	Item No:	P-103	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Increase the pressure of the feed stream

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		TAG	1
Quantity (lb/hr):		277237	277237
Composition:			
	C14FFA	15329.22	15329.22
	C16FFA	117508.7	117508.7
	C18FFA	27431.78	27431.78
	C20FFA	102796.7	102796.7
	Propane	14170.64	14170.64
Temperature (°F):		77	78
Vaport Fraction:		0	0

Design Data:

Type:	Centrifugal Pump
Material:	Cast Iron
Net Work Req (HP):	423.79
Pressure (psi):	764.36
Efficiency:	0.75

Utilities: 316 kW

C_P	$	94,068
C_{BM}	$	310,423

Feed Storage Tank

Identification:	Item:	Tank	Date:	April, 5, 2010
	Item No:	T-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Holds TAG stream from the lipid extraction step

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		TAG	TAG
Quantity (lb/hr):		277237	277237
Composition:			
	C14FFA	15329.22	15329.22
	C16FFA	117508.7	117508.7
	C18FFA	27431.78	27431.78
	C20FFA	102796.7	102796.7
	Propane	14170.64	14170.64

Design Data:

Type:	Floating Roof Tank
Material:	Carbon Steel
Volume:	951875.34 ft3

C_P	$	1,484,142
C_{BM}	$	4,526,634

Product Storage Tank

Identification:	Item:	Tank	Date:	April, 5, 2010
	Item No:	T-102	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Holds the n-alkane product stream from hydrotreating

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		N-ALKANE	N-ALKANE
Quantity (lb/hr):		226189.9	226189.9
Composition:			
	C13ALKN	7900.03	7900.03
	C14ALKN	4788.34	4788.34
	C15ALKN	62265.41	62265.41
	C16ALKN	37347.51	37347.51
	C17ALKN	14838.79	14838.79
	C18ALKN	8834.19	8834.19
	C19ALKN	56524.41	56524.41
	C20ALKN	33456.29	33456.29
	WATER	234.93	234.93

Design Data:

Type:	Floating Rood
Material:	Carbon Steel
Volume:	226057.63 ft3

C_P	$	712,938
C_{BM}	$	2,174,460

Furnace

Identification:	Item:	Furnace	Date:	April, 5, 2010
	Item No:	F-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Heat the feed up the reactor inlet temperature

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		3	4
Quantity (lb/hr):		277237	277237
Composition:			
	C14FFA	15329.22	15329.22
	C16FFA	117508.7	117508.7
	C18FFA	27431.78	27431.78
	C20FFA	102796.7	102796.7
	Propane	14170.64	14170.64
Temperature (°F):		617	662
Pressure (psig):		783	710.49
Vapor Fraction		0	0

Design Data:

Type:	Fired Heater
Material:	Carbon Steel
Heat Duty:	9265792.31 BTU/HR

C_P	$	1,007,592
C_{BM}	$	1,874,121

Heat Exchanger

Identification:	Item:	Heat Exchanger	Date:	April, 5, 2010
	Item No:	E-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Heat the feed stream from ambient to higher temperature

Operation: Continuous

Materials Handled:	**Hot Stream**		**Cold Stream**	
Inlet Stream ID:	7	8	1	2
Quantity (lb/hr):	213192.4	213192.4	277237	277237
Composition:				
C14FFA			15329.22	15329.22
C16FFA			117508.7	117508.7
C18FFA			27431.78	27431.78
C20FFA			102796.7	102796.7
C13ALKN	6020.3	6020.3		
C14ALKN	3962.59	3962.59		
C15ALKN	54632.48	54632.48		
C16ALKN	34124.31	34124.31		
C17ALKN	13965.85	13965.85		
C18ALKN	8469.89	8469.89		
C19ALKN	54913.79	54913.79		
C20ALKN	32818.69	32818.69		
Propane	2069.27	2069.27	14170.64	14170.64
H2	106.5	106.5		
WATER	1517.58	1517.58		
CO	76.46	76.46		
CO2	273.25	273.25		
CH4	241.5	241.5		
	In	Out	In	Out
Temperature (°F):	437	186.7	78	303.3
Pressure (psig):	666.9	666.9	783	783
Vapor Fraction:	0	0.02	0	0

Design Data:

Type:	Shell and Tube
Material:	Stainless Steel
Heat Transfer Area:	1867.6 sq. ft.
Heat Transfer Coefficient:	149.6937 BTU/HR-SQFT-R
Heat Duty:	33721285.2 btu/hr

C_P	$	78,835
C_{BM}	$	249,907

Heat Exchanger

Identification:	Item:	Heat Exchanger	Date:	April, 5, 2010
	Item No:	E-102	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Heat the feed stream to the furnace inlet temperature

Operation: Continuous

Materials Handled:

	Hot Stream		Cold Stream	
Inlet Stream ID:	5	6	2	3
Quantity (lb/hr):	362443.8	362443.8	277237	277237
Composition:				
C14FFA			15329.22	15329.22
C16FFA			117508.7	117508.7
C18FFA			27431.78	27431.78
C20FFA			102796.7	102796.7
C13ALKN	7920.1	7920.1		
C14ALKN	4794	4794		
C15ALKN	62298.33	62298.33		
C16ALKN	37356.83	37356.83		
C17ALKN	14840.35	14840.35		
C18ALKN	8834.62	8834.62		
C19ALKN	56525.7	56525.7		
C20ALKN	33456.6	33456.6		
Propane	52185.58	52185.58	14170.64	14170.64
H2	19732.5	19732.5		
WATER	22452.08	22452.08		
CO	9628.65	9628.65		
CO2	13929.14	13929.14		
CH4	18489.35	18489.35		
	In	Out	In	Out
Temperature (°F):	662	519	303.3	617
Pressure (psig):	710.49	710.49	783	783
Vapor Fraction:	1	0.94	0	0

Design Data:

Type:	Shell and Tube
Material:	Stainless Steel
Heat Transfer Area:	3551 sq. ft.
Heat Transfer Coefficient:	149.6937 BTU/HR-SQFT-R
Heat Duty:	57893017.3 btu/hr

C_P	$	119,577
C_{BM}	$	379,058

Air Cooler

Identification:	Item:	Cooler	Date:	April, 5, 2010
	Item No:	H-101	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Cool the vapor stream from the HT separator overhead

Operation: Continuous

Materials Handled:	**Inlet**	**Outlet**
Inlet Stream ID:	9	10
Quantity (lb/hr):	149251.5	149251.5
Composition:		
C13ALKN	1899.8	1899.8
C14ALKN	831.42	831.42
C15ALKN	7665.87	7665.87
C16ALKN	3232.53	3232.53
C17ALKN	874.51	874.51
C18ALKN	364.74	364.74
C19ALKN	1611.92	1611.92
C20ALKN	637.91	637.91
Propane	50116.31	50116.31
H2	19626	19626
WATER	20934.51	20934.51
CO	9552.19	9552.19
CO2	13655.9	13655.9
CH4	18247.87	18247.87
	In	Out
Temperature (°F):	437	68
Pressure (psig):	666.9	608.9
Vapor Fraction:	1	0.92

Design Data:

Type:	Air Fin Cooler
Material:	Stainless Steel
Heat Duty:	71292563 BTU/HR

C_P	$	85,537
C_{BM}	$	185,614

Air Cooler

Identification:	Item:	Cooler	Date:	April, 5, 2010
	Item No:	H-102	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Cool the bottom stream leaving the stripper

Operation: Continuous

Materials Handled:		**Inlet**	**Outlet**
Inlet Stream ID:		14	15
Quantity (lb/hr):		231126.5	231126.5
Composition:			
	C13ALKN	7900.02	7900.02
	C14ALKN	4788.34	4788.34
	C15ALKN	62265.41	62265.41
	C16ALKN	37347.51	37347.51
	C17ALKN	14838.79	14838.79
	C18ALKN	8834.19	8834.19
	C19ALKN	56524.41	56524.41
	C20ALKN	33456.28	33456.28
	WATER	5171.52	5171.52
		In	Out
Temperature (°F):		198.69	198.69
Pressure (psig):		14.3	14.3
Vapor Fraction:		0	0

Design Data:

Type:	Air Fin Cooler
Material:	Stainless Steel
Heat Duty:	15127226 BTU/HR

C_P	$	55,830
C_{BM}	$	121,150

Air Cooler

Identification:	Item:	Cooler	Date:	April, 5, 2010
	Item No:	H-103	By:	LC/ML/CO/AX
	No. Required:	1		

Function: Cool the overhead stream leaving the stripper

Operation: Continuous

Materials Handled:	**Inlet**	**Outlet**
Inlet Stream ID:	16	17
Quantity (lb/hr):	22043.45	22043.45
Composition:		
C13ALKN	19.67	19.67
C14ALKN	5.6	5.6
C15ALKN	32.74	32.74
C16ALKN	9.3	9.3
C17ALKN	1.56	1.56
C18ALKN	0.44	0.44
C19ALKN	1.3	1.3
C20ALKN	0.32	0.32
Propane		4666.89
H2		113.94
WATER	16382.91	16382.91
CO	86.97	86.97
CO2	425.65	425.65
CH4	296.14	296.14

	In	Out
Temperature (°F):	189.42	77
Pressure (psig):	14.3	14.3
Vapor Fraction:	1	0.18

Design Data:

Type:	Air Fin Cooler
Material:	Stainless Steel
Heat Duty:	19491178 BTU/HR

C_P	$	62,471
C_{BM}	$	135,562

F. FIXED-CAPITAL INVESTMENT SUMMARY

TABLE 19. EQUIPMENT COST SUMMARY FOR HYDROTREATING PROCESS.

Designation	Equipment Description	Purchase Cost	Bare Module Factor	Bare Module Cost
R-101	Reactor	$687,000	4.16	$2,859,000
V-101	HT Separator	$238,000	4.16	$991,000
V-102	LT Separator	$115,000	3.05	$352,000
V-103	Product Stripper	$236,000	4.16	$981,000
V-104	Decanter	$63,000	3.05	$191,000
V-105	Overhead Accumulator	$90,000	3.05	$275,000
V-106/107	Scrubber	$1,723,000	3.34	$5,754,000
V-108	Feed Surge Drum	$132,000	3.05	$401,000
V-109	Makeup Comp. KO Drum	$65,000	3.05	$199,000
V-110	Recycle Comp. KO Drum	$102,000	3.05	$310,000
C-101	Makeup Compressor	$926,000	2.15	$1,990,000
C-102	Recycle Compressor	$476,000	2.15	$1,023,000
P-101	Feed Tank Pump	$94,000	3.30	$310,000
P-102	Product Tank Pump	$86,000	3.30	$284,000
P-103	Centrifugal Pump	$266,000	3.30	$877,000
T-101	Feed Storage Tank	$1,485,000	3.05	$4,527,000
T-102	Product Storage Tank	$713,000	3.05	$2,174,000
F-101	Fired Heater	$1,008,000	1.86	$1,874,000
E-101	Heat Exchanger 1	$79,000	3.20	$250,000
E-102	Heat Exchanger 2	$120,000	3.20	$379,000
H-101	Air Cooler 1	$86,000	2.17	$186,000
H-102	Air Cooler 2	$56,000	2.20	$121,000
H-103	Air Cooler 3	$62,000	2.20	$136,000
TOTAL:		**$8,906,000**		**$26,447,000**

Table 19 shows the equipment cost summary for each of the equipment items of the hydrotreating process. The purchase cost is the cost of the physical equipment, while the bare module cost is the cost of the equipment after installation costs are factored in. The bare module factor varies depending on the equipment type and size; a listing of such values can be found in Table 22.11 of Product and Process Design Principles.[44] The purchase costs for most of these equipment units have been estimated using unit-specific correlations listed in Chapter 22 of Product and Process Design Principles.[44] The purchase cost associated with the Amine Scrubber System is not for an individual piece of equipment; rather it is estimation for the purchase cost of an amine scrubber system (including an absorber and regenerator) based on calculations performed by a Senior Design group at the University of Pennsylvania.[31]

TABLE 20: FIXED CAPITAL INVESTMENT SUMMARY FOR HYDROTREATING PROCESS.

C_{TBM}	**Total Bare Module Cost**			
C_{PM}	Equipment Bare Module Costs		$	26,447,000
C_{cat}	Initial Charge of NiMo Catalyst		$	975,000
$C_{storage}$	Storage		$	558,000
		C_{TBM}	$	27,980,000

C_{DPI}	**Direct Permanent Investment**			
C_{TBM}	Total Bare Module Cost		$	27,980,000
C_{site}	Site Preparation		$	1,399,000
C_{serv}	Service Facilities		$	1,399,000
C_{alloc}	Allocated Costs for Utility Plants		$	-
		C_{DPI}	$	30,778,000

C_{TDC}	**Total Depreciable Capital**			
C_{DPI}	Direct Permanent Investment		$	30,778,000
C_{cont}	Contingencies and Contractor's Fees		$	5,540,000
		C_{TDC}	$	36,318,000

C_{TPI}	**Total Permanent Investment**			
C_{TDC}	Total Depreciable Capital		$	36,318,000
C_{land}	Land		$	726,000
$C_{royalty}$	Royalty		$	726,000
$C_{startup}$	Plant Startup		$	3,632,000
		C_{TPI}	$	41,402,000

C_{TCI}	**Total Capital Investment**			
C_{TPI}	Total Permanent Investment		$	41,402,000
C_{WC}	Working Capital		$	4,449,000
		C_{TCI}	$	45,852,000

The Fixed Capital Investment Summary **(Table 20)** lists the various capital investments that were estimated for the hydrotreating process. The direct permanent investment, C_{DPI}, includes the total bare-module cost of the equipment, the cost of site preparation, service facilities cost, and allocated costs for utility plants. The total bare-module cost for the equipment is $26,447,000, while the initial charge of NiMo catalyst is calculated at $975,000. The cost of site preparations and the cost of service facilities are estimated to each cost 5.0% of total bare-module costs. Since the hydrotreating unit is located at a refinery with existing utility infrastructure, it is not necessary to add an additional allocated cost for utilities. Utilities such as electricity, hydrogen, and steam are provided by the refinery at a specified cost which includes the vendor investment cost. The total depreciable capital, C_{TDC}, is calculating by adding the cost of contingencies and contractor's fees (18% of C_{DPI}) to C_{DPI}.

The total permanent investment, C_{TPI}, is calculated based on the total depreciable capital and other nondepreciable investments such as land and plant startups. Land costs are estimated to be approximately 2% of C_{TDC} while startup costs are generally assessed at 10% of C_{TDC}. An initial royalty fee would be paid to one of the hydrotreating licensing vendors, such as UOP or Haldor Topose, for the use of their licensed hydrotreating technology and design. This royalty is approximately 2% of C_{TDC} as suggested in Section 23.2 of Product and Process Design Principles.[44]

The working capital is the funds required by a company for it to meet its obligations until payments are received from others for the products they have received. As suggested in Section 23.3 of Product and Process Design Principles,[44] the working capital includes 30 days of cash reserves and 30 days of accounts receivable. Since the triglyceride feedstock arrives at the refinery location by rail, a seven day raw material inventory is kept so that the hydrotreating process can continue in case of any transportation disruptions. The n-alkane product only has two days of inventory because the product can be directly blended into diesel products or upgraded to naptha or jet fuel onsite without transportation concerns. Nevertheless, a two day storage capacity and inventory implemented in case a refinery unit downstream is temporarily shut down. These factors contribute to the cost of working capital, which is fully recovered at the end of the plant's life. When adding the working capital, C_{WC}, to $C_{TCI,}$ the total capital investment C_{TCI} is $45,852,000.

G. OTHER IMPORTANT CONSIDERATIONS

Safety and Environmental

The hydrotreating process has many potential risks. One of the main risks is the possibility of a release of toxic gases and hydrocarbons, including H_2S, ammonia and methane into the air. H_2S and ammonia are very toxic gases that can cause severe health complications. Gas leaks may result in fires and explosion. Monitors and sensors should be used to detect and address any leaks that may occur. Another danger concerns the reactor, where the main reactions take place. Since it operates at very high temperature and pressure, special care (through uses of pressure relief valves and other safety equipment as well as proper operating procedures) must be taken to ensure that the reactor and its contents do not reach a temperature and pressure where the reactor could break down or explode.

H_2S

The presence of hydrogen sulfide is not modeled in the ASPEN PLUS simulation but is a major safety concern in the physical hydrotreating plant. It is a highly toxic and flammable gas which can affect the nervous system of the human body. The hydrogen sulfide is generally removed from the process through the amine scrubber.

Offgas

The offgas (purge gas) from the amine scrubber can be purified to recover valuable products or used as fuel gas in the Fired Heater. The purge gas exiting the amine scrubber contains products such as methane, CO, CO_2, propane, and hydrogen (>60%mole). Hydrogen is a high-value product and in some refineries it is possible to combine this purge stream with other H_2-rich streams of the refinery to recover H_2 using a membrane system. The propane is a valuable liquefied petroleum gas (LPG) product that can be used for feed for the Fired Heater, for space heating, or for use in a grill. A membrane system can also be used to recover propane from the purge stream. The purge gas can also be used as fuel for the Fired Heater; no additional separation steps are required.

The offgas from the product stripper usually contains much less H_2 (<40 %mole) and is usually used as a fuel gas (for use in furnaces). A purification process, such as a membrane separator, is generally required to remove H_2S and other particulates from the offgas before it can be used as a fuel gas.

Product Quality and Upgrading

The products produced in this hydrotreating process are n-alkanes with carbon chains of C13 to C20, which is generally within the diesel range. The product has a high cetane number (over 70), which is higher than that the cetane number of conventional diesel (40-50).[41] In addition, it has no sulfur (compared to 15ppm in conventional diesel).[7] The n-alkanes can be blended directly into the refinery diesel pool.

If the refinery sees a stronger demand or higher margins for gasoline and/or jet fuel and wants to increase its output of such products, it could convert the n-alkanes to these products through a hydrocracking/hydroisomerization (HC/HI) process. This process would require equipment similar to the hydrotreating process. In the HC/HI reactor, there are a variety of reaction pathways and mechanisms. The hydrocracking pathway cracks apart the n-alkane chain, forming shorter n-alkane chains. The isomerization pathway isomerizes the n-alkane to form branched alkane chains, which have lower freezing points. The naphtha produced in the HC/HI process can be sent to a catalytic reforming process to improve its octane value and to be used as a gasoline blending component.

H. OPERATING COSTS

Introduction

The objective of this analysis is to calculate the cost of processing lipid feedstock. This analysis is based on a 20,000 barrel per day output of n-alkanes since industrial hydrotreaters range from 20-40 kbpd production. The key component of this analysis is that the triglyceride feedstock is priced at $0.072/lb as discussed in the **Assembly of Database** section. Since it requires 7.87 lb of triglyceride feedstock to produce 1 gallon of n-alkane, the equivalent price of the TAG is $0.57 per gallon of n-alkane produced.

The n-alkane product priced as a diesel product because its properties are comparable to diesel grade specifications as mentioned in earlier sections. Since the n-alkane product from the triglyceride feedstock has high cetane value and does not contain sulfur or other impurities, it might be able to sell at a premium compared to some petroleum derived diesel products. The current selling price of diesel is $3.02/gallon, or $0.47/lb of n-alkane (based on an n-alkane density of 6.42 lb/gallon). Based on this price, the annual revenue from the hydrotreating process is $788,386,000.

Variable Costs

TABLE 21. VARIABLE COSTS OF THE HYDROTREATING PROCESS.

		Annual Cost
General Expenses		
	Selling/Transfer Expenses	$ 25,205,000
	Direct Research	$ 40,329,000
	Allocated Research	$ 4,201,000
	Administrative Expense	$ 16,804,000
	Management Incentive Compensation	$ 10,502,000
		$ 97,041,000
Feedstock (raw materials)		
	Triglyceride	$ 158,322,000
	Hydrogen	$ 65,172,000
	MEA	$ 3,000
		$ 223,497,000
Utilities		
	Low Pressure Steam	$ 388,000
	Electricity	$ 1,940,000
	Fuel Oil	$ 191,000
		$ 2,519,000
Byproducts		
	Fuel Gas	$ 510,000
	Propane	$ 30,852,000

	Hydrogen	$	31,978,000
		$	**(63,340,000)**
Total Variable Costs		**$**	**259,923,000**

The variable costs in the hydrotreating process include raw material costs, utilities, and other general expenses, as seen in **Table 21**. Raw material costs include the cost of triglyceride feedstock, hydrogen, and MEA and total $223,497,000. General expenses include selling/transfer expenses, direct research, allocated research, administrative expense, management incentive compensation, and royalties. These costs can be calculated based on Chapter 23 of <u>Product and Process Design Principles</u>[44] and equal $97,041,000 per year. Additional variable costs, such as utilities, have an annual cost of $2,519,000. The byproducts, such as propane, hydrogen, and fuel gas, generate $63,340,000 in annual revenue. The total annual variable costs are $259,923,000.

Fixed Costs

TABLE 22. FIXED COSTS OF THE HYDROTREATING PROCESS.

			Annual Cost
Operations			
	Direct Wages and Benefits	$	1,456,000
	Direct Salaries and Benefits	$	218,000
	Operating Supplies and Services	$	87,000
		$	**1,761,000**
Maintenance			
	Wages and Benefits	$	1,634,000
	Salaries and Benefits	$	409,000
	Materials and Services	$	1,634,000
	Maintenance Overhead	$	82,000
		$	**3,759,000**
Operating Overhead			
	General Plant Overhead	**$**	264,000
	Mechanical Department Services	**$**	89,000
	Employee Relations Department	**$**	219,000
	Business Services	**$**	275,000
		$	**847,000**

Property Taxes and Insurance	**$**	**726,000**
Other Annual Expenses		
NiMo Catalyst Replacement	$	488,000
		488,000
Total Fixed Costs	**$**	**7,582,000**

The annual fixed costs for the hydrotreating process are costs incurred regardless of the production rate. As seen in **Table 22**, these costs include operating costs, maintenance costs, operating overhead, property taxes and insurance, and other annual expenses. These values have been calculated based on a specified percentage of total depreciable capital (C_{TDC}) as suggested in Section 23.2 of Product and Design Principles. The operating costs are calculated with the assumption that there are four operators per shift, which is typical for a refinery unit. Maintenance costs include costs for keeping equipment in acceptable working order, engineering and supervisory personnel salaries, materials and services, and maintenance overhead. Operating Overhead includes the cost of providing services that are not directly related to the plant operation. These costs include fire protection, first aid and medical services, purchasing and receiving, warehousing, and others costs. Other fixed costs include Property Taxes and Insurance and NiMo catalyst replacement. Although the catalyst has to be replaced every two years, the annualized cost of NiMo catalyst is determined in order to include the cost of NiMo replacement in the Profitability Analysis Spreadsheet. The total annual fixed costs amount to $7,582,000.

IX. OVERALL ECONOMIC ANALYSIS

The overall profitability of an algae-to-fuel venture combining all three modules of the supply chain is evaluated using the Profitability Analysis Spreadsheet (see **Appendix VII** on page 171) and yields encouraging results. At an n-alkane selling price competitive with diesel ($3.02/gallon), with a 15% discount rate, the net present value (NPV) of the project is $289,406,000. The Return on Investment (ROI) is 13.04% and the Investor's Rate of Return (IRR) is 17.10%. **Table 25** shows the ROI analysis for the third year of production.

TABLE 25. ROI ANALYSIS FOR THIRD YEAR OF PRODUCTION.

Annual Sales	$	788,386,000
Annual Costs	$	45,421,000
Annual Variable Costs (excluding byproducts)	$	(452,187,000)
Annual Byproducts	$	631,127,000
Annual Fixed Costs	$	(117,389,000)
Depreciation	$	(220,254,000)
Income Tax	$	(245,421,000)
Net Earnings	$	368,132,000
Total Capital Investment	$	2,807,818,000
ROI		**13.04 %**

Fixed-Capital Investment

TABLE 26. FIXED CAPITAL INVESTMENT SUMMARY FOR OVERALL ALGAE-TO-FUEL VENTURE.

C_{TBM}	Total Bare Module Cost	$	2,251,207,000
C_{DPI}	Direct Permanent Investment	$	2,296,231,000
C_{TDC}	Total Depreciable Capital	$	2,502,892,000
C_{TPI}	Total Permanent Investment	$	2,753,181,000
C_{TCI}	Total Capital Investment	$	2,807,818,000

When evaluating the overall economic analysis of this algae-to-fuel venture, it is important to note that the bare-module costs of **Module I** (algae cultivation) are extremely high. At $2.2 billion (which includes land, equipment, storage, and installation for 36.6 thousand acres, at $60k per acre), the fixed cost for **Module I** is nearly 40 times that of **Modules II** ($30 million) and **III** ($28 million) combined. Bare-module costs are $2.3 billion out of the $2.8 billion needed for total capital investment. With such a high capital investment, depreciation and annual fixed costs, which are calculated as a percentage of capital investment, are nearly half of each year's revenue. In addition, IRR, a key profitability metric, measures net profits against capital investment. Although the total capital investment is $2.8 billion, in this analysis the IRR is above the 15% target because of the large volume of sales and the high value of byproducts, which offset the other variable costs.

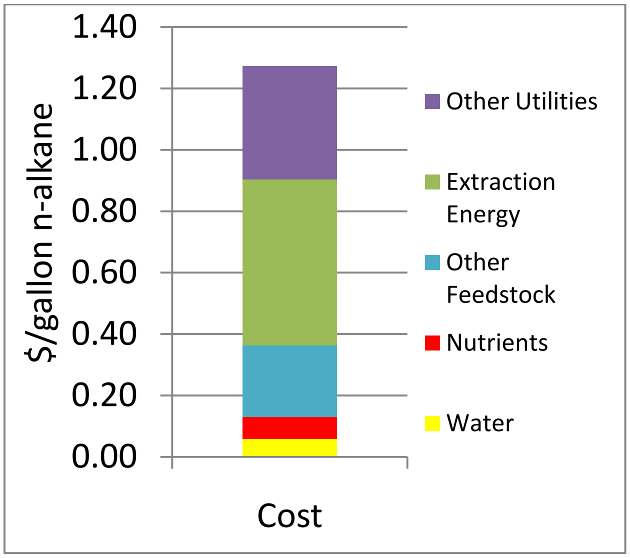
Variable Costs

TABLE 27. VARIABLE COST SUMMARY FOR OVERALL ALGAE-TO-FUEL VENTURE.

		Annual Cost
General Expenses	$	97,247,000
Feedstock (raw materials)	$	101,631,000
Utilities	$	253,309,000
Byproducts	$	(631,127,000)
Total Variable Costs	**$**	**(178,940,000)**

It is important to note that this calculated value for the total variable cost is highly variable due to the uncertainties in the raw material costs, byproduct values, and utility costs. In terms of raw materials, there is great uncertainty in the cost of the f/2 medium used as nutrients for algal growth. There is also high variability in the utility cost due to uncertainty in electricity requirements for the Simgae™ and OriginOil™ processes. **Figure 13** shows a breakdown of these feedstock and utility costs.

FIGURE 13. BREAKDOWN OF FEEDSTOCK AND UTILITY COSTS.



In this analysis, the value of the byproducts offsets the other variable costs and results in additional revenue for the process. However, it is to be seen whether the full value of these byproducts are realized. A more detailed analysis of these variable costs could lead to significantly different profitability analysis.

Fixed Costs

TABLE 28. FIXED COST SUMMARY FOR OVERALL ALGAE-TO-FUEL VENTURE.

		Annual Cost
Operations	$	1,761,000
Maintenance	$	57,567,000
Operating Overhead	$	7,515,005
Property Taxes and Insurance	$	50,057,839
Other Annual Expenses	$	488,000
Total Fixed Costs	**$**	**117,389,000**

The annual fixed costs for the entire algae-to-fuel venture are costs incurred regardless of the production rate. As seen in **Table 28**, these costs include operating costs, maintenance costs, operating overhead, property taxes and insurance, and other annual expenses.

Sensitivity Analysis

Since there is great uncertainty of the variable cost, a sensitivity analysis is performed to show how a change in the variable cost would impact the profitability of the algae-to-fuel venture.

TABLE 29. SENSITIVITY ANALYSIS OF CHANGE IN VARIABLE COSTS.

Variable Costs (million)	$ 452	$ 326	$ 200	$ 74	$ (53)	$(179)	$(305)	$(431)	$(558)	$(684)
IRR	1.88%	5.71%	8.98%	11.91%	14.60%	17.10%	19.47%	21.72%	23.89%	25.98%

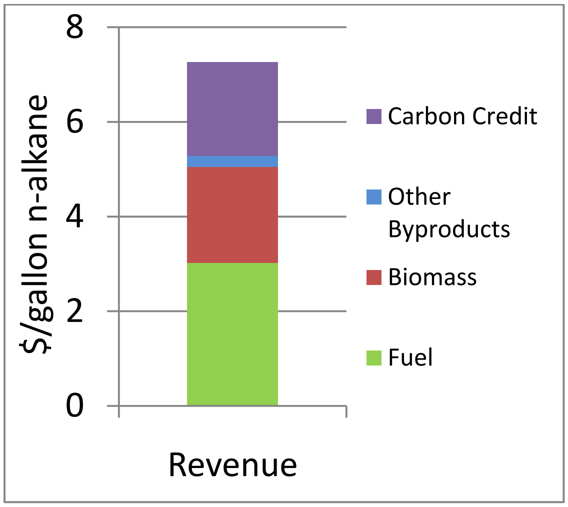
The sensitivity analysis shows that even the value of the byproducts is not included in the analysis (resulting in a variable cost of $452 million instead of -$179 million), the IRR is slightly positive.

OTHER IMPORTANT CONSIDERATIONS

Carbon Credits

In order to reduce CO_2 emissions, governments have proposed implementing a carbon cap-and-trade system where CO_2 polluters (coal plants, oil refineries, etc.) must purchase permits to emit CO_2 into the atmosphere. Over time, the number of permits would be reduced, and the price of the permits would increase. Likewise, projects that reduce CO_2 emissions would be issued a credit per ton CO_2 consumed and these credits could be sold to the CO_2 polluters in order to offset the amount of CO_2 emitted into the atmosphere. The project reduces 0.1 metric tons of carbon per gallon of n-alkane produced. Thus at the April 2010 carbon price of $20 on the Europe Climate Exchange, carbon credits add $2 of additional revenue per gallon of n-alkane. The following graph shows a breakdown of revenue per gallon of n-alkane from the various sources.

FIGURE 14. BREAKDOWN OF REVENUE FOR OVERALL ALGAE-TO-FUEL VENTURE.



Also, note the prices used in this analysis are current market prices, while the project has a long term horizon of 20 years. Long term trends in energy demand suggest that the diesel price may rise faster than the general inflation rate of 2%. The EIA's Annual Energy Outlook forecasts diesel prices to grow 2.2% annually for the next 25 years, reaching $4.11 per gallon by 2035.[50] There is also a potential of carbon credits becoming more valuable as economies grow while allowances remain fixed or reduced. A study from Yale University estimates that carbon at $30 per metric ton will lead to a 9 cent increase in gas prices.[51] Thus, increases in the price of carbon may be coupled with increases in the selling price of the n-alkane product.

Processing Costs

Contrary to what some may expect, in this analysis the lipid processing cost has a small impact on algae-to-fuel economics. The utility cost of the entire process is $0.90/gal product, a fraction of the $2.26/gal product generated from byproducts of this process (without carbon credit). As discussed earlier, fixed costs associated with **Modules II** and **III** are small as well, contributing to 2.5% of total bare-module costs. Revenues from carbon credit and byproducts are more than enough to offset the processing costs.

The marginal contribution of **Modules II** and **III** to total costs and, by extension, profitability, is reassuring. Recall this analysis did not include any costs for the Quantum Fracturing^{TM} equipment for algae extraction. However, the economic uncertainties associated with the OriginOil^{TM} technology should not jeopardize the findings of this report, since variable cost remains the most salient economic factor.

Government Subsidies and Incentives

To support the algae-to-fuels venture as a viable renewable fuel source, there are different options that governments can implement. The U.S. federal government has supported FAME biodiesel production with a $1/gallon tax credit. While the tax credit is not long term, such a subsidy for algae-derived transportation fuels would reduce the tax liability of algae-based fuel producers and support them financially.[52] However, the impact of these government tax subsidies in uncertain. Tax credits offered to biodiesel producers, first introduced in 2002, have generally been renewed every few years.[53] However, the renewal of these tax incentives is not guaranteed depending on the political climate and the tax credits might be allowed to expire by one administration before being renewed again by another. Consequently, biodiesel blenders who are depending on government subsidies face considerable investment and development challenges due to the uncertainty of the continuation of the tax credits over a long period of time.[52]

Government can also support algae-to-fuel ventures through regulation mandating that transportation fuels must contain a minimum volume of renewable fuel. First introduced in the Energy Policy Act of 2005, the current Renewable Fuel Standard specifies that 7.5 billion gallons of renewable fuel to be blended into gasoline by 2012.[54] This mandate ensures that there will be a market for renewable fuels since fuel marketers will be required to blend in various categories of renewable fuels into their retail fuel product. If the government includes algae-based fuel in the Renewable Fuel Standard, then it would be beneficial for potential algae-to-fuel ventures since they could be assured of the existence of a market for their product. However, such a benefit would be hard to quantify without more specific proposals from the government to include algae-based fuels in Renewable Fuel Standards.

X. CONCLUSIONS AND RECOMMENDATIONS

This study detailed the process of a potential algae-to-fuel venture, and examined its economic feasibility under various scenarios. While the overall economic analysis shows that the algae-to-fuel venture is profitable with a return of investment of 13.04% and an Investor's Rate of Return of 17.10%, there are many factors that could jeopardize the profitability of such a process.

When evaluating the Simgae^{TM} algal cultivation process, it is important to note the uncertainties in nutrient cost and consumption, electricity requirements, land requirements, and CO_2 injection requirements. However, the greatest obstacle for this process is the incredibly high capital requirement at $2.2 billion. Even if the profitability analysis shows a positive return on investment, it will be difficult to convince venture capitalists to invest such a large amount of money in an unproven technology.

The OriginOil^{TM} lipid extraction process claims to significantly reduce energy costs compared to conventional extraction processes. However, the company provides limited information about its technology and it is uncertain whether such energy savings will be fully realized. The capital investment requirements are based on rough estimates and assumptions due to the lack of detail and specifications provided by the company. Unless the company provides more information about the process, investors should be highly cautious about investing in this process.

The lipid extraction process is probably the least risky of the three steps of an algae-to-fuel process. While used in an innovative way to break up triglycerides, the fundamental technology behind catalytic hydrotreating is used in petroleum refineries worldwide with extensive research and development. When adapting this technology for a lipid extraction process, it is important to focus on the catalyst selection and hydrotreater design to account for a lipid feedstock instead of a crude oil feedstock. Nevertheless, this process should be promising for investors to consider investing in.

The profitability of the proposed algae-to-fuel venture depends on accurately determining costs and sources of revenues. Byproducts such as biomass (55% of algae product) could be used in pharmaceuticals, chemicals, and energy generation. These products are more valuable than livestock feed and could potentially bring in even greater value. Carbon credits from potential cap-and-trade programs could be considered as an additional source of byproduct revenue. This study shows that the sales of byproducts, under reasonable scenarios, can exceed revenue from fuel. Therefore, it is important for any algae-to-fuel venture to optimize the value of its byproducts.

In order to convince investors to support an algae-to-fuel venture, it is critical to reduce the total capital investment requirements of $2.8 billion. With great uncertainty in various costs, venture capitalists would be hesitant to invest so much money in a risky venture. Therefore, additional analysis should be focused on accurately determining these costs and minimizing them. With such a high algae cultivation cost, it would be wise to evaluate other algae cultivation processes as well. In particular, NASA's proposed OMEGA system provides a possible solution to the high capital costs by coupling wastewater treatment with non-terrestrial farms, eliminating land purchase costs. Concepts in this direction are worthy of further exploration.

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APPENDIX

I. Problem Statement

Suggested Design Projects – 2009-2010

1. Algae to Alkanes
(recommended by John Wismer, Arkema, Inc.)

Of all the embryonic biofuel technologies, the ones involving cultivating, harvesting, and processing hydrocarbons from algae are drawing the most research attention. The NREL lists over thirty companies targeting this area. Some (such as OriginOil) are publicly traded. Most are still in the venture capital stage. In addition, some of the major oil companies (Shell, Chevron, Exxon) have already announced strategic partnerships. The advantages of algae are numerous: 1) its cultivation does not encroach on the food sector, 2) its biomass productivity per acre far exceeds that of any agricultural commodity, 3) it produces lipids that can be converted easily to biodiesel or fuel range hydrocarbons.

The conversion of algae to useful biofuels can be thought of as occurring in three process modules: 1) algae cultivation, 2) lipid extraction, and 3) lipid conversion. For all three modules, there are a variety of different approaches with widely varying claims as to cost effectiveness. Your client is a venture capital firm that invests in alternative energy and has hired Penn Consultants to evaluate the long term potential for biofuels from algae. Your client has been burned in the past by biofuel ventures and is well aware of the problems of negative energy balances, and water and land use issues that have bedeviled this industry. NASA has expressed skepticism that terrestrially cultivated algae could become cost competitive due the high energy requirements of processing[12]. Your client wants to know if, under a reasonable best case scenario, a large-scale algae-to-fuel venture would be profitable. In this sense, you are free to pick and choose the best available technology for the three steps of the supply chain.

There are three competing approaches to the first module. The first involves cultivation in open-air "raceway" ponds, but they have been hampered by contamination and low growth rates. Another is a compact photo-bioreactor with complex internals designed to optimize the growth environment. The third is a hybrid approach – one that utilizes agricultural resources and infrastructure, yet cultivates the algae in enclosed tubes. The reactor design is potentially quite complex. It requires accounting for carbon dioxide concentration, light exposure, and mass transfer from gas to liquid. Furthermore, nitrogen starvation is sometimes intentionally used to maximize lipid production at the expense of the protein fraction. Rather than tackle the details of this design, you can use References 1-3 to develop a basic material and energy balance and assume the productivities are as given. Site selection will be important since a carbon dioxide source, water access, and adequate sunlight are all design considerations.

For the second module, the key is extracting the desirable triglyceride fraction way from the proteins, carbohydrates, phospholipids, and nucleic acids that make up the rest of the biomass. As a chemical extraction agent, hexane seems to be the solvent of choice. Alternatively, OriginOil claims that algae cell lysis and lipid removal can be induced by combinations of pH modification, microwaves, and ultrasonic pulses[4,5]. Their technology apparently disrupts the cell wall enough to allow most of the lipids to escape. Their patent application has not been published yet. However, the process is illustrated on their website and appears to show a lipid fraction rising to the surface of an aqueous layer while the protein laden residue sinks to the bottom[6]. OriginOil is claiming dramatic reductions in the cost of lipid extraction. You can use a "black box" approach on the process – a material balance based on a lipid-rich algae strain.

The conversion of the lipid fraction to useful products has a number of options. One approach is to convert it to biodiesel[8]. The disadvantage of this is its low energy content and high viscosity relative to straight hydrocarbon diesel. Another approach chemically processes the lipids to alkanes that could be used in fuels ranging from gasoline to jet fuels[7]. These are relatively high-value products with broad acceptance in a variety of markets. Your client is particularly interested in the potential for this technology. This process module involves conventional chemical processing and should be done in sufficient detail to allow for an evaluation of lipids processing economics irrespective of the cost of the feedstock.

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Algae Cultivation

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Lipid Isolation

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II. Module I Calculations

Cost and Make Up of the Nutrients

Trace Metal Solution	Amt. per L Water	Stock Concentration	Purchase Price	COST
$FeCl_3.6H_2O$	1.3 g		0.106 $/g	$0.137
$Na_2EDTA.2H_2O$	8.7 g		0.104 $/g	$0.906
$CuSO_4.5H_2O$	1 ml	9.8 mg /ml dH_20	0.098 $/g	$0.001
$Na_2MoO_4.2H_2O$	1 ml	6.3 mg /ml dH_20	0.200 $/g	$0.001
$ZnSO_4.7H_2O$	1 ml	0.022 g /ml dH_20	0.070 $/g	$0.002
$CoCl_2.6H_2O$	1 ml	0.01 g /ml dH_20	0.464 $/g	$0.005
$MnCl_2.4H_2O$	1 ml	0.18 g /ml dH_20	0.118 $/g	$0.021
				1.0730 $/L

Vitamin Solution	Amt. per L Water	Stock Concentration	Purchase Price	COST
Vitamin B12	1 ml	1 mg /ml dH_2O	40.20 $/g	$0.040
Biotin	1 ml	1 mg /ml dH_2O	35.96 $/g	$0.036
Thiamine HCl	200 mg		0.307 $/g	$0.061
				0.1376 $/L

Material	Amt. per L of Sea Water	Stock Concentration	Purchase Price	COST
$NaNO_3$	1 ml	75 g/L dH_2O	0.056 $/g	$0.004
$NaH_2PO_4.H_2O$	1 ml	5 g/L dH_2O	0.122 $/g	$0.001
$Na_2SiO_3.9H_2O$	1 ml	30 g/L dH_2O	0.130 $/g	$0.004
F/2 Trace Metal Solution	1 ml		0.001 $/mL	$0.001
F/2 Vitamin Solution	0.5 ml		0.00006 $/mL	$0.00007
			TOTAL COST	0.0098 $/L

Determination of Algae Composition

FIRST ALGAE COMPOSITION[55]

	C	O	H	N	P	SUM
mol	1	0.48	1.83	0.11	0.01	
MW (g/mol)	12.01	16.00	1.01	14.01	30.97	
Total g	12.01	7.68	1.84	1.54	0.31	23.39
wt. %	0.51	0.33	0.08	0.07	0.01	1

SECOND ALGAE COMPOSITION[56]

	C	O	H	N	P	SUM
mol	106	45	181	15	1	
MW (g/mol)	12.01	16	1.01	14.01	30.97	
Total g	1273	720	182	210	31	2417
wt %	0.53	0.30	0.08	0.09	0.01	1

Algae are approximately .50 wt Carbon. Algae take about 93% of its carbon from carbon dioxide. These values were used to calculate the amount of required CO_2 to produce an amount of algae. It was assumed that algae take all of their CO_2 from carbon dioxide.

Calculation of CO_2 Enriched Air

The following values detail the flue gas flow coming from the W.A. Parish Electric Generating Station located in Thompsons, TX.

FLUE GAS FLOW RATE **FLUE GAS COMPOSITION**[31]

Component	Mass Flow (lb/s)	Component	wt
CO_2	0.57	CO_2	0.32
H_2O	0.11	H_2O	0.06
O_2	0.06	O_2	0.03
N_2	1.04	N_2	0.58
SO_2	0.01	SO_2	0.01
NO_X	0.01	NO_X	0.01
Hg	Trace	Hg	Trace
Flue Gas Flow Rate	1.8	SUM	1

The following table details the composition of dry air.

AIR FLOW RATE **AIR COMPOSITION**

Component	Mass Flow (lb/s)	Component	Wt
N_2	5.43	N_2	0.75
O_2	1.67	O_2	0.23
Ar	0.09	Ar	0.01
CO_2	Trace	CO_2	Trace
Air Flow Rate	7.20	SUM	1

Mixing the flue gas with dry air using the total flue gas and air flow rates from above

COMBINED INCOMING FLOW STREAM **CO_2 ENRICHED AIR COMPOSITION**

Component	Mass Flow (lb/s)		Wt
CO_2	0.57	CO_2	0.06
H_2O	0.11	H_2O	0.01
O_2	1.73	O_2	0.19
N_2	6.47	N_2	0.72
SO_2	0.01	SO_2	Trace
NO_X	0.01	NO_X	Trace
Hg	Trace	Hg	Trace
Ar	0.09	Ar	0.01
CO_2 Enriched Air Flow	9.00	SUM	1

Production Conversions

Conversion of Assumed Production Rate

The following values are conversions of the production rate used to model our algae species. Assuming *Nannochloropsis sp.* have a water content of 0.8 wt, a lipid content of 0.46 dry wt., and 0.8 wt of lipid being TAG:

$$\frac{100\ dry\ tons\ alge}{acre \cdot yr} \cdot \frac{907kg}{ton} \cdot \frac{0.46\ kg\ lipid}{kg\ algae} \cdot \frac{0.8\ kg\ TAG}{kg\ lipid} = 33377.6\frac{kg\ TAG}{acre \cdot yr}$$

Assuming the TAG within *Nannochloropsis sp.* have a density of 922.3 kg TAG/m^3, a value taken from

$$\frac{33377.6kg\ TAG}{acre \cdot yr} \cdot \frac{m^3}{922.3\ kg\ TAG} \cdot \frac{264.17\ gallons}{m^3} = 9560.19\ \frac{gallons\ TAG}{acre \cdot yr}$$

Conversion of Compared Production Rate

The following values are conversions of the compared production rates, taken from various sources.

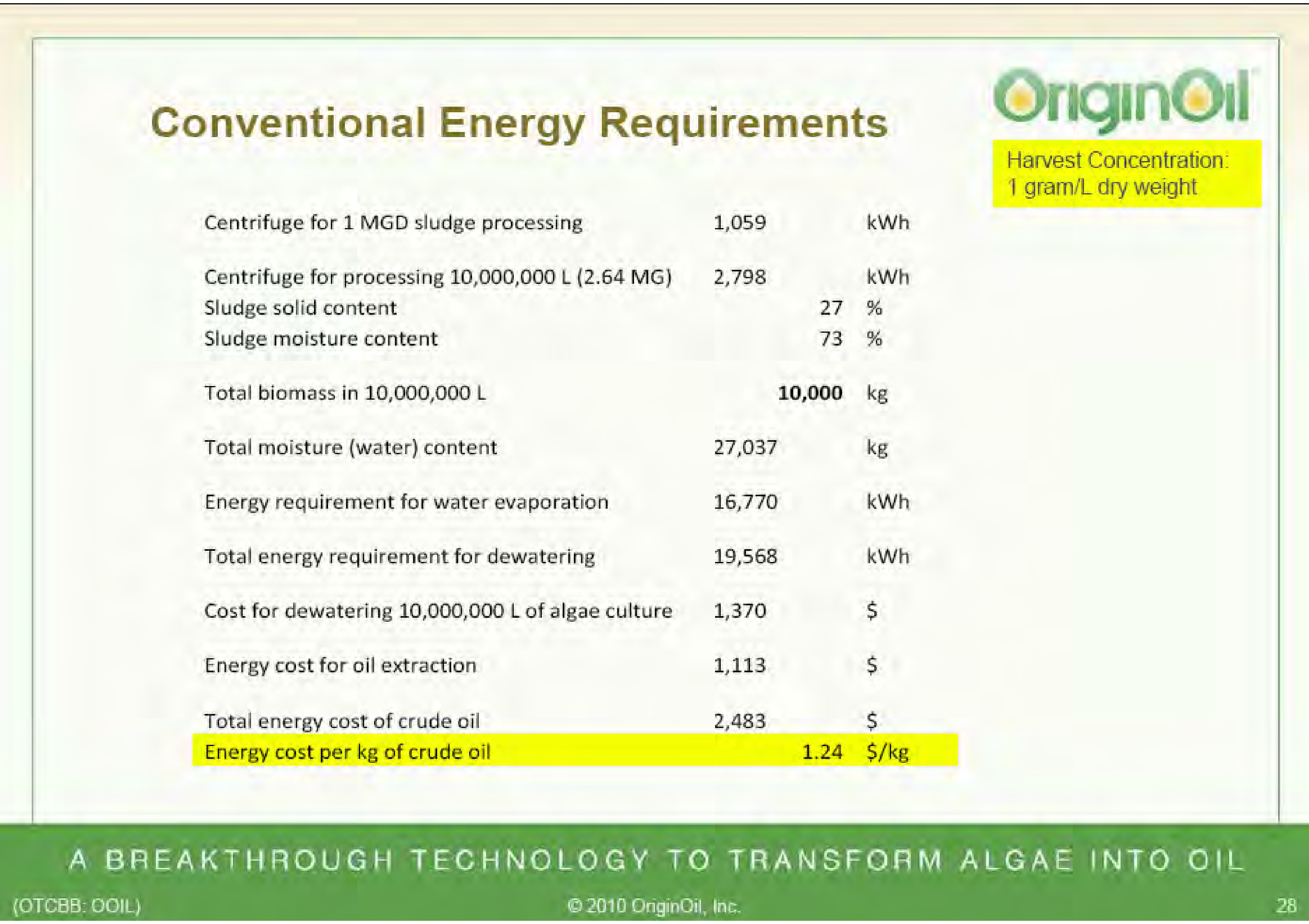
A value of 50 g algae/m^2*day taken from studies done by the National Renewable Energy Laboratory and US Department of Energy. This value is interpreted as a dry weight:

$$\frac{.050\ kg}{m^2 \cdot day} \cdot \frac{0.46\ kg\ lipid}{kg\ algae} \cdot \frac{0.8\ kg\ TAG}{kg\ lipid} \cdot \frac{4046.86\ m^2}{acre} \cdot \frac{365\ day}{yr} = 27178.7\frac{kg\ TAG}{acre \cdot yr}$$

A value of 2000 g lipid/acre*year taken from a NASA article in which algae energy is explored.

$$\frac{10000\ gallons\ lipid}{acre \cdot yr} \cdot \frac{0.8\ gallon\ TAG}{gallon\ lipid} = 8000\frac{gallons\ TAG}{acre \cdot yr}$$

III. Module II: Conventional Energy Requirements



Conventional Energy Requirements

OriginOil

Harvest Concentration:
1 gram/L dry weight

Centrifuge for 1 MGD sludge processing	1,059	kWh
Centrifuge for processing 10,000,000 L (2.64 MG)	2,798	kWh
Sludge solid content	27	%
Sludge moisture content	73	%
Total biomass in 10,000,000 L	**10,000**	kg
Total moisture (water) content	27,037	kg
Energy requirement for water evaporation	16,770	kWh
Total energy requirement for dewatering	19,568	kWh
Cost for dewatering 10,000,000 L of algae culture	1,370	$
Energy cost for oil extraction	1,113	$
Total energy cost of crude oil	2,483	$
Energy cost per kg of crude oil	1.24	$/kg

A BREAKTHROUGH TECHNOLOGY TO TRANSFORM ALGAE INTO OIL

(OTCBB: OOIL)

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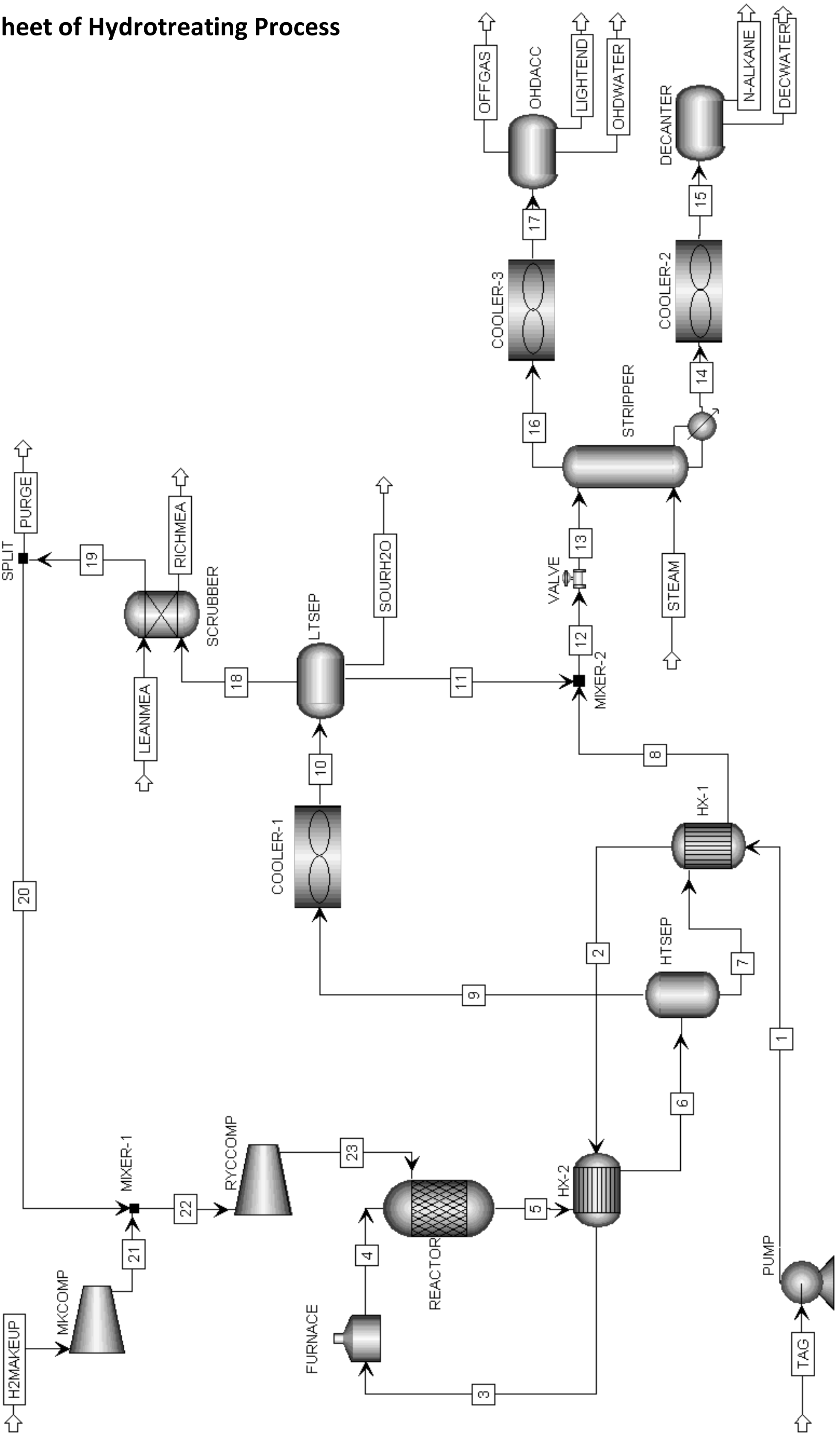
IV. ASPEN PLUS Simulation

ASPEN Flowsheet of Hydrotreating Process



ASPEN Simluation Results

```
BLOCK:  COOLER-1 MODEL: HEATER
------------------------------
  INLET STREAM:          9
  OUTLET STREAM:         10
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            13901.2         13901.2         0.00000
      MASS(LB/HR   )            149252.         149252.        0.194999E-15
      ENTHALPY(BTU/HR  )      -0.243575E+09   -0.314868E+09    0.226421

                         ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE              F                          68.0000
  SPECIFIED PRESSURE                 PSIA                      667.174
  MAXIMUM NO. ITERATIONS                                        30
  CONVERGENCE TOLERANCE                                          0.000100000



                          ***  RESULTS  ***
  OUTLET TEMPERATURE    F                                    68.000
  OUTLET PRESSURE       PSIA                                 667.17
  HEAT DUTY             BTU/HR                             -0.71293E+08
  OUTLET VAPOR FRACTION                                      0.91684
  PRESSURE-DROP CORRELATION PARAMETER                        4368.1


  V-L PHASE EQUILIBRIUM :

     COMP              F(I)           X(I)           Y(I)           K(I)
     C13ALKAN        0.74127E-03    0.23153E-16    0.80851E-03    0.34920E+14
     C14ALKAN        0.30147E-03    0.79672E-17    0.32881E-03    0.41270E+14
     C15ALKAN        0.25961E-02    0.58818E-16    0.28315E-02    0.48140E+14
     C16ALKAN        0.10269E-02    0.19827E-16    0.11200E-02    0.56489E+14
     C17ALKAN        0.26161E-03    0.44179E-17    0.28533E-03    0.64585E+14
     C18ALKAN        0.10310E-03    0.14784E-17    0.11245E-03    0.76060E+14
     C19ALKAN        0.43182E-03    0.52757E-17    0.47099E-03    0.89274E+14
     C20ALKAN        0.16241E-03    0.17143E-17    0.17714E-03    0.10333E+15
     H2              0.70035        0.26764E-05    0.76387        0.28541E+06
     CO              0.24532E-01    0.42195E-07    0.26757E-01    0.63413E+06
     CO2             0.22321E-01    0.17690E-04    0.24344E-01     1376.2
     WATER           0.83593E-01    0.99998        0.47578E-03    0.47579E-03
     CH4             0.81824E-01    0.17458E-05    0.89245E-01     51121.
     PROPANE         0.81756E-01    0.16958E-06    0.89172E-01    0.52584E+06
BLOCK:  COOLER-2 MODEL: HEATER
------------------------------
  INLET STREAM:          14
  OUTLET STREAM:         15
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            1237.43         1237.43         0.00000
      MASS(LB/HR   )            231126.         231126.         0.00000
      ENTHALPY(BTU/HR  )      -0.210890E+09   -0.226018E+09    0.669294E-01
```

```
                    ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE             F                        77.0000
  SPECIFIED PRESSURE                PSIA                     29.0075
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                       0.000100000


                     ***  RESULTS  ***
  OUTLET TEMPERATURE    F                                  77.000
  OUTLET PRESSURE       PSIA                               29.008
  HEAT DUTY             BTU/HR                            -0.15127E+08
  OUTLET VAPOR FRACTION                                     0.0000
  PRESSURE-DROP CORRELATION PARAMETER                       0.0000


  V-L PHASE EQUILIBRIUM :

     COMP              F(I)           X(I)           Y(I)           K(I)
     C13ALKAN        0.34628E-01    0.34628E-01    0.70924E-05    0.37925E-04
     C14ALKAN        0.19505E-01    0.19505E-01    0.14529E-05    0.13793E-04
     C15ALKAN        0.23688        0.23688        0.58057E-05    0.45383E-05
     C16ALKAN        0.13328        0.13328        0.11801E-05    0.16395E-05
     C17ALKAN        0.49867E-01    0.49867E-01    0.13019E-06    0.48342E-06
     C18ALKAN        0.28052E-01    0.28052E-01    0.25644E-07    0.16928E-06
     C19ALKAN        0.17011        0.17011        0.53156E-07    0.57862E-07
     C20ALKAN        0.95688E-01    0.95688E-01    0.85811E-08    0.16606E-07
     WATER           0.23198        0.23198        0.99998        0.79819
BLOCK:  COOLER-3 MODEL: HEATER
------------------------------
  INLET STREAM:          16
  OUTLET STREAM:         17
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                                IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)          1103.33         1103.33        0.00000
      MASS(LB/HR   )          22043.4         22043.4        0.00000
      ENTHALPY(BTU/HR  )    -0.100664E+09   -0.120155E+09    0.162217

                    ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE             F                        77.0000
  SPECIFIED PRESSURE                PSIA                     29.0075
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                       0.000100000


                     ***  RESULTS  ***
  OUTLET TEMPERATURE    F                                  77.000
  OUTLET PRESSURE       PSIA                               29.008
  HEAT DUTY             BTU/HR                            -0.19491E+08
  OUTLET VAPOR FRACTION                                    0.17786
  PRESSURE-DROP CORRELATION PARAMETER                       0.0000


  V-L PHASE EQUILIBRIUM :
```

```
          COMP              F(I)          X(I)          Y(I)          K(I)
          C13ALKAN       0.96690E-04   0.27530E-16   0.54364E-03   0.19747E+14
          C14ALKAN       0.25605E-04   0.64329E-17   0.14397E-03   0.22379E+14
          C15ALKAN       0.13972E-03   0.31482E-16   0.78555E-03   0.24953E+14
          C16ALKAN       0.37225E-04   0.74545E-17   0.20930E-03   0.28077E+14
          C17ALKAN       0.58870E-05   0.10823E-17   0.33099E-04   0.30582E+14
          C18ALKAN       0.15622E-05   0.25463E-18   0.87832E-05   0.34494E+14
          C19ALKAN       0.43916E-05   0.63727E-18   0.24692E-04   0.38746E+14
          C20ALKAN       0.10315E-05   0.13592E-18   0.57996E-05   0.42668E+14
          H2             0.51230E-01   0.53645E-07   0.28804       0.53694E+07
          CO             0.28141E-02   0.14538E-08   0.15822E-01   0.10883E+08
          CO2            0.87660E-02   0.19535E-05   0.49278E-01    25225.
          WATER          0.82423        1.0000       0.11719E-01   0.11719E-01
          CH4            0.16731E-01   0.10759E-06   0.94067E-01   0.87428E+06
          PROPANE        0.95922E-01   0.80010E-07   0.53932       0.67406E+07

     BLOCK:  DECANTER MODEL: DECANTER
     --------------------------------
        INLET STREAM:          15
        FIRST LIQUID OUTLET:   N-ALKANE
        SECOND LIQUID OUTLET:  DECWATER
        PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                          ***  MASS AND ENERGY BALANCE  ***
                                       IN              OUT        RELATIVE DIFF.
         TOTAL BALANCE
            MOLE(LBMOL/HR)           1237.43         1237.43         0.00000
            MASS(LB/HR   )           231126.         231126.       -0.872805E-07
            ENTHALPY(BTU/HR  )      -0.226018E+09   -0.228790E+09    0.121165E-01

                              ***  INPUT DATA  ***

        LIQUID-LIQUID SPLIT, TP SPECIFICATION
        SPECIFIED TEMPERATURE            F                           77.0000
        SPECIFIED PRESSURE               PSIA                      29.0075
        CONVERGENCE TOLERANCE ON EQUILIBRIUM                       0.10000E-03
        MAXIMUM NO ITERATIONS ON EQUILIBRIUM                       30
        EQUILIBRIUM METHOD                              EQUATION-SOLVING
        KLL COEFFICIENTS FROM                          OPTION SET OR EOS
        KLL BASIS                                                   MOLE
        KEY COMPONENT(S):        WATER

                              ***  RESULTS  ***

        OUTLET TEMPERATURE       F                                 77.000
        OUTLET PRESSURE          PSIA                              29.008
        CALCULATED HEAT DUTY     BTU/HR                          -0.27721E+07
        MOLAR RATIO 1ST LIQUID / TOTAL LIQUID                     0.77856

        L1-L2 PHASE EQUILIBRIUM :
          COMP         F             X1            X2            K
          C13ALKAN   0.034628      0.044478      0.800157-19   0.179902-17
          C14ALKAN   0.019505      0.025053      0.142241-19   0.567772-18
          C15ALKAN   0.23688       0.30426       0.503821-19   0.165589-18
          C16ALKAN   0.13328       0.17119       0.896615-20   0.523742-19
          C17ALKAN   0.049867      0.064051      0.903453-21   0.141053-19
          C18ALKAN   0.028052      0.036031      0.360306-21   0.100000-19
          C19ALKAN   0.17011       0.21849       0.218495-20   0.100000-19
          C20ALKAN   0.095688      0.12290       0.122905-20   0.100000-19
          WATER      0.23198       0.013536      1.00000       73.8763

     BLOCK:  FURNACE  MODEL: HEATER
```

```
------------------------------
  INLET STREAM:          3
  OUTLET STREAM:         4
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            1272.07         1272.07         0.00000
      MASS(LB/HR   )            277237.         277237.         0.00000
      ENTHALPY(BTU/HR  )      -0.278203E+09   -0.268937E+09   -0.333059E-01

                         ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE                  F                        662.000
  SPECIFIED PRESSURE                     PSIA                     754.196
  MAXIMUM NO. ITERATIONS                                           30
  CONVERGENCE TOLERANCE                                             0.000100000



                          ***  RESULTS  ***
  OUTLET TEMPERATURE    F                                       662.00
  OUTLET PRESSURE       PSIA                                    754.20
  HEAT DUTY             BTU/HR                                 0.92658E+07
  OUTLET VAPOR FRACTION                                         0.0000
  PRESSURE-DROP CORRELATION PARAMETER                          0.13809E+06



  V-L PHASE EQUILIBRIUM :

     COMP              F(I)           X(I)           Y(I)           K(I)
     C14FFA           0.52767E-01    0.52767E-01    0.90583E-02    0.12996
     C16FFA           0.36024        0.36024        0.44654E-01    0.93838E-01
     C18FFA           0.75803E-01    0.75803E-01    0.69363E-02    0.69271E-01
     C20FFA           0.25856        0.25856        0.17678E-01    0.51759E-01
     PROPANE          0.25262        0.25262        0.92167         2.7620

BLOCK:  HTSEP    MODEL: FLASH2
------------------------------
  INLET STREAM:          6
  OUTLET VAPOR STREAM:   9
  OUTLET LIQUID STREAM:  7
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            14981.7         14981.7       -0.151048E-06
      MASS(LB/HR   )            362444.         362444.       -0.382316E-06
      ENTHALPY(BTU/HR  )      -0.361693E+09   -0.389131E+09    0.705101E-01

                         ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE F                                   437.000
  SPECIFIED PRESSURE    PSIA                                681.677
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                       0.000100000

                          ***  RESULTS  ***
  OUTLET TEMPERATURE    F                                       437.00
  OUTLET PRESSURE       PSIA                                    681.68
```

```
  HEAT DUTY             BTU/HR                             -0.27437E+08
  VAPOR FRACTION                                            0.92788


  V-L PHASE EQUILIBRIUM :

     COMP             F(I)          X(I)          Y(I)          K(I)
     C13ALKAN       0.28674E-02   0.30221E-01   0.74127E-03   0.24528E-01
     C14ALKAN       0.16129E-02   0.18485E-01   0.30147E-03   0.16309E-01
     C15ALKAN       0.19576E-01   0.23803       0.25961E-02   0.10907E-01
     C16ALKAN       0.11011E-01   0.13947       0.10269E-02   0.73630E-02
     C17ALKAN       0.41192E-02   0.53749E-01   0.26161E-03   0.48671E-02
     C18ALKAN       0.23171E-02   0.30801E-01   0.10310E-03   0.33472E-02
     C19ALKAN       0.14051E-01   0.18926       0.43182E-03   0.22816E-02
     C20ALKAN       0.79035E-02   0.10750       0.16241E-03   0.15108E-02
     H2             0.65336       0.48895E-01   0.70035        14.324
     CO             0.22945E-01   0.25264E-02   0.24532E-01    9.7100
     CO2            0.21126E-01   0.57461E-02   0.22321E-01    3.8846
     WATER          0.83187E-01   0.77961E-01   0.83593E-01    1.0722
     CH4            0.76927E-01   0.13931E-01   0.81824E-01    5.8737
     PROPANE        0.78992E-01   0.43430E-01   0.81756E-01    1.8825

BLOCK:  HX-1     MODEL: HEATX
-----------------------------
  HOT SIDE:
  ---------
  INLET STREAM:           7
  OUTLET STREAM:          8
  PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE
  COLD SIDE:
  ----------
  INLET STREAM:           1
  OUTLET STREAM:          2
  PROPERTY OPTION SET:    RK-SOAVE  STANDARD RKS EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                 IN               OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)           2352.58         2352.58         0.00000
      MASS(LB/HR   )           490429.         490429.         0.00000
      ENTHALPY(BTU/HR  )      -0.515372E+09   -0.515372E+09    0.115654E-15

                        ***  INPUT DATA  ***

  FLASH SPECS FOR HOT SIDE:
  TWO    PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                   30
  CONVERGENCE TOLERANCE                                     0.000100000

  FLASH SPECS FOR COLD SIDE:
  TWO    PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                   30
  CONVERGENCE TOLERANCE                                     0.000100000

  FLOW DIRECTION AND SPECIFICATION:
    COUNTERCURRENT   HEAT EXCHANGER
    SPECIFIED COLD TEMP CHANGE
    SPECIFIED VALUE               F                       225.0000
    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:
                  --------------------------------------
                  |                                    |
  7         ----->|                HOT                 |-----> 8
  T=  4.3700D+02  |                                    |       T=  1.8677D+02
  P=  6.8168D+02  |                                    |       P=  6.8168D+02
  V=  0.0000D+00  |                                    |       V=  1.7637D-02
                  |                                    |
  2         <-----|                COLD                |<----- 1
  T=  3.0333D+02  |                                    |       T=  7.8327D+01
  P=  7.9771D+02  |                                    |       P=  7.9771D+02
  V=  0.0000D+00  |                                    |       V=  0.0000D+00
                  --------------------------------------

  DUTY AND AREA:
    CALCULATED HEAT DUTY           BTU/HR            33721285.1721
    CALCULATED (REQUIRED) AREA     SQFT                  1867.5825
    ACTUAL EXCHANGER AREA          SQFT                  1867.5825
    PER CENT OVER-DESIGN                                    0.0000

  HEAT TRANSFER COEFFICIENT:
    AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R          149.6937
    UA (DIRTY)                     BTU/HR-R             279565.2586

  LOG-MEAN TEMPERATURE DIFFERENCE:
    LMTD CORRECTION FACTOR                                  1.0000
    LMTD (CORRECTED)               F                      120.6204
    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
        -------------------------------------------------------------
        |                                                           |
7       |                           COND                            | 8
------> |                                                           |------>
 437.0  |                                                           |  186.8
        |                                                           |
```

```
2       |                           LIQ                               | 1
<------ |                                                             |<------
 303.3  |                                                             |   78.3
        |                                                             |
        ---------------------------------------------------------------
                                    COLD

  ZONE HEAT TRANSFER AND AREA:

  ZONE       HEAT DUTY       AREA       DTLM       AVERAGE U       UA
             BTU/HR          SQFT        F         BTU/HR-SQFT-R   BTU/HR-R
    1   33721285.172      1867.5825     120.6204   149.6937      279565.2586

BLOCK:  HX-2     MODEL: HEATX
-----------------------------
  HOT SIDE:
  ---------
  INLET STREAM:          5
  OUTLET STREAM:         6
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
  COLD SIDE:
  ----------
  INLET STREAM:          2
  OUTLET STREAM:         3
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            16253.8         16253.8         0.00000
      MASS(LB/HR   )            639681.         639681.         0.00000
      ENTHALPY(BTU/HR  )      -0.639896E+09   -0.639896E+09    0.220740E-09

                         ***  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 COLD OUTLET TEMP
    SPECIFIED VALUE                F                      617.0000
    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:
                  ---------------------------------------
                  |                                     |
  5         ----->|                HOT                  |-----> 6
  T=  6.6200D+02  |                                     |       T=  5.1900D+02
  P=  7.2519D+02  |                                     |       P=  7.2519D+02
  V=  1.0000D+00  |                                     |       V=  9.3995D-01
                  |                                     |
  3         <-----|                COLD                 |<----- 2
  T=  6.1700D+02  |                                     |       T=  3.0333D+02
  P=  7.9771D+02  |                                     |       P=  7.9771D+02
  V=  0.0000D+00  |                                     |       V=  0.0000D+00
                  ---------------------------------------

  DUTY AND AREA:
    CALCULATED HEAT DUTY           BTU/HR            57893017.2738
    CALCULATED (REQUIRED) AREA     SQFT                  3579.1225
    ACTUAL EXCHANGER AREA          SQFT                  3579.1225
    PER CENT OVER-DESIGN                                    0.0000

  HEAT TRANSFER COEFFICIENT:
    AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R          149.6937
    UA (DIRTY)                     BTU/HR-R            535771.9275

  LOG-MEAN TEMPERATURE DIFFERENCE:
    LMTD CORRECTION FACTOR                                  1.0000
    LMTD (CORRECTED)               F                      108.0553
    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
        -------------------------------------------------------------
        |                             |                             |
5       |             VAP             |             COND            | 6
------> |                             |                             |------>
 662.0  |                        659.6|                             |  519.0
        |                             |                             |
3       |             LIQ             |             LIQ             | 2
<------ |                             |                             |<------
 617.0  |                        613.5|                             |  303.3
        |                             |                             |
        -------------------------------------------------------------
                                    COLD

  ZONE HEAT TRANSFER AND AREA:

  ZONE       HEAT DUTY       AREA       DTLM       AVERAGE U       UA
```

```
             BTU/HR          SQFT        F          BTU/HR-SQFT-R   BTU/HR-R
    1     704497.836       103.3166      45.5519   149.6937       15465.8418
    2   57188519.438      3475.8058     109.9132   149.6937      520306.0857

BLOCK:  LTSEP    MODEL: FLASH2
------------------------------
  INLET STREAM:          10
  OUTLET VAPOR STREAM:   18
  OUTLET LIQUID STREAM:  11
  OUTLET WATER STREAM:   SOURH2O
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
  FREE WATER OPTION SET: SYSOP12   ASME STEAM TABLE
  SOLUBLE WATER OPTION:  THE MAIN PROPERTY OPTION SET (RK-SOAVE).

                     ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            13901.2         13901.2       -0.130851E-15
      MASS(LB/HR   )            149252.         149251.        0.277395E-06
      ENTHALPY(BTU/HR  )      -0.314868E+09   -0.315823E+09    0.302552E-02

                         ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  FREE WATER CONSIDERED
  SPECIFIED TEMPERATURE F                                   68.0000
  SPECIFIED PRESSURE    PSIA                               652.670
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                      0.000100000

                          ***  RESULTS  ***
  OUTLET TEMPERATURE    F                                     68.000
  OUTLET PRESSURE       PSIA                                  652.67
  HEAT DUTY             BTU/HR                              -0.95553E+06
  VAPOR FRACTION                                             0.90628
  1ST LIQUID/TOTAL LIQUID                                    0.11520

  V-L1-L2 PHASE EQUILIBRIUM :

     COMP          F(I)      X1(I)     X2(I)     Y(I)      K1(I)     K2(I)
     C13ALKAN      0.741E-03 0.686E-01  0.00     0.176E-06 0.257E-05
     C14ALKAN      0.301E-03 0.279E-01  0.00     0.268E-07 0.959E-06
     C15ALKAN      0.260E-02 0.240      0.00     0.779E-07 0.324E-06
     C16ALKAN      0.103E-02 0.951E-01  0.00     0.114E-07 0.120E-06
     C17ALKAN      0.262E-03 0.242E-01  0.00     0.881E-09 0.364E-07
     C18ALKAN      0.103E-03 0.955E-02  0.00     0.125E-09 0.130E-07
     C19ALKAN      0.432E-03 0.400E-01  0.00     0.183E-09 0.457E-08
     C20ALKAN      0.162E-03 0.150E-01  0.00     0.203E-10 0.135E-08
     H2            0.700     0.246E-01  0.00     0.772      31.4
     CO            0.245E-01 0.250E-02  0.00     0.270E-01  10.8
     CO2           0.223E-01 0.231E-01  0.00     0.244E-01  1.06
     WATER         0.836E-01 0.136E-01  1.00     0.579E-03 0.425E-01 0.579E-03
     CH4           0.818E-01 0.227E-01  0.00     0.900E-01  3.97
     PROPANE       0.818E-01 0.393      0.00     0.855E-01 0.218

BLOCK:  MKCOMP   MODEL: COMPR
-----------------------------
  INLET STREAM:          H2MAKEUP
  OUTLET STREAM:         21
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
```

```
      MOLE(LBMOL/HR)            4082.00         4082.00         0.00000
      MASS(LB/HR   )            8228.81         8228.81         0.00000
      ENTHALPY(BTU/HR  )        39820.0        0.564916E+07   -0.992951

                          ***  INPUT DATA  ***

  ISENTROPIC CENTRIFUGAL COMPRESSOR
   OUTLET PRESSURE  PSIA                                  652.670
   ISENTROPIC EFFICIENCY                                    0.72000
   MECHANICAL EFFICIENCY                                    1.00000

                          ***  RESULTS  ***

   INDICATED  HORSEPOWER REQUIREMENT  HP                2,204.55
   BRAKE      HORSEPOWER REQUIREMENT  HP                2,204.55
   NET WORK REQUIRED                  HP                2,204.55
   POWER LOSSES                       HP                    0.0
   ISENTROPIC HORSEPOWER REQUIREMENT  HP                1,587.28
   CALCULATED OUTLET TEMP  F                              272.272
   ISENTROPIC TEMPERATURE  F                              217.280
   EFFICIENCY (POLYTR/ISENTR) USED                          0.72000
   OUTLET VAPOR FRACTION                                    1.00000
   HEAD DEVELOPED,       FT-LBF/LB                    381,928.
   MECHANICAL EFFICIENCY USED                               1.00000
   INLET HEAT CAPACITY RATIO                                1.40780
   INLET VOLUMETRIC FLOW RATE , CUFT/HR                82,015.4
   OUTLET VOLUMETRIC FLOW RATE, CUFT/HR                50,129.3
   INLET  COMPRESSIBILITY FACTOR                            1.01197
   OUTLET COMPRESSIBILITY FACTOR                            1.02042
   AV. ISENT. VOL. EXPONENT                                 1.42563
   AV. ISENT. TEMP EXPONENT                                 1.40126
   AV. ACTUAL VOL. EXPONENT                                 1.64723
   AV. ACTUAL TEMP EXPONENT                                 1.61988

BLOCK:  OHDACC   MODEL: FLASH3
------------------------------
  INLET STREAM:          17
  OUTLET VAPOR STREAM:   OFFGAS
  FIRST LIQUID OUTLET:   LIGHTEND
  SECOND LIQUID OUTLET:  OHDWATER
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            1103.33         1103.33       -0.206080E-15
      MASS(LB/HR   )            22043.4         22043.5       -0.105248E-06
      ENTHALPY(BTU/HR  )      -0.120155E+09   -0.120166E+09    0.898110E-04

                         ***  INPUT DATA  ***
  THREE  PHASE  TP  FLASH
  SPECIFIED TEMPERATURE F                                  77.0000
  SPECIFIED PRESSURE    PSIA                               29.0075
  MAXIMUM NO. ITERATIONS                                   30
  CONVERGENCE TOLERANCE                                     0.000100000
  KEY COMPONENT:          WATER
  KEY LIQUID STREAM:      OHDWATER

                          ***  RESULTS  ***
  OUTLET TEMPERATURE    F                                    77.000
  OUTLET PRESSURE       PSIA                                 29.008
  HEAT DUTY             BTU/HR                              -10792.
  VAPOR FRACTION                                            0.17749
```

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  1ST LIQUID/TOTAL LIQUID                                   0.44177E-03

  V-L1-L2 PHASE EQUILIBRIUM :

     COMP           F(I)      X1(I)     X2(I)     Y(I)      K1(I)     K2(I)
     C13ALKAN      0.967E-04 0.262     0.468E-18 0.923E-05 0.353E-04 0.197E+14
     C14ALKAN      0.256E-04 0.700E-01 0.397E-19 0.886E-06 0.127E-04 0.223E+14
     C15ALKAN      0.140E-03 0.384     0.635E-19 0.158E-05 0.412E-05 0.249E+14
     C16ALKAN      0.372E-04 0.102     0.537E-20 0.151E-06 0.147E-05 0.280E+14
     C17ALKAN      0.589E-05 0.162E-01 0.229E-21 0.698E-08 0.431E-06 0.305E+14
     C18ALKAN      0.156E-05 0.430E-02 0.186E-22 0.641E-09 0.149E-06 0.344E+14
     C19ALKAN      0.439E-05 0.121E-01 0.157E-22 0.609E-09 0.504E-07 0.386E+14
     C20ALKAN      0.103E-05 0.284E-02 0.957E-24 0.407E-10 0.143E-07 0.426E+14
     H2            0.512E-01 0.417E-03 0.537E-07 0.289      693.     0.537E+07
     CO            0.281E-02 0.685E-04 0.146E-08 0.159E-01  231.     0.109E+08
     CO2           0.877E-02 0.241E-02 0.196E-05 0.494E-01  20.5     0.252E+05
     WATER         0.824     0.140E-01  1.00     0.117E-01 0.837     0.117E-01
     CH4           0.167E-01 0.114E-02 0.108E-06 0.943E-01  82.6     0.874E+06
     PROPANE       0.959E-01 0.129     0.801E-07 0.540      4.19     0.674E+07

BLOCK:  PUMP     MODEL: PUMP
----------------------------
  INLET STREAM:          TAG
  OUTLET STREAM:         1
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            1272.07         1272.07         0.00000
      MASS(LB/HR   )            277237.         277237.         0.00000
      ENTHALPY(BTU/HR  )      -0.370895E+09   -0.369817E+09   -0.290735E-02

                         ***  INPUT DATA  ***
   OUTLET PRESSURE  PSIA                                 797.708
   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                       5,665.92
   PRESSURE CHANGE  PSI                                  764.360
   NPSH AVAILABLE   FT-LBF/LB                              0.0
   FLUID POWER  HP                                       314.968
   BRAKE POWER  HP                                       423.797
   ELECTRICITY  KW                                       316.026
   PUMP EFFICIENCY USED                                    0.74320
   NET WORK REQUIRED  HP                                 423.797
   HEAD DEVELOPED FT-LBF/LB                            2,249.47

BLOCK:  REACTOR  MODEL: RSTOIC
------------------------------
  INLET STREAMS:         4           23
  OUTLET STREAM:         5
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                             IN          OUT       GENERATION   RELATIVE DIFF.
  TOTAL BALANCE
```

```
MOLE(LBMOL/HR)         15206.1       14981.7      -224.334      0.529334E-07
MASS(LB/HR   )         362444.       362444.                   -0.229342E-07
ENTHALPY(BTU/HR  )   -0.346915E+09 -0.303800E+09               -0.124281

                       ***  INPUT DATA  ***
STOICHIOMETRY MATRIX:

 REACTION #   1:
  SUBSTREAM MIXED   :
  C13ALKAN   1.00    CO2         1.00    C14FFA    -1.00

 REACTION #   2:
  SUBSTREAM MIXED   :
  C13ALKAN   1.00    H2         -1.00    CO          1.00    WATER      1.00
  C14FFA    -1.00

 REACTION #   3:
  SUBSTREAM MIXED   :
  C14ALKAN   1.00    H2         -3.00    WATER       2.00    C14FFA    -1.00

 REACTION #   4:
  SUBSTREAM MIXED   :
  C15ALKAN   1.00    CO2         1.00    C16FFA    -1.00

 REACTION #   5:
  SUBSTREAM MIXED   :
  C15ALKAN   1.00    H2         -1.00    CO          1.00    WATER      1.00
  C16FFA    -1.00

 REACTION #   6:
  SUBSTREAM MIXED   :
  C16ALKAN   1.00    H2         -3.00    WATER       2.00    C16FFA    -1.00

 REACTION #   7:
  SUBSTREAM MIXED   :
  C17ALKAN   1.00    CO2         1.00    C18FFA    -1.00

 REACTION #   8:
  SUBSTREAM MIXED   :
  C17ALKAN   1.00    H2         -1.00    CO          1.00    WATER      1.00
  C18FFA    -1.00

 REACTION #   9:
  SUBSTREAM MIXED   :
  C18ALKAN   1.00    H2         -3.00    WATER       2.00    C18FFA    -1.00

 REACTION #  10:
  SUBSTREAM MIXED   :
  C19ALKAN   1.00    CO2         1.00    C20FFA    -1.00

 REACTION #  11:
  SUBSTREAM MIXED   :
  C19ALKAN   1.00    H2         -1.00    CO          1.00    WATER      1.00
  C20FFA    -1.00

 REACTION #  12:
  SUBSTREAM MIXED   :
  C20ALKAN   1.00    H2         -3.00    WATER       2.00    C20FFA    -1.00

 REACTION #  13:
  SUBSTREAM MIXED   :
  H2        -3.00    CO         -1.00    WATER       1.00    CH4        1.00
```

```
 REACTION #  14:
  SUBSTREAM MIXED   :
  H2        -1.00    CO         1.00    CO2       -1.00    WATER      1.00


REACTION CONVERSION SPECS: NUMBER=   14
  REACTION #   1:
  SUBSTREAM:MIXED    KEY COMP:C14FFA   CONV FRAC: 0.3200
  REACTION #   2:
  SUBSTREAM:MIXED    KEY COMP:C14FFA   CONV FRAC: 0.3200
  REACTION #   3:
  SUBSTREAM:MIXED    KEY COMP:C14FFA   CONV FRAC: 0.3600
  REACTION #   4:
  SUBSTREAM:MIXED    KEY COMP:C16FFA   CONV FRAC: 0.3200
  REACTION #   5:
  SUBSTREAM:MIXED    KEY COMP:C16FFA   CONV FRAC: 0.3200
  REACTION #   6:
  SUBSTREAM:MIXED    KEY COMP:C16FFA   CONV FRAC: 0.3600
  REACTION #   7:
  SUBSTREAM:MIXED    KEY COMP:C18FFA   CONV FRAC: 0.3200
  REACTION #   8:
  SUBSTREAM:MIXED    KEY COMP:C18FFA   CONV FRAC: 0.3200
  REACTION #   9:
  SUBSTREAM:MIXED    KEY COMP:C18FFA   CONV FRAC: 0.3600
  REACTION #  10:
  SUBSTREAM:MIXED    KEY COMP:C20FFA   CONV FRAC: 0.3200
  REACTION #  11:
  SUBSTREAM:MIXED    KEY COMP:C20FFA   CONV FRAC: 0.3200
  REACTION #  12:
  SUBSTREAM:MIXED    KEY COMP:C20FFA   CONV FRAC: 0.3600
  REACTION #  13:
  SUBSTREAM:MIXED    KEY COMP:CO       CONV FRAC: 0.9000
  REACTION #  14:
  SUBSTREAM:MIXED    KEY COMP:CO2      CONV FRAC: 0.5000



TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE F                                 662.000
SPECIFIED PRESSURE    PSIA                              725.189
MAXIMUM NO. ITERATIONS                                   30
CONVERGENCE TOLERANCE                                     0.000100000
SIMULTANEOUS REACTIONS
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES          NO

                        ***  RESULTS  ***
OUTLET TEMPERATURE    F                                    662.00
OUTLET PRESSURE       PSIA                                 725.19
HEAT DUTY             BTU/HR                              0.43116E+08
VAPOR FRACTION                                             1.0000


REACTION EXTENTS:

   REACTION          REACTION
   NUMBER            EXTENT
                     LBMOL/HR
   1                  21.479
   2                  21.479
   3                  24.164
   4                  146.64
```

```
      5                   146.64
      6                   164.97
      7                   30.857
      8                   30.857
      9                   34.714
      10                  105.25
      11                  105.25
      12                  118.41
      13                  245.27
      14                  12.273

   V-L PHASE EQUILIBRIUM :

      COMP              F(I)           X(I)           Y(I)           K(I)
      C13ALKAN        0.28674E-02    0.14037E-01    0.28674E-02    0.20722
      C14ALKAN        0.16129E-02    0.10021E-01    0.16129E-02    0.16327
      C15ALKAN        0.19576E-01    0.15159        0.19576E-01    0.13100
      C16ALKAN        0.11011E-01    0.10666        0.11011E-01    0.10472
      C17ALKAN        0.41192E-02    0.49524E-01    0.41192E-02    0.84376E-01
      C18ALKAN        0.23171E-02    0.34153E-01    0.23171E-02    0.68823E-01
      C19ALKAN        0.14051E-01    0.25509        0.14051E-01    0.55875E-01
      C20ALKAN        0.79035E-02    0.17728        0.79035E-02    0.45224E-01
      H2              0.65337        0.90807E-01    0.65337         7.2988
      CO              0.22945E-01    0.39191E-02    0.22945E-01     5.9390
      CO2             0.21126E-01    0.59347E-02    0.21126E-01     3.6111
      WATER           0.83187E-01    0.48261E-01    0.83187E-01     1.7486
      CH4             0.76927E-01    0.17959E-01    0.76927E-01     4.3453
      PROPANE         0.78992E-01    0.34757E-01    0.78992E-01     2.3055

 BLOCK:  RYCCOMP  MODEL: COMPR
 -----------------------------
   INLET STREAM:          22
   OUTLET STREAM:         23
   PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(LBMOL/HR)           13934.0         13934.0         0.00000
       MASS(LB/HR   )           85206.8         85206.8         0.00000
       ENTHALPY(BTU/HR  )     -0.804180E+08   -0.779776E+08   -0.303470E-01

                          ***  INPUT DATA  ***

   ISENTROPIC CENTRIFUGAL COMPRESSOR
    OUTLET PRESSURE  PSIA                                       725.189
    ISENTROPIC EFFICIENCY                                         0.72000
    MECHANICAL EFFICIENCY                                         1.00000

                          ***  RESULTS  ***

    INDICATED  HORSEPOWER REQUIREMENT  HP                       959.130
    BRAKE      HORSEPOWER REQUIREMENT  HP                       959.130
    NET WORK REQUIRED                  HP                       959.130
    POWER LOSSES                       HP                         0.0
    ISENTROPIC HORSEPOWER REQUIREMENT  HP                       690.574
    CALCULATED OUTLET TEMP  F                                   142.117
    ISENTROPIC TEMPERATURE  F                                   135.981
    EFFICIENCY (POLYTR/ISENTR) USED                               0.72000
    OUTLET VAPOR FRACTION                                         1.00000
    HEAD DEVELOPED,       FT-LBF/LB                          16,047.3
    MECHANICAL EFFICIENCY USED                                    1.00000
    INLET HEAT CAPACITY RATIO                                     1.35960
```

```
   INLET VOLUMETRIC FLOW RATE , CUFT/HR              136,040.
   OUTLET VOLUMETRIC FLOW RATE, CUFT/HR              127,434.
   INLET  COMPRESSIBILITY FACTOR                           1.02415
   OUTLET COMPRESSIBILITY FACTOR                           1.02698
   AV. ISENT. VOL. EXPONENT                                1.39355
   AV. ISENT. TEMP EXPONENT                                1.34458
   AV. ACTUAL VOL. EXPONENT                                1.61214
   AV. ACTUAL TEMP EXPONENT                                1.54690

BLOCK:  SCRUBBER MODEL: SEP
---------------------------
  INLET STREAMS:         18          LEANMEA
  OUTLET STREAMS:        RICHMEA     19
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                 IN               OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)           12598.4         12598.4        0.144382E-15
      MASS(LB/HR   )           108509.         108509.         0.00000
      ENTHALPY(BTU/HR  )      -0.155197E+09   -0.155524E+09    0.210289E-02


                         ***  INPUT DATA  ***

  INLET PRESSURE   PSIA                                         652.670

  FLASH SPECS FOR STREAM RICHMEA
  TWO    PHASE  TP  FLASH
  PRESSURE DROP        PSI                                     0.0
  MAXIMUM NO. ITERATIONS                                      30
  CONVERGENCE TOLERANCE                                        0.000100000

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

  FRACTION OF FEED
    SUBSTREAM= MIXED
      STREAM= 19        CPT= C13ALKAN  FRACTION=          0.0
                             C14ALKAN                     0.0
                             C15ALKAN                     0.0
                             C16ALKAN                     0.0
                             C17ALKAN                     0.0
                             C18ALKAN                     0.0
                             C19ALKAN                     0.0
                             C20ALKAN                     0.0
                             H2                           1.00000
                             CO                           1.00000
                             CO2                          0.100000
                             WATER                        0.0
                             CH4                          1.00000
                             C14FFA                       0.0
                             C16FFA                       0.0
                             C18FFA                       0.0
                             C20FFA                       0.0
                             MEA                          0.0
                             PROPANE                      1.00000


                          ***  RESULTS  ***
```

```
 HEAT DUTY              BTU/HR                              -0.32705E+06

COMPONENT = C13ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = C14ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = C15ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = C16ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = C17ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = C18ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = C19ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = C20ALKAN
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = H2
  STREAM     SUBSTREAM    SPLIT FRACTION
  19         MIXED                 1.00000

COMPONENT = CO
  STREAM     SUBSTREAM    SPLIT FRACTION
  19         MIXED                 1.00000

COMPONENT = CO2
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 0.90000
  19         MIXED                 0.100000

COMPONENT = WATER
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = CH4
  STREAM     SUBSTREAM    SPLIT FRACTION
  19         MIXED                 1.00000

COMPONENT = MEA
  STREAM     SUBSTREAM    SPLIT FRACTION
  RICHMEA    MIXED                 1.00000

COMPONENT = PROPANE
  STREAM     SUBSTREAM    SPLIT FRACTION
  19         MIXED                 1.00000
```

```
BLOCK:  STRIPPER MODEL: RADFRAC
-------------------------------
   INLETS   - STEAM    STAGE  17
              13       STAGE   1
   OUTLETS  - 16       STAGE   1
              14       STAGE  17
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                   IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)            2340.75         2340.75         0.00000
      MASS(LB/HR   )            253170.         253170.        0.231789E-11
      ENTHALPY(BTU/HR  )      -0.311555E+09   -0.311555E+09    0.200285E-06


                        **********************
                        ****  INPUT DATA  ****
                        **********************

  ****   INPUT PARAMETERS   ****

   NUMBER OF STAGES                                            17
   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                          50
   FLASH TOLERANCE                                              0.000100000
   OUTSIDE LOOP CONVERGENCE TOLERANCE                           0.000100000

  ****   COL-SPECS   ****

   MOLAR VAPOR DIST / TOTAL DIST                                1.00000
   CONDENSER DUTY (W/O SUBCOOL)   BTU/HR                        0.0
   REBOILER DUTY                  BTU/HR                        0.0

  ****    PROFILES   ****

   P-SPEC          STAGE   1  PRES, PSIA                       29.0075

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


  ***   COMPONENT SPLIT FRACTIONS   ***

                               OUTLET STREAMS
                               --------------
               16           14
   COMPONENT:
   C13ALKAN    .24834E-02   .99752
   C14ALKAN    .11691E-02   .99883
   C15ALKAN    .52562E-03   .99947
   C16ALKAN    .24896E-03   .99975
   C17ALKAN    .10525E-03   .99989
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   C18ALKAN    .49651E-04   .99995
   C19ALKAN    .23018E-04   .99998
   C20ALKAN    .96115E-05   .99999
   H2          1.0000       .93167E-46
   CO          1.0000       .53235E-40
   CO2         1.0000       .57747E-27
   WATER       .76007       .23993
   CH4         1.0000       .63276E-34
   PROPANE     1.0000       .56421E-18


  ***    SUMMARY OF KEY RESULTS    ***

   TOP STAGE TEMPERATURE          F                        189.417
   BOTTOM STAGE TEMPERATURE       F                        198.694
   TOP STAGE LIQUID FLOW          LBMOL/HR               1,216.26
   BOTTOM STAGE LIQUID FLOW       LBMOL/HR               1,237.43
   TOP STAGE VAPOR FLOW           LBMOL/HR               1,103.33
   BOILUP VAPOR FLOW              LBMOL/HR               1,134.88
   CONDENSER DUTY (W/O SUBCOOL)   BTU/HR                     0.0
   REBOILER DUTY                  BTU/HR                     0.0

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

   DEW POINT                        0.61457E-02  STAGE=  4
   BUBBLE POINT                     0.48876E-03  STAGE=  4
   COMPONENT MASS BALANCE           0.12805E-04  STAGE=  5 COMP=C20ALKAN
   ENERGY BALANCE                   0.20129E-03  STAGE=  2


  ****    PROFILES   ****

  **NOTE** REPORTED VALUES FOR STAGE LIQUID AND VAPOR RATES ARE THE FLOWS
           FROM THE STAGE EXCLUDING ANY SIDE PRODUCT.  FOR THE FIRST STAGE,
           THE REPORTED VAPOR FLOW IS THE VAPOR DISTILLATE FLOW.  FOR THE
           LAST STAGE, THE REPORTED LIQUID FLOW IS THE LIQUID BOTTOMS FLOW.

                                         ENTHALPY
STAGE TEMPERATURE   PRESSURE             BTU/LBMOL          HEAT DUTY
      F             PSIA           LIQUID       VAPOR        BTU/HR

  1   189.42        29.008      -0.17197E+06  -91237.
  2   192.76        29.008      -0.16991E+06 -0.10259E+06
  3   192.90        29.008      -0.16984E+06 -0.10306E+06
  7   192.93        29.008      -0.16984E+06 -0.10310E+06
  8   192.92        29.008      -0.16983E+06 -0.10310E+06
  9   192.93        29.008      -0.16983E+06 -0.10310E+06
 10   192.94        29.008      -0.16983E+06 -0.10310E+06
 16   193.29        29.008      -0.16987E+06 -0.10310E+06
 17   198.69        29.008      -0.17043E+06 -0.10306E+06

STAGE     FLOW RATE                  FEED RATE                PRODUCT RATE
           LBMOL/HR                   LBMOL/HR                  LBMOL/HR
      LIQUID     VAPOR        LIQUID    VAPOR    MIXED      LIQUID    VAPOR
  1  1216.       1103.      1040.5683  190.0164                      1103.3268
  2  1262.       1089.
  3  1264.       1134.
  7  1264.       1136.
  8  1264.       1136.
  9  1264.       1137.
 10  1264.       1137.
 16  1262.       1136.
 17  1237.       1135.               1110.1687            1237.4265
```

```
   ****  MASS FLOW PROFILES  ****

STAGE      FLOW RATE                   FEED RATE                PRODUCT RATE
            LB/HR                        LB/HR                      LB/HR
       LIQUID      VAPOR        LIQUID     VAPOR    MIXED      LIQUID     VAPOR
   1 0.2311E+06 0.2204E+05  .22856+06 4612.5475                             .22043+05
   2 0.2317E+06 0.1993E+05
   3 0.2317E+06 0.2053E+05
   7 0.2317E+06 0.2055E+05
   8 0.2317E+06 0.2055E+05
   9 0.2317E+06 0.2055E+05
  10 0.2317E+06 0.2055E+05
  16 0.2317E+06 0.2054E+05
  17 0.2311E+06 0.2053E+05             .20000+05            .23113+06

                          ****   MOLE-X-PROFILE     ****
  STAGE     C13ALKAN      C14ALKAN      C15ALKAN      C16ALKAN      C17ALKAN
     1     0.35324E-01   0.19869E-01   0.24114       0.13564       0.50741E-01
     2     0.34056E-01   0.19155E-01   0.23247       0.13076       0.48915E-01
     3     0.34007E-01   0.19127E-01   0.23213       0.13057       0.48844E-01
     7     0.34002E-01   0.19124E-01   0.23210       0.13055       0.48837E-01
     8     0.33999E-01   0.19123E-01   0.23208       0.13054       0.48832E-01
     9     0.34000E-01   0.19123E-01   0.23208       0.13054       0.48833E-01
    10     0.34001E-01   0.19124E-01   0.23209       0.13055       0.48835E-01
    16     0.34063E-01   0.19153E-01   0.23242       0.13072       0.48898E-01
    17     0.34628E-01   0.19505E-01   0.23688       0.13328       0.49867E-01

                          ****   MOLE-X-PROFILE     ****
  STAGE     C18ALKAN      C19ALKAN      C20ALKAN      H2            CO
     1     0.28542E-01   0.17307       0.97354E-01   0.90649E-04   0.10935E-04
     2     0.27514E-01   0.16685       0.93851E-01   0.17810E-06   0.46898E-07
     3     0.27474E-01   0.16660       0.93714E-01   0.34764E-09   0.19984E-09
     7     0.27471E-01   0.16658       0.93701E-01    0.0000        0.0000
     8     0.27468E-01   0.16656       0.93692E-01    0.0000        0.0000
     9     0.27469E-01   0.16657       0.93694E-01    0.0000        0.0000
    10     0.27469E-01   0.16657       0.93698E-01    0.0000        0.0000
    16     0.27505E-01   0.16679       0.93816E-01    0.0000        0.0000
    17     0.28052E-01   0.17011       0.95688E-01    0.0000        0.0000

                          ****   MOLE-X-PROFILE     ****
  STAGE     CO2           WATER         CH4           PROPANE
     1     0.20171E-03   0.21032       0.14849E-03   0.75452E-02
     2     0.50716E-05   0.24578       0.14515E-05   0.64390E-03
     3     0.12672E-06   0.24748       0.14099E-07   0.54612E-04
     7     0.49314E-13   0.24763        0.0000       0.28213E-08
     8     0.12332E-14   0.24771        0.0000       0.23940E-09
     9      0.0000       0.24769        0.0000       0.20318E-10
    10      0.0000       0.24766        0.0000       0.17245E-11
    16      0.0000       0.24664        0.0000        0.0000
    17      0.0000       0.23198        0.0000        0.0000

                          ****   MOLE-Y-PROFILE     ****
  STAGE     C13ALKAN      C14ALKAN      C15ALKAN      C16ALKAN      C17ALKAN
     1     0.96690E-04   0.25605E-04   0.13972E-03   0.37225E-04   0.58870E-05
     2     0.10364E-03   0.27658E-04   0.15219E-03   0.40867E-04   0.65190E-05
     3     0.10371E-03   0.27678E-04   0.15230E-03   0.40902E-04   0.65247E-05
     7     0.10387E-03   0.27727E-04   0.15260E-03   0.40988E-04   0.65399E-05
     8     0.10398E-03   0.27760E-04   0.15281E-03   0.41050E-04   0.65511E-05
     9     0.10407E-03   0.27776E-04   0.15290E-03   0.41076E-04   0.65557E-05
    10     0.10414E-03   0.27805E-04   0.15308E-03   0.41127E-04   0.65645E-05
    16     0.10560E-03   0.28209E-04   0.15542E-03   0.41788E-04   0.66772E-05
    17     0.12588E-03   0.34002E-04   0.18968E-03   0.51526E-04   0.83470E-05
```

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                    ****   MOLE-Y-PROFILE      ****
STAGE     C18ALKAN      C19ALKAN      C20ALKAN      H2            CO
  1     0.15622E-05   0.43916E-05   0.10315E-05   0.51230E-01   0.28141E-02
  2     0.17446E-05   0.49465E-05   0.11726E-05   0.10124E-03   0.12212E-04
  3     0.17463E-05   0.49516E-05   0.11739E-05   0.19808E-06   0.52160E-07
  7     0.17507E-05   0.49649E-05   0.11773E-05    0.0000        0.0000
  8     0.17540E-05   0.49750E-05   0.11793E-05    0.0000        0.0000
  9     0.17553E-05   0.49789E-05   0.11809E-05    0.0000        0.0000
 10     0.17578E-05   0.49866E-05   0.11829E-05    0.0000        0.0000
 16     0.17895E-05   0.50811E-05   0.12067E-05    0.0000        0.0000
 17     0.22615E-05   0.64931E-05   0.15637E-05    0.0000        0.0000

                    ****   MOLE-Y-PROFILE      ****
STAGE     CO2           WATER         CH4           PROPANE
  1     0.87660E-02   0.82423       0.16731E-01   0.95922E-01
  2     0.22528E-03   0.99073       0.16584E-03   0.84269E-02
  3     0.56405E-05   0.99894       0.16143E-05   0.71613E-03
  7     0.21941E-11   0.99966       0.14336E-13   0.36989E-07
  8     0.54836E-13   0.99966        0.0000       0.31373E-08
  9     0.13713E-14   0.99966        0.0000       0.26621E-09
 10      0.0000       0.99966        0.0000       0.22593E-10
 16      0.0000       0.99965        0.0000        0.0000
 17      0.0000       0.99958        0.0000        0.0000

                    ****   K-VALUES            ****
STAGE     C13ALKAN      C14ALKAN      C15ALKAN      C16ALKAN      C17ALKAN
  1     0.27371E-02   0.12886E-02   0.57936E-03   0.27442E-03   0.11601E-03
  2     0.30510E-02   0.14480E-02   0.65670E-03   0.31360E-03   0.13378E-03
  3     0.30641E-02   0.14547E-02   0.65994E-03   0.31524E-03   0.13453E-03
  7     0.30661E-02   0.14557E-02   0.66044E-03   0.31549E-03   0.13464E-03
  8     0.30652E-02   0.14552E-02   0.66022E-03   0.31538E-03   0.13459E-03
  9     0.30661E-02   0.14557E-02   0.66046E-03   0.31550E-03   0.13464E-03
 10     0.30671E-02   0.14562E-02   0.66069E-03   0.31562E-03   0.13470E-03
 16     0.30999E-02   0.14727E-02   0.66868E-03   0.31965E-03   0.13654E-03
 17     0.36352E-02   0.17434E-02   0.80077E-03   0.38661E-03   0.16740E-03

                    ****   K-VALUES            ****
STAGE     C18ALKAN      C19ALKAN      C20ALKAN      H2            CO
  1     0.54728E-04   0.25372E-04   0.10594E-04    565.17        257.37
  2     0.63666E-04   0.29777E-04   0.12554E-04    567.20        259.92
  3     0.64045E-04   0.29964E-04   0.12638E-04    567.40        260.07
  7     0.64103E-04   0.29993E-04   0.12651E-04    567.41        260.09
  8     0.64077E-04   0.29980E-04   0.12645E-04    567.44        260.10
  9     0.64105E-04   0.29994E-04   0.12651E-04    567.42        260.09
 10     0.64132E-04   0.30007E-04   0.12657E-04    567.40        260.09
 16     0.65056E-04   0.30462E-04   0.12861E-04    566.74        260.01
 17     0.80622E-04   0.38173E-04   0.16343E-04    557.07        258.80

                    ****   K-VALUES            ****
STAGE     CO2           WATER         CH4           PROPANE
  1      43.460        3.9190        112.68        12.713
  2      44.371        4.0306        114.07        13.078
  3      44.413        4.0351        114.15        13.094
  7      44.419        4.0360        114.16        13.096
  8      44.418        4.0354        114.16        13.095
  9      44.420        4.0359        114.16        13.096
 10      44.422        4.0364        114.16        13.097
 16      44.490        4.0530        114.20        13.131
 17      45.531        4.3088        114.81        13.637

                    ****   MASS-X-PROFILE      ****
STAGE     C13ALKAN      C14ALKAN      C15ALKAN      C16ALKAN      C17ALKAN
```

```
     1     0.34281E-01   0.20749E-01   0.26963       0.16168       0.64228E-01
     2     0.34196E-01   0.20697E-01   0.26894       0.16126       0.64063E-01
     3     0.34194E-01   0.20696E-01   0.26893       0.16125       0.64059E-01
     7     0.34194E-01   0.20696E-01   0.26892       0.16125       0.64059E-01
     8     0.34194E-01   0.20695E-01   0.26892       0.16125       0.64058E-01
     9     0.34194E-01   0.20695E-01   0.26892       0.16125       0.64058E-01
    10     0.34194E-01   0.20696E-01   0.26892       0.16125       0.64058E-01
    16     0.34215E-01   0.20703E-01   0.26898       0.16127       0.64064E-01
    17     0.34181E-01   0.20717E-01   0.26940       0.16159       0.64202E-01

                         ****   MASS-X-PROFILE      ****
 STAGE       C18ALKAN      C19ALKAN      C20ALKAN      H2            CO
     1     0.38236E-01   0.24464       0.14480       0.96190E-06   0.16122E-05
     2     0.38137E-01   0.24401       0.14442       0.19554E-08   0.71544E-08
     3     0.38135E-01   0.24399       0.14441       0.38221E-11   0.30529E-10
     7     0.38134E-01   0.24399       0.14441        0.0000        0.0000
     8     0.38134E-01   0.24399       0.14441        0.0000        0.0000
     9     0.38134E-01   0.24399       0.14441        0.0000        0.0000
    10     0.38134E-01   0.24399       0.14441        0.0000        0.0000
    16     0.38137E-01   0.24400       0.14442        0.0000        0.0000
    17     0.38222E-01   0.24456       0.14475        0.0000        0.0000

                         ****   MASS-X-PROFILE      ****
 STAGE       CO2           WATER         CH4           PROPANE
     1     0.46728E-04   0.19944E-01   0.12539E-04   0.17514E-02
     2     0.12156E-05   0.24115E-01   0.12682E-06   0.15464E-03
     3     0.30417E-07   0.24315E-01   0.12336E-08   0.13134E-04
     7     0.11838E-13   0.24334E-01    0.0000       0.67861E-09
     8     0.29607E-15   0.24343E-01    0.0000       0.57588E-10
     9      0.0000       0.24341E-01    0.0000       0.48874E-11
    10      0.0000       0.24338E-01    0.0000       0.41481E-12
    16      0.0000       0.24208E-01    0.0000        0.0000
    17      0.0000       0.22375E-01    0.0000        0.0000

                         ****   MASS-Y-PROFILE      ****
 STAGE       C13ALKAN      C14ALKAN      C15ALKAN      C16ALKAN      C17ALKAN
     1     0.89224E-03   0.25426E-03   0.14855E-02   0.42192E-03   0.70857E-04
     2     0.10440E-02   0.29980E-03   0.17662E-02   0.50561E-03   0.85650E-04
     3     0.10565E-02   0.30341E-03   0.17876E-02   0.51177E-03   0.86696E-04
     7     0.10593E-02   0.30426E-03   0.17930E-02   0.51339E-03   0.86988E-04
     8     0.10604E-02   0.30462E-03   0.17954E-02   0.51416E-03   0.87136E-04
     9     0.10613E-02   0.30479E-03   0.17965E-02   0.51449E-03   0.87197E-04
    10     0.10619E-02   0.30511E-03   0.17985E-02   0.51512E-03   0.87314E-04
    16     0.10768E-02   0.30953E-03   0.18260E-02   0.52337E-03   0.88808E-04
    17     0.12826E-02   0.37281E-03   0.22268E-02   0.64484E-03   0.11093E-03

                         ****   MASS-Y-PROFILE      ****
 STAGE       C18ALKAN      C19ALKAN      C20ALKAN      H2            CO
     1     0.19899E-04   0.59025E-04   0.14588E-04   0.51691E-02   0.39453E-02
     2     0.24259E-04   0.72572E-04   0.18103E-04   0.11151E-04   0.18690E-04
     3     0.24557E-04   0.73469E-04   0.18327E-04   0.22064E-07   0.80728E-07
     7     0.24644E-04   0.73743E-04   0.18400E-04    0.0000        0.0000
     8     0.24690E-04   0.73892E-04   0.18430E-04    0.0000        0.0000
     9     0.24709E-04   0.73951E-04   0.18457E-04    0.0000        0.0000
    10     0.24744E-04   0.74064E-04   0.18487E-04    0.0000        0.0000
    16     0.25189E-04   0.75464E-04   0.18858E-04    0.0000        0.0000
    17     0.31808E-04   0.96360E-04   0.24418E-04    0.0000        0.0000

                         ****   MASS-Y-PROFILE      ****
 STAGE       CO2           WATER         CH4           PROPANE
     1     0.19310E-01   0.74321       0.13434E-01   0.21171
     2     0.54169E-03   0.97516       0.14536E-03   0.20303E-01
     3     0.13716E-04   0.99438       0.14310E-05   0.17449E-02
```

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  7    0.53411E-11   0.99613        0.12721E-13   0.90220E-07
  8    0.13349E-12   0.99612         0.0000       0.76520E-08
  9    0.33381E-14   0.99612         0.0000       0.64930E-09
 10     0.0000       0.99611         0.0000       0.55106E-10
 16     0.0000       0.99606         0.0000        0.0000
 17     0.0000       0.99521         0.0000        0.0000
```

V. Module III: Equipment Design Calculations

R-101	**Reactor**	**Blocks**	From F-101 and C-102	To E-102
		Streams	From 4 and 23	To 5
Properties	Vertical pressure tower			
	Platform and ladders			
	Reactor Internals			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	8071.33	ft3/hr			ASPEN
Liquid Hourly Space Velocity	LHSV	1.5	hr-1			Donnis
Number of Catalyst Beds	N_{cb}	3				
Diameter	D	9.13	ft	2.78	m	
Hemispherical Head	H_h	9.13	ft	2.78	m	
Total Height	H	49.65	ft	15.13	m	
Number of Quench Zones	N_{qz}	2				
Tangent-Tangent Height	H_t	40.52	ft	12.35	m	
Height per Quench Zone	H_q	6.56	ft	2	m	
Aspect Ratio (H/D)	AR	3				
Height of Catalyst Bed	H_b	27.39	ft	8.35	m	
Weight	W			187727.43	lb	
Reactor Pressure	P	725.19	psi	50.00	bar	
Design Pressure	P_d	814.4	psi			
Maximum Allowable Stress	S	15000	psi			SSLW, pg. 575
Weld Efficiency	E	1				SSLW, pg. 575
Corrosion Allowance	t_c	1/8	in			
Shell Thickness	t_s	3.25	in			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	4.16	Vertical Pressure Vessels			SSLW, Table 22.11

Equations	**Source**
V = Q/LHSV	
D = (π*V/(Ncb*AR))^(1/3)	
Hb = D*AR	
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (tp+tw)/2	SSLW, pg. 576
ts = tv + tc	SSLW, pg. 576
Ht = Hb+2*Hq	
H = Ht + Hh	
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(12*Ht+0.8*D)*ts*0.284	SSLW, (22.59)
Cv = exp(7.0132+0.18255*(lnw+0.02297*lnw^2))	SSLW, (22.54)
Cpl = 300.9*(D^0.63316)*(L^0.80161)	SSLW, (22.58)
Cm = 0.10*Cv	Estimated Cost of Reactor Internals
Cp = FM*Cv+Cm+Cpl	
Cbm = FBM*Cp	

C_P	**$687,144**
C_{BM}	**$2,858,518**

V-101	**HT Separator**	**Blocks**	From E-102	To E-101 and H-101
		Streams	From 6	To 7 and 9
Properties	Flash Drum			
	Vertical Pressure Vessel			
	Aspect Ratio (H/D) = 4			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Density of Liquid	ρ_L	36.923014	lb/ft3			ASPEN
Density of Vapor	ρ_V	0.75	lb/ft3			ASPEN
	k	0.295				Souders-Brown
Vapor Volumetric Flowrate	Q	55.483807	ft3/s	199742	ft3/hr	
Pressure	P	652.67	psi	45	bar	
Design Pressure	P_D	738	psi			
Diameter	D	5.8665825	ft	70.399	inches	
Tangent-to-Tangent Height	Ht	23.46633	ft	281.596	inches	
Weight	W	43655.442	lb			
Maximum Allowable Stress	S	15000	psi			SSLW, pg. 575
Weld Efficiency	E	1				SSLW, pg. 575
Shell Thickness	ts	2.25	in			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	4.16	Vertical Pressure Vessels			SSLW, Table 22.11

Equations	**Source**
Ut=k*SQRT((ρL-ρV)/ρV)	Souders-Brown
A=Q/Ut	
D=(4*A/π)^0.5	
L = 4D	Aspect Ratio
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = tv + tc	SSLW, pg. 576
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(Ht+0.8*D)*ts*0.284	SSLW, (22.59)
Cv = exp(7.0132+0.18255*(lnW+0.02297*lnW^2))	SSLW, (22.54)
Cpl = 361.8*(D^0.73960)*(Ht^0.70684)	SSLW, (22.56)
Cp = FM*Cv+Cpl	SSLW, (22.52)
Cbm = FBM*Cfob	SSLW, (22.12)

C_P	**$238,287**
C_{BM}	**$991,275**

V-102	**LT Separator**	**Blocks**	From H-101	To V-106/107, E-101 and V-103
		Streams	From 10	To 11, 18 and Sour H2O
Properties	Three Phase Flash Drum			
	Horizontal Pressure Vessel			
	Aspect Ratio (L/D) = 4			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Density of Liquid	ρ_L	41.163203	lb/ft3			ASPEN
Density of Vapor	ρ_V	0.9766978	lb/ft3			ASPEN
	k	0.295				Souders-Brown
Vapor Volumetric Flowrate	Q	30.860174	ft3/s	111096.63	ft3/hr	
Pressure	P	609.158	psi	42	bar	
Design Pressure	P_D	691.92189	psi			
Diameter	D	4.6	ft	54.7	inches	
Length	L	18.2	ft	218.7	inches	
Weight	W	19735.2	lb			
Maximum Allowable Stress	S	15000	psi			SSLW, pg. 575
Weld Efficiency	E	1				SSLW, pg. 575
Shell Thickness	ts	1.5	in			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	3.05	Horizontal Pressure Vessels			SSLW, Table 22.11

Equations	**Source**
Ut=k*SQRT((ρL-ρV)/ρV)	Souders-Brown
A=Q/Ut	
D=(4*A/π)^0.5	
L = 4D	Aspect Ratio
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = (tv+0.125)/2	SSLW, pg. 576
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(L+0.8*D)*ts*0.284	SSLW, (22.59)
Cv = exp(8.9552-0.2330*(ln(W)+0.04333*ln(W)^2))	SSLW, (22.53)
Cpl = 2005(D)^0.20294	SSLW, (22.55)
Cp = FM*Cv+Cpl	SSLW, (22.52)
Cbm = FBM*Cp	SSLW, (22.12)

C_P	**$115,268**
C_{BM}	**$351,567**

V-103	**Product Stripper**	**Blocks**	From V-102 and E-101	To H-102 ad H-103
		Streams	From 13 and Steam	To 14 and 16
Properties	Tower			
	25 Stages			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Liquid Flow Rate	L	5147.6	lb/hr			
Vapor Flow Rate	V	260739	lb/hr			
Liquid Density	ρl	44.89	flb/ft3			
Vapor Density	ρv	8.45	flb/ft3			
Surface Tension	σ	22.46	dyne/cm2			
Diameter	D	6.59	ft	2.01	m	
Foaming Factor	F_F	1				
Hole Area Factor	F_{HA}	1				
Tangent-Tangent Height	Ht	36	ft	10.97	m	
Hemispherical Head	Hh	14	ft	4.27	m	
Total Height	H	50	ft	15.24	m	
Design Pressure	Pd	40.7	psi			
Pressure	Pd	29.00	psi	2	bar	
Weight	w	15385	lb			
Maximum Allowable Stress	S	15000	psi			SSLW, pg. 575
Weld Efficiency	E	1				SSLW, pg. 575
Shell Thickness	ts	0.4375	in			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	4.16	Vertical Pressure Vessel			SSLW, Table 22.11

Equations	**Source**
Flg =(L/V)*(ρv/ρl)^0.5	SSLW, pg. 505
Fst = (σ/20)^0.2	SSLW, pg. 505
ρ = ((ρl-ρv)/ρv)^0.5	SSLW, pg. 505
C=Csb*Fst*Ff*Fha	SSLW, (19.13)
Uf = C*ρ	SSLW, (19.12)
D = 2*(V/(0.9*π*U))^0.5	SSLW, pg. 505
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = (tv+0.125)/2	SSLW, pg. 576
Ht = Hb+2*Hq	
H = Ht + Hh	
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2)	SSLW, (22.61)
w = π*(D+ts)*(12*Ht+0.8*D)*ts*0.284	SSLW, (22.59)
Cv = exp(7.0132+0.18255*(lnw+0.02297*lnw^2))	SSLW, (22.54)
Cpl = 300.9*(Ht^0.63316)*(Ht^0.80161)	SSLW, (22.58)
Cp = FM*Cv+Cpl	SSLW, (22.52)
Cbm= FBM*Cp	SSLW, (22.12)

C_P	**$235,897**
C_{BM}	**$981,330**

V-104	**Decanter**	**Blocks**	From H-102	To P-102
		Streams	From 15	To N-Alkanes and Water
Properties	Horizontal Pressure Vessel			
	Aspect Ratio (L/D) = 3			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	4851.65	ft3/hr			ASPEN
Residence Time	τ	0.083333	hr	5	mins	Assumption
Length	L	35.21262	ft	422.55	inches	
Diamter	D	11.73754	ft	140.85	inches	
Aspect Ratio (H/D)	AR	3				Specified
Weight	w	25290.33	lb			
Pressure	P	29.00	psi	2	bar	ASPEN
Design Pressure	Pd	40.7	psi			
Maximum Allowable Stress	S	15000	psi			SSLW, pg. 575
Weld Efficiency	E	1				SSLW, pg. 575
Shell Thickness	ts	0.375	in			
Material Factor	F_M	1	Carbon Steel			SSLW, Table 22.26
Bare Module Factor	F_{BM}	3.05	Horizontal Pressure Vessel			SSLW, Table 22.11

Equations	**Source**
V = Q * τ	
L = 3D	Aspect Ratio
D = (4*V)^(1/3)	
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = (tv+0.125)/2	SSLW, pg. 576
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(L+0.8*D)*ts*0.284	SSLW, (22.59)
Cv =exp(8.9552-0.233*(LN(W))+0.04333*((LN(W))^2))	SSLW, (22.53)
Cp = Fm*Cv	SSLW, (22.52)
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$62,729**
C_{BM}	**$191,323**

V-105	**Overhead Accumulator**	**Blocks**	From H-103	
		Streams	From 17	To Offgas, Light Ends and Water
Properties	Horizontal Pressure Vessel Aspect Ratio (L/D) = 2 τ = 2mins			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	38795.3205	ft3/hr			
Residence Time	τ	0.033333333	hr	2	mins	
Volume	V	1293.17735	ft3			
Diameter	D	9.372297609	ft	112.47	in	
Length	L	18.74459522	ft	224.94	in	
Pressure	P	29.0075475	psi			
Design Pressure	Pd	40.11334852	psi			
Maximum Allowable Stress	S	15000	psi			
Weld Efficiency	E	0.85				
Corrosion Allowance	t_c	1/8	in			
Wall Thickness	t_s	0.4375	in			
Weight	W	13878.5811	lb			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	3.05	Horizontal Pressure Vessel			SSLW, Table 22.11

<u>Equations</u>	**Source**
V = Q*τ	
D = (2*V/π)^(1/3)	
L=2D	Aspect Ratio
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = (tv+0.125)/2	SSLW, pg. 576
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(12*L+0.8*D)*ts*0.284	SSLW, (22.59)
Cv =exp(8.952-0.233*(lnw+0.0433*lnw^2))	SSLW, (22.53)
Cp = Fm*Cv	SSLW, (22.52)
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$ 90,291**
C_{BM}	**$ 275,388**

V-106	**Absorption Column**	**Blocks**	From V-102	To V-110
V-107	**Stripping Column**	**Streams**	From 18 and Lean MEA	To 19 and Rich MEA
Properties	Amine Scrubber System			

Note: The values listed below are based on a University of Pennsylvania Senior Design Report, The Capture and Sequestration of Carbon Dioxide, by Czarniak, Lau, McLeod.

	C_P	F_{BM}	C_{BM}
Absorption Column	$ 526,000	4.16	$ 2,190,000
Absorption Column Flash Drum	$ 113,000	4.16	$ 471,000
Stripping Column	$ 427,000	4.16	$ 1,780,000
Stripping Column Reflux Drum	$ 58,400	4.16	$ 243,000
Absorption Column Condenser 1	$ 593,000	3.17	$ 1,880,000
Absorption Column Condenser 2	$ 593,000	3.17	$ 2,510,000
Absorption Column Condenser 3	$ 593,000	3.17	$ 2,510,000
Absorption Column Condenser 4	$ 593,000	3.17	$ 2,510,000
Heat Exchanger 1	$ 155,000	3.17	$ 491,000
Heat Exchanger 2	$ 155,000	3.17	$ 491,000
Heat Exchanger 3	$ 155,000	3.17	$ 491,000
Heat Exchanger 4	$ 155,000	3.17	$ 491,000
Stripping Column Condenser	$ 326,000	3.17	$ 1,030,000
Stripping Column Rebioler	$ 935,000	3.17	$ 2,960,000
Recycle Stream Cooler	$ 605,000	3.17	$ 1,920,000
Pump	$ 29,800	3.3	$ 98,200
TOTAL	**$ 6,610,000**		**$ 22,100,000**

Purchase Cost of MEA Scrubber System	$6,610,000
Bare Module Cost of MEA Scrubber System	$22,100,000

Amount of CO_2 to be removed in Hydrotreating Process	13503.49	lb/hr
Amount of CO_2 removed in MEA Scrubber System	51,808.63	lb/hr

Scale of HT Amine Scrubber relative to MEA Scrubber	0.26

C_P	$1,722,842
C_{BM}	$5,754,292

V-108	**Feed Surge Drum**	**Blocks**	From P-101	To P-103
Properties	Horizontal Pressure Vessel Aspect Ratio (L/D) = 2 τ = 20 mins			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	5665.925	ft3/hr			
Residence Time	τ	0.333333	hr	20	mins	
Volume	V	1888.642	ft3			
Diameter	D	10.63351	ft	127.6021	in	
Length	L	21.26702	ft	255.2042	in	
Pressure	P	14.7	psi			
Design Pressure	Pd	21.522	psi			
Maximum Allowable Stress	S	15000	psi			
Weld Efficiency	E	0.85				
Corrosion Allowance	t_c	1/8	in			
Wall Thickness	t_s	0.625	in			
Weight	W	25547.23	lb			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	3.05	Horizontal Pressure Vessel			SSLW, Table 22.11

Equations	**Source**
V = Q*τ	
D = (2*V/π)^(1/3)	
L=2D	Aspect Ratio
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = (tv+0.125)/2	SSLW, pg. 576
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(12*L+0.8*D)*ts*0.284	SSLW, (22.59)
Cv =exp(8.952-0.233*(lnw+0.0433*lnw^2))	SSLW, (22.53)
Cp = Fm*Cv	SSLW, (22.52)
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$**	**131,762**
C_{BM}	**$**	**401,874**

V-109	**K.O. Drum**	**Blocks**		To C-101
		Streams	From H2MAKEUP	To 21
Properties	Flash Drum			
	Horizontal Pressure Vessel			
	Aspect Ratio (L/D) = 3			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Density of Liquid	ρ_L	4.23	lb/ft3			ASPEN
Density of Vapor	ρ_V	0.1003326	lb/ft3			ASPEN
	k	0.295				Souders-Brown
Vapor Volumetric Flowrate	Q	82015.355	ft3/hr			
Vapor Superficial Velocity	U_T	6813.3554	ft/hr	1.8926	ft/s	
Pressure	P	290.07548	psi	20	bar	
Design Pressure	P_D	330.60756	psi			
Diameter	D	4.2526841	ft	51.0322	inches	
Length	L	12.758052	ft	153.097	inches	
Maximum Allowable Stress	S	15000	psi			
Weld Efficiency	E	0.85				
Corrosion Allowance	t_c	1/8	in			
Wall Thickness	t_s	0.625	in			
Weight	W	7858.3599	lb			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	3.05	Horizontal Pressure Vessel			SSLW, Table 22.11

Equations	**Source**
Ut=k*SQRT((ρL-ρV)/ρV)	Souders-Brown
A=Q/Ut	
D = (2*V/π)^(1/3)	
L=3D	Aspect Ratio
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = (tv+0.125)/2	SSLW, pg. 576
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(12*L+0.8*D)*ts*0.284	SSLW, (22.59)
Cv =exp(8.952-0.233*(lnw+0.0433*lnw^2))	SSLW, (22.53)
Cp = Fm*Cv	SSLW, (22.52)
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$ 65,351**
C_{BM}	**$199,319**

V-110	**K.O. Drum**	**Blocks**	From C-101 and V106/7	To C-102
		Streams	From H2MAKEUP	To 21
Properties	Flash Drum			
	Horizontal Pressure Vessel			
	Aspect Ratio (L/D) = 3			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Density of Liquid	ρ_L	4.23	lb/ft3			ASPEN
Density of Vapor	ρ_V	0.6686375	lb/ft3			ASPEN
	k	0.295				Souders-Brown
Vapor Volumetric Flowrate	Q	127433.5	ft3/hr			
Vapor Superficial Velocity	U_T	6048.864	ft/hr	1.68024	ft/s	
Pressure	P	652.66982	psi	45	bar	
Design Pressure	P_D	694.92794	psi			
Diameter	D	4.7471245	ft	56.9655	in	
Length	L	14.241374	ft	170.896	in	
Maximum Allowable Stress	S	15000	psi			
Weld Efficiency	E	0.85				
Corrosion Allowance	t_c	1/8	in			
Wall Thickness	t_s	0.625	in			
Weight	W	16937.705	lb			
Material Factor	F_M	2.1	Stainless Steel 316			SSLW, Table 22.26
Bare Module Factor	F_{BM}	3.05	Horizontal Pressure Vessel			SSLW, Table 22.11

<u>Equations</u>	**Source**
Ut=k*SQRT((ρL-ρV)/ρV)	Souders-Brown
A=Q/Ut	
D = (2*V/π)^(1/3)	
L=3D	Aspect Ratio
tp = D*Pd/(2*S*E-1.2*Pd)	SSLW, (22.60)
tw = 0.228*(D+18)*Ht^2/(S*D^2)	SSLW, (22.62)
tv = (2*tp+tw)/2	SSLW, pg. 576
ts = (tv+0.125)/2	SSLW, pg. 576
Pd = exp(0.60608+0.91615*(lnP+0.0015655*lnP^2))	SSLW, (22.61)
w = π*(D+ts)*(12*L+0.8*D)*ts*0.284	SSLW, (22.59)
Cv =exp(8.952-0.233*(lnw+0.0433*lnw^2))	SSLW, (22.53)
Cp = Fm*Cv	SSLW, (22.52)
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$ 101,787**
C_{BM}	**$ 310,449**

C-101	**Makeup Compressor**	**Blocks**	From V-109	To V-110
		Streams	From H2MAKEUP	To 21
Properties	Centrifugal Compressor			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Consumed Power	P_C	2204.55457	hp			ASPEN
Compressor Drive	F_D	1	Electric Drive			SSLW, pg. 569
Material Factor	F_M	1	Cast Iron			SSLW, pg. 569
Bare Module Factor	F_{BM}	2.15	Compressors and drivers			SSLW, Table 22.11

Equations	**Source**
Cb = exp{7.5800+0.80[ln(Pc)])	SSLW, (22.36)
Cp = Fd*Fm*Cb	SSLW, (22.35)

C_P	**$**	**925,995**
C_{BM}	**$**	**1,990,890**

C-102	**Recycle Compressor**	**Blocks**	From V-110	To R-101
		Streams	From 22	To 23
Properties	Centrifugal Compressor			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Consumed Power	P_C	959.130378	hp			ASPEN
Compressor Drive	F_D	1	Electric Drive			SSLW, pg. 569
Material Factor	F_M	1	Cast Iron			SSLW, pg. 569
Bare Module Factor	F_{BM}	2.15	Compressors and drivers			SSLW, Table 22.11

Equations	**Source**
Cb = exp{7.5800+0.80[ln(Pc)])	SSLW, (22.36)
Cp = Fd*Fm*Cb	SSLW, (22.35)

C_P	**$**	**475,833**
C_{BM}	**$**	**1,023,040**

P-101	**Feed Tank Pump**	**Blocks**	From T-101	To V-108
Properties	Centrifugal Pump			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	5665.92465	ft3/hr			ASPEN
Pump Head	H	73.57360943	ft			ASPEN
Material Factor	F_M	1	Cast Iron			SSLW, Table 22.21
Pump Type Factor	F_T	8.9				SSLW, Table 22.20
Bare Module Factor	F_{BM}	3.3	Pumps and drivers			SSLW, Table 22.11

Equations	**Source**
S = Q*H^0.5	SSLW, (22.13)
Cb = exp(9.7171-0.6019*lnS+0.0519*lnS^2)	SSLW, (22.14)
Cp = Fm*Ft*Cb	SSLW, (22.15)

C_P	**$**	**94,068**
C_{BM}	**$**	**310,423**

P-102	**Product Storage Pump**	**Blocks**	From V-104	To T-102
Properties	Centrifugal Pump			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	4709.53394	ft3/hr			ASPEN
Pump Head	H	74.95613957	ft			ASPEN
Material Factor	F_M	1	Cast Iron			SSLW, Table 22.21
Pump Type Factor	F_T	8.9				SSLW, Table 22.20
Bare Module Factor	F_{BM}	3.3	Pumps and drivers			SSLW, Table 22.11

Equations	**Source**
S = Q*H^0.5	SSLW, (22.13)
Cb = exp(9.7171-0.6019*lnS+0.0519*lnS^2)	SSLW, (22.14)
Cp = Fm*Ft*Cb	SSLW, (22.15)

C_P	**$**	**86,024**
C_{BM}	**$**	**283,879**

P-103	**Centriugal Pump**	**Blocks**	From V-108	To E-101
		Streams	From TAG	To 1
Properties	Centrifugal Pump			

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	5665.92465	ft3/hr			ASPEN
Pump Head	H	2249.47019	ft			ASPEN
Material Factor	F_M	1	Cast Iron			SSLW, Table 22.21
Pump Type Factor	F_T	8.9				SSLW, Table 22.20
Bare Module Factor	F_{BM}	3.3	Pumps and drivers			SSLW, Table 22.11

Equations	**Source**
S = Q*H^0.5	SSLW, (22.13)
Cb = exp(9.7171-0.6019*lnS+0.0519*lnS^2)	SSLW, (22.14)
Cp = Fm*Ft*Cb	SSLW, (22.15)

C_P	**$**	**265,610**
C_{BM}	**$**	**876,514**

T-101	**Feed Storage Tank**	**Blocks** **Streams**	To P-101
Properties	Horizontal Pressure Vessel Floating Roof Tank		

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	5665.92465	ft3/hr			ASPEN
Holding Time	T	7	days	168	hours	
Bare Module Factor	F_{BM}	3.05	Horizontal Presure Vessel			SSLW, Table 22.11

Equations	**Source**
V = Q*T	
Cp = 475 V^0.51	SSLW, Table 23.32
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$1,484,142**
C_{BM}	**$4,526,634**

T-102	**Product Storage Tank**	**Blocks**	From P-102
Properties	Horizontal Pressure Vessel Floating Roof Tank		

Data		**Value**	**Units**	**Value**	**Units**	**Source**
Volumetric Flow Rate	Q	4709.53394	ft3/hr			ASPEN
Holding Time	T	2	days	48	hours	
Bare Module Factor	F_{BM}	3.05	Horizontal Pressure Vessel			SSLW, Table 22.11

Equations	**Source**
V = Q*T	
Cp = 475 V^0.51	SSLW, Table 23.32
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$712,938**
C_{BM}	**$2,174,460**

F-101	**Fired Heater**	**Blocks**	From E-102	To R-101
		Streams	From 3	To 4
Properties				

Data		**Value**	**Units**	**Source**
Heat Duty	Q	9265792.3	Btu/hr	ASPEN
Pressure	P	754.19624	psig	ASPEN
Material Factor	F_M	1.7	Stainless Steel	SSLW, pg. 573
Bare Module Factor	F_{BM}	1.86	Furnaces and direct fired heaters, Field-fabricated	SSLW, Table 22.11

Equations	**Source**
$Fp = 0.986 - 0.035(P/500) + 0.0175(P/500)^2$	SSLW, (22.51)
$Cb = \exp\{0.32325+0.766[\ln(Q)]\}$	SSLW, (22.49)
$Cp=Fp*Fm*Cb$	SSLW, (22.50)
$Cbm = Fbm*Cp$	SSLW, (22.12)

C_P	**$1,007,592**
C_{BM}	**$1,874,121**

E-101	**Heat Exchanger 1**	**Blocks**	From V-101 and P-103	To E-102 and V-105
		Streams	From 7 and 1	To 2 and 8
Properties				

Data		**Value**	**Units**	**Source**
Hot Inlet Temp	Thi	437	F	
Hot Outlet Temp	Tho	186.8	F	
Cold Inlet Temp	Tci	78.3	F	
Cold Outlet Temp	Tco	303.3	F	
Surface Area	A	1867.6	sqft	
Heat Duty	Q	33721285.2	Btu/hr	
Heat Transfer Coefficient	U	149.7	Btu/hr-sqft-R	
Pressure	P	797.7	psi	
Tube Length Correction	F_L	1		
Materials of Construction	a	2.7		
Materials of Construction	b	0.07		
Material Factor	F_M	3.9	Stainless steel/stainless steel	SSLW, pg. 571
Bare Module Factor	F_{BM}	3.17	Shell-and-tube heat exchangers	SSLW, Table 22.11

Equations	**Source**
ΔTlm = (Thi-Tco)-(Tho-Tci)/ln((Thi-Tco)/(Thc-Tci))	SSLW, (18.3)
A= Q/(U*Ft*ΔTlm)	SSLW, (18.2)
Fp = 0.9803+0.018*(P/100)+0.0017*(P/100)^2	SSLW, (22.45)
Cb = exp(11.0545-0.9228*(lnA+0.09861*lnA^2))	SSLW, (22.40)
Cp = $F_P F_M F_L C_B$	SSLW, (22.43)
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$78,835**
C_{BM}	**$249,907**

E-102	**Heat Exchanger 2**	**Blocks**	From E-101 and R-101	To F-101 and V-101
		Streams	From 2 and 5	3 and 6
Properties				

Data		**Value**	**Units**	**Source**
Hot Inlet Temp	Thi	662	F	
Hot Outlet Temp	Tho	519	F	
Cold Inlet Temp	Tci	303.3	F	
Cold Outlet Temp	Tco	617	F	
Surface Area	A	108.9	sqft	
Heat Duty	Q	57893017.3	Btu/hr	
Heat Transfer Coefficient	U	149.7	Btu/hr-sqft-R	
Pressure	P	797.7	psi	
Tube Length Correction	F_L	1		
Materials of Construction	a	2.7		
Materials of Construction	b	0.07		
Material Factor	F_M	4.0	Stainless steel/stainless steel	SSLW, pg. 571
Bare Module Factor	F_{BM}	3.2	Shell-and-tube heat exchangers	SSLW, Table 22.11

Equations	**Source**
ΔTlm = (Thi-Tco)-(Tho-Tci)/ln((Thi-Tco)/(Thc-Tci))	SSLW, (18.3)
A= Q/(U*Ft*ΔTlm)	SSLW, (18.2)
Fp = 0.9803+0.018*(P/100)+0.0017*(P/100)^2	SSLW, (22.45)
Cb = exp(11.0545-0.9228*(lnA+0.09861*lnA^2))	SSLW, (22.40)
Cp = $F_P F_M F_L C_B$	SSLW, (22.43)
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$119,577**
C_{BM}	**$379,058**

H-101	**Air Cooler 1**	**Blocks**	From V-101	To V-102
		Streams	From 9	To 10
Properties	Fin fan cooler			

Data		**Value**	**Units**	**Source**
Hot Inlet Temp	Thi	471	F	
Hot Outlet Temp	Tho	68	F	
Surface Area	A	6847.4	sqft	
Heat Duty	Q	71292563	Btu/hr	
Heat Transfer Coefficient	U	50	Btu/hr-sqft-R	[Source 51]
Pressure	P	609	psi	
Materials of Construction	a	2.7		
Materials of Construction	b	0.07		
Material Factor	F_M	3.2	Stainless steel/stainless steel	SSLW, pg. 571
Bare Module Factor	F_{BM}	2.17	Fin-fan air cooler	SSLW, Table 22.11

Equations	**Source**
ΔTlm = (Thi-Tco)-(Tho-Tci)/ln((Thi-Tco)/(Thc-Tci))	SSLW, (18.3)
A= Q/(U*Ft*ΔTlm)	SSLW, (18.2)
Fm = a + (A/100)^b	SSLW, (22.44)
Cb = exp(11.0545-0.9228*(lnA+0.09861*lnA^2))	SSLW, (22.40)
Cp = 2500*A^0.40	SSLW, Table 23.1
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$85,508**
C_{BM}	**$185,551**

H-102	**Air Cooler 2**	**Blocks**	From V-103	To V-104
		Streams	From 14	To 15
Properties				

Data		**Value**	**Units**	**Source**
Hot Inlet Temp	Thi	198.7	F	
Hot Outlet Temp	Tho	77	F	
Surface Area	A	2356.7	sqft	
Heat Duty	Q	15127226	Btu/hr	
Heat Transfer Coefficient	U	50	Btu/hr-sqft-R	[Source 51]
Pressure	P	609	psi	
Materials of Construction	a	2.7		
Materials of Construction	b	0.07		
Material Factor	F_M	3.2	Stainless steel/stainless steel	SSLW, pg. 571
Bare Module Factor	F_{BM}	2.17	Fin-fan air cooler	SSLW, Table 22.11

Equations	**Source**
ΔTlm = (Thi-Tco)-(Tho-Tci)/ln((Thi-Tco)/(Thc-Tci))	SSLW, (18.3)
A= Q/(U*Ft*ΔTlm)	SSLW, (18.2)
Cb = exp(11.0545-0.9228*(lnA+0.09861*lnA^2))	SSLW, (22.40)
Cp = 2500*A^0.40	SSLW, Table 23.1
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$55,830**
C_{BM}	**$121,150**

H-103	**Air Cooler 3**	**Blocks**	From V-103	To V-105
		Streams	From 16	To 17
Properties				

Data		**Value**	**Units**	**Source**
Hot Inlet Temp	Thi	189	F	
Hot Outlet Temp	Tho	77	F	
Surface Area	A	3121.4	sqft	
Heat Duty	Q	19491178	Btu/hr	
Heat Transfer Coefficient	U	50	Btu/hr-sqft-R	[Source 51]
Pressure	P	29	psi	
Materials of Construction	a	2.7		
Materials of Construction	b	0.07		
Material Factor	F_M	3.2	Stainless steel/stainless steel	SSLW, pg. 571
Bare Module Factor	F_{BM}	2.17	Fin-fan air cooler	SSLW, Table 22.11

Equations	**Source**
ΔTlm = (Thi-Tco)-(Tho-Tci)/ln((Thi-Tco)/(Thc-Tci))	SSLW, (18.3)
A= Q/(U*Ft*ΔTlm)	SSLW, (18.2)
Cb = exp(11.0545-0.9228*(lnA+0.09861*lnA^2))	SSLW, (22.40)
Cp = 2500*A^0.40	SSLW, Table 23.1
Cbm = Fbm*Cp	SSLW, (22.12)

C_P	**$62,471**
C_{BM}	**$135,562**

VI. Profitability Analysis Spreadsheet

General Information

Process Title:	Algae to Alkanes
Product:	n-alkane
Plant Site Location:	Thompsons, TX
Site Factor:	1.00
Operating Hours per Year:	7920
Operating Days Per Year:	330
Operating Factor:	0.9041

Product Information

This Process will Yield

35,230	gal of n-alkane per hour
845,514	gal of n-alkane per day
279,019,678	gal of n-alkane per year

Price $3.02 /gal

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 15 year MACRS	Product Price
2010	Design		0.0%		
2011	Construction	100%	0.0%		
2012	Production	0%	45.0%	5.00%	$3.02
2013	Production	0%	67.5%	9.50%	$3.08
2014	Production	0%	90.0%	8.55%	$3.14
2015	Production		90.0%	7.70%	$3.20
2016	Production		90.0%	6.93%	$3.27
2017	Production		90.0%	6.23%	$3.33
2018	Production		90.0%	5.90%	$3.40
2019	Production		90.0%	5.90%	$3.47
2020	Production		90.0%	5.91%	$3.54
2021	Production		90.0%	5.90%	$3.61
2022	Production		90.0%	5.91%	$3.68
2023	Production		90.0%	5.90%	$3.75
2024	Production		90.0%	5.91%	$3.83
2025	Production		90.0%	5.90%	$3.90
2026	Production		90.0%	5.91%	$3.98

Equipment Costs

Equipment Description		Bare Module Cost
Reactor	Process Machinery	$2,858,518
NiMo Catalyst	Catalysts	$975,166
HT Separator	Process Machinery	$991,275
LT Separator	Process Machinery	$351,567
Product Stripper	Process Machinery	$981,330
Decanter	Process Machinery	$191,323
Overhead Accumulator	Process Machinery	$275,388
Scrubber	Process Machinery	$5,754,292
Makeup Compressor	Process Machinery	$1,990,890
Makeup Compressor KO Drum	Process Machinery	$199,319
Recycke Compressor	Process Machinery	$1,023,040
Recycke Compressor KO Drum	Process Machinery	$310,449
Feed Storage Tank	Storage	$4,526,634
Feed Tank Pump	Process Machinery	$310,423
Product Storage Tank	Storage	$2,174,460
Product Tank Pump	Process Machinery	$283,879
Centrifugal Pump	Process Machinery	$876,514
Heat Exchanger 1	Process Machinery	$249,907
Heat Exchanger 2	Process Machinery	$379,058
Air Cooler 1	Process Machinery	$185,551
Air Cooler 2	Process Machinery	$121,150
Air Cooler 3	Process Machinery	$135,562
Feed Surge Drum	Process Machinery	$401,874
Furnace	Process Machinery	$1,874,121
Mod 2 Centrifuges	Process Machinery	$4,621,985
Mod 2 Clarifiers	Process Machinery	$8,973,828
Mod 2 Dryers	Process Machinery	$16,523,426
Mod 1 Equipment	Process Machinery	$2,199,808,863
Total		*$2,257,349,796*

Raw Materials

	Raw Material:	Unit:	Required Ratio:		Cost of Raw Material:	
1	Diluted Nutrient Mix	L	7.38348502	L per gal of n-alkane	$9.809E-03	per L
2	Hydrogen	lb	0.23344653	lb per gal of n-alkane	$1.00	per lb
3	Monoethanolamine	lb	2.2256E-05	lb per gal of n-alkane	$1.20	per lb
4	Water	L	22.0862508	L per gal of n-alkane	$0.00	per L
	Total Weighted Average:				$0.364	per gal of n-alkane

Byproducts

	Byproduct:	Unit:	Ratio to Product		Byproduct Selling Price	
1	Purge	MM Btu	0.00060968	MM Btu per gal of n-alkane	$3.000	per MM Btu
2	Propane	gal	0.09778302	gal per gal of n-alkane	$1.130	per gal
3		lb	0.11454032	lb per gal of n-alkane	$1.000	per lb
4	Livestock feed	kg	7.01752098	kg per gal of n-alkane	$0.290	per kg
	Total Weighted Average:				$2.262	per gal of n-alkane

Utilities

	Utility:	Unit:	Required Ratio		Utility Cost	
1	Low Pressure Steam	lb	0.46316923	lb per gal of n-alkane	$3.000E-03	per lb
2	Electricity	kWh	0.0988745	kWh per gal of n-alkane	$0.070	per kWh
3	Fuel Gas	gal	0.0002626	gal per gal of n-alkane	$2.600	per gal
4	Electricity Mod2	kWh	7.7045061	kWh per gal of n-alkane	$0.070	per kWh
5	Electricity Mod1	kWh	5.1363374	kWh per gal of n-alkane	$0.070	per kWh
	Total Weighted Average:				$0.908	per gal of n-alkane

Variable Costs

General Expenses:

Selling / Transfer Expenses:	3.00%	of Sales
Direct Research:	4.80%	of Sales
Allocated Research:	0.50%	of Sales
Administrative Expense:	2.00%	of Sales
Management Incentive Compensation:	1.25%	of Sales

Working Capital

Accounts Receivable	⇨	30	Days
Cash Reserves (excluding Raw Materials)	⇨	30	Days
Accounts Payable	⇨	30	Days
n-alkane Inventory	⇨	2	Days
Raw Materials	⇨	7	Days

Total Permanent Investment

Cost of Site Preparations:	1.00%	of Total Bare Module Costs
Cost of Service Facilities:	1.00%	of Total Bare Module Costs
Allocated Costs for utility plants and related facilities:	$0	
Cost of Contingencies and Contractor Fees:	9.00%	of Direct Permanent Investment
Cost of Land:	0.00%	of Total Depreciable Capital
Cost of Royalties:	$0	
Cost of Plant Start-Up:	10.00%	of Total Depreciable Capital

Fixed Costs

Operations

Operators per Shift:	4	(assuming 5 shifts)
Direct Wages and Benefits:	$35	/operator hour
Direct Salaries and Benefits:	15%	of Direct Wages and Benefits
Operating Supplies and Services:	6%	of Direct Wages and Benefits
Technical Assistance to Manufacturing:	$0.00	per year, for each Operator per Shift
Control Laboratory:	$0.00	per year, for each Operator per Shift

Maintenance

Wages and Benefits:	1.00%	of Total Depreciable Capital
Salaries and Benefits:	25%	of Maintenance Wages and Benefits
Materials and Services:	100%	of Maintenance Wages and Benefits
Maintenance Overhead:	5%	of Maintenance Wages and Benefits

Operating Overhead

General Plant Overhead:	7.10%	of Maintenance and Operations Wages and Benefits
Mechanical Department Services:	2.40%	of Maintenance and Operations Wages and Benefits
Employee Relations Department:	5.90%	of Maintenance and Operations Wages and Benefits
Business Services:	7.40%	of Maintenance and Operations Wages and Benefits

Property Taxes and Insurance

Property Taxes and Insurance:	2%	of Total Depreciable Capital

Straight Line Depreciation

Direct Plant:	8.00%	of Total Depreciable Capital, less 1.18 times the Allocated Costs for Utility Plants and Related Facilities
Allocated Plant:	6.00%	of 1.18 times the Allocated Costs for Utility Plants and Related Facilities

Other Annual Expenses

Rental Fees (Office and Laboratory Space):	$0
Licensing Fees:	$0
Miscellaneous:	$487,583

Depletion Allowance

Annual Depletion Allowance:	$0

Variable Cost Summary

Variable Costs at 100% Capacity:

General Expenses

Selling / Transfer Expenses:	$	25,259,079
Direct Research:	$	40,414,526
Allocated Research:	$	4,209,846
Administrative Expense:	$	16,839,386
Management Incentive Compensation:	$	10,524,616
Total General Expenses	$	97,247,452

Raw Materials	$0.364242	per gal of n-alkane	$101,630,781
Byproducts	$2.261945	per gal of n-alkane	($631,127,241)
Utilities	$0.907853	per gal of n-alkane	$253,308,716
Total Variable Costs		$	(178,940,291)

Fixed Cost Summary

Operations

Direct Wages and Benefits	$	1,456,000
Direct Salaries and Benefits	$	218,400
Operating Supplies and Services	$	87,360
Technical Assistance to Manufacturing	$	-
Control Laboratory	$	-
Total Operations	$	1,761,760

Maintenance

Wages and Benefits	$	25,028,919
Salaries and Benefits	$	6,257,230
Materials and Services	$	25,028,919
Maintenance Overhead	$	1,251,446
Total Maintenance	$	57,566,515

Operating Overhead

General Plant Overhead:	$	2,340,199
Mechanical Department Services:	$	791,053
Employee Relations Department:	$	1,944,672
Business Services:	$	2,439,081
Total Operating Overhead	$	7,515,005

Property Taxes and Insurance

Property Taxes and Insurance:	$	50,057,839

Other Annual Expenses

Rental Fees (Office and Laboratory Space):	$	-
Licensing Fees:	$	-
Miscellaneous:	$	487,583
Total Other Annual Expenses	$	487,583

Total Fixed Costs	$	117,388,702

Investment Summary

Bare Module Costs

Fabricated Equipment	$ -	
Process Machinery	$ 2,249,673,536	
Spares	$ -	
Storage	$ 558,300	
Other Equipment	$ -	
Catalysts	$ 975,166	
Computers, Software, Etc.	$ -	
Total Bare Module Costs:		$ 2,251,207,002

Direct Permanent Investment

Cost of Site Preparations:	$ 22,512,070	
Cost of Service Facilities:	$ 22,512,070	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		$ 2,296,231,142

Total Depreciable Capital

Cost of Contingencies & Contractor Fees	$ 206,660,803	
Total Depreciable Capital		$ 2,502,891,945

Total Permanent Investment

Cost of Land:	$ -	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 250,289,195	
Total Permanent Investment - Unadjusted		$ 2,753,181,140
Site Factor		1.00
Total Permanent Investment		$ 2,753,181,140

Working Capital

	2011	2012	2013
Accounts Receivable	$ 31,141,330	$ 15,570,665	$ 15,570,665
Cash Reserves	$ 13,692,693	$ 6,846,346	$ 6,846,346
Accounts Payable	$ (13,127,899)	$ (6,563,950)	$ (6,563,950)
n-alkane Inventory	$ 2,076,089	$ 1,038,044	$ 1,038,044
Raw Materials	$ 877,088	$ 438,544	$ 438,544
Total	$ 34,659,299	$ 17,329,650	$ 17,329,650
Present Value at 15%	*$ 30,138,521*	*$ 13,103,705*	*$ 11,394,526*

Total Capital Investment	$ 2,807,817,891

Cash Flow Summary

Year	Percentage of Design Capacity	Product Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Depletion Allowance	Taxible Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 15%
2010	0%		-	-	-	-	-	-	-	-	-	-	-	-
2011	0%		-	(2,753,181,100)	(34,659,300)	-	-	-	-	-	-	-	(2,787,840,400)	(2,424,209,100)
2012	45%	$3.02	378,886,200	-	(17,329,600)	80,523,100	(117,388,700)	(125,144,600)	-	216,876,000	(86,750,400)	130,125,600	237,940,600	(2,244,291,800)
2013	68%	$3.08	579,695,900	-	(17,329,600)	123,200,400	(119,736,500)	(237,774,700)	-	345,385,000	(138,154,000)	207,231,000	427,676,100	(1,963,087,900)
2014	90%	$3.14	788,386,400	-	-	167,552,500	(122,131,200)	(213,997,300)	-	619,810,400	(247,924,200)	371,886,300	585,883,500	(1,628,107,100)
2015	90%	$3.20	804,154,100	-	-	170,903,600	(124,573,800)	(192,722,700)	-	657,761,200	(263,104,500)	394,656,700	587,379,400	(1,336,075,700)
2016	90%	$3.27	820,237,200	-	-	174,321,700	(127,065,300)	(173,450,400)	-	694,043,100	(277,617,200)	416,425,900	589,876,300	(1,081,055,900)
2017	90%	$3.33	836,641,900	-	-	177,808,100	(129,606,600)	(155,930,200)	-	728,913,200	(291,565,300)	437,347,900	593,278,100	(858,020,700)
2018	90%	$3.40	853,374,700	-	-	181,364,200	(132,198,700)	(147,670,600)	-	754,869,600	(301,947,900)	452,921,800	600,592,400	(661,686,000)
2019	90%	$3.47	870,442,200	-	-	184,991,500	(134,842,700)	(147,670,600)	-	772,920,400	(309,168,200)	463,752,300	611,422,900	(487,881,400)
2020	90%	$3.54	887,851,100	-	-	188,691,400	(137,539,600)	(147,920,900)	-	791,082,000	(316,432,800)	474,649,200	622,570,100	(333,991,600)
2021	90%	$3.61	905,608,100	-	-	192,465,200	(140,290,400)	(147,670,600)	-	810,112,300	(324,044,900)	486,067,400	633,738,000	(197,773,900)
2022	90%	$3.68	923,720,300	-	-	196,314,500	(143,096,200)	(147,920,900)	-	829,017,700	(331,607,100)	497,410,600	645,331,500	(77,156,900)
2023	90%	$3.75	942,194,700	-	-	200,240,800	(145,958,100)	(147,670,600)	-	848,806,700	(339,522,700)	509,284,000	656,954,700	29,616,600
2024	90%	$3.83	961,038,600	-	-	204,245,600	(148,877,300)	(147,920,900)	-	868,486,000	(347,394,400)	521,091,600	669,012,500	124,167,300
2025	90%	$3.90	980,259,300	-	-	208,330,500	(151,854,800)	(147,670,600)	-	889,064,400	(355,625,800)	533,438,700	681,109,300	207,871,900
2026	90%	$3.98	999,864,500	-	69,318,600	212,497,100	(154,891,900)	(147,920,900)	-	909,548,800	(363,819,500)	545,729,300	762,968,800	289,406,300

Profitability Measures

The Internal Rate of Return (IRR) for this project is	17.10%
The Net Present Value (NPV) of this project in 2010 is	$ 289,406,300

ROI Analysis (Third Production Year)

Annual Sales	788,386,359
Annual Costs	45,421,325
Depreciation	(220,254,491)
Income Tax	(245,421,277)
Net Earnings	368,131,916
Total Capital Investment	2,822,499,738
ROI	13.04%

Sensitivity Analyses

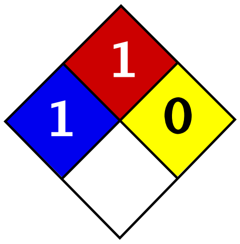
Note: The Sensitivity Analyses section below takes quite a bit of memory to update each time a cell is changed; therefore, automatic calculations are turned off. After making your axis selections, press "F9" to recalculate the IRR values. (These two lines may be deleted before printing.)

	Vary Initial Value by +/-
x-axis	353%
y-axis	100%

							Variable Costs					
		$452,187,000	$325,961,542	$199,736,083	$73,510,625	##############	#############	##############	##############	##############	##############	##############
Fixed Costs	.00%	6.07%	9.35%	12.28%	14.97%	17.48%	19.86%	22.12%	24.30%	26.40%	28.44%	30.43%
	$23,477,740	5.28%	8.65%	11.64%	14.37%	16.92%	19.31%	21.60%	23.79%	25.90%	27.95%	29.95%
	$46,955,481	4.48%	7.94%	10.99%	13.77%	16.34%	18.77%	21.07%	23.27%	25.40%	27.46%	29.47%
	$70,433,221	3.64%	7.21%	10.33%	13.16%	15.77%	18.21%	20.54%	22.76%	24.90%	26.97%	28.98%
	$93,910,962	2.78%	6.47%	9.66%	12.54%	15.18%	17.66%	20.00%	22.24%	24.40%	26.48%	28.50%
	$117,388,702	1.88%	5.71%	8.98%	11.91%	14.60%	17.10%	19.47%	21.72%	23.89%	25.98%	28.02%
	$140,866,442	0.95%	4.92%	8.29%	11.28%	14.00%	16.54%	18.93%	21.20%	23.38%	25.49%	27.53%
	$164,344,183	-0.02%	4.11%	7.58%	10.63%	13.40%	15.97%	18.38%	20.68%	22.87%	24.99%	27.04%
	$187,821,923	-1.05%	3.28%	6.85%	9.97%	12.79%	15.39%	17.83%	20.15%	22.36%	24.49%	26.55%
	$211,299,664	-2.14%	2.42%	6.11%	9.31%	12.17%	14.81%	17.28%	19.62%	21.85%	23.99%	26.06%
	$234,777,404	Negative IRR	1.52%	5.35%	8.63%	11.55%	14.23%	16.73%	19.08%	21.33%	23.49%	25.57%

VII. Material Safety Data Sheets (MSDS)

ScienceLab.com
Chemicals & Laboratory Equipment



Health	1
Fire	1
Reactivity	0
Personal Protection	E

Material Safety Data Sheet
Eicosane MSDS

Section 1: Chemical Product and Company Identification

Product Name: Eicosane

Catalog Codes: SLE2197

CAS#: 112-95-8

RTECS: Not available.

TSCA: TSCA 8(b) inventory: Eicosane

CI#: Not applicable.

Synonym:

Chemical Name: Eicosane

Chemical Formula: $C_{20}H_{42}$

Contact Information:

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

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

Order Online: ScienceLab.com

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

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

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

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Eicosane	112-95-8	100

Toxicological Data on Ingredients: Not applicable.

Section 3: Hazards Identification

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

Potential Chronic Health Effects:
CARCINOGENIC EFFECTS: Not available.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.
DEVELOPMENTAL TOXICITY: Not available.
Repeated or prolonged exposure is not known to aggravate medical condition.

Section 4: First Aid Measures

Eye Contact: No known effect on eye contact, rinse with water for a few minutes.

Skin Contact:

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

Serious Skin Contact: Not available.

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

Serious Inhalation: Not available.

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

Serious Ingestion: Not available.

Section 5: Fire and Explosion Data

Flammability of the Product: May be combustible at high temperature.

Auto-Ignition Temperature: Not available.

Flash Points: Not available.

Flammable Limits: Not available.

Products of Combustion: These products are carbon oxides (CO, CO2).

Fire Hazards in Presence of Various Substances: Slightly flammable to flammable in presence of open flames and sparks.

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

Fire Fighting Media and Instructions:
SMALL FIRE: Use DRY chemical powder.
LARGE FIRE: Use water spray, fog or foam. Do not use water jet.

Special Remarks on Fire Hazards: Not available.

Special Remarks on Explosion Hazards: Not available.

Section 6: Accidental Release Measures

Small Spill:
Use appropriate tools to put the spilled solid in a convenient waste disposal container. Finish cleaning by spreading water on the contaminated surface and dispose of according to local and regional authority requirements.

Large Spill:
Use a shovel to put the material into a convenient waste disposal container. Finish cleaning by spreading water on the contaminated surface and allow to evacuate through the sanitary system.

Section 7: Handling and Storage

Precautions:
Keep away from heat. Keep away from sources of ignition. Empty containers pose a fire risk, evaporate the

residue under a fume hood. Ground all equipment containing material. Do not breathe dust.

Storage:
Keep container dry. Keep in a cool place. Ground all equipment containing material. Keep container tightly closed. Keep in a cool, well-ventilated place. Combustible materials should be stored away from extreme heat and away from strong oxidizing agents.

Section 8: Exposure Controls/Personal Protection

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

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

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

Exposure Limits: Not available.

Section 9: Physical and Chemical Properties

Physical state and appearance: Solid.

Odor: Not available.

Taste: Not available.

Molecular Weight: 282.56 g/mole

Color: Not available.

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

Boiling Point: Not available.

Melting Point: 37°C (98.6°F)

Critical Temperature: Not available.

Specific Gravity: Not available.

Vapor Pressure: Not applicable.

Vapor Density: Not available.

Volatility: Not available.

Odor Threshold: Not available.

Water/Oil Dist. Coeff.: Not available.

Ionicity (in Water): Not available.

Dispersion Properties: See solubility in water, diethyl ether.

Solubility:
Soluble in diethyl ether.
Insoluble in cold water.

Section 10: Stability and Reactivity Data

Stability: The product is stable.

Instability Temperature: Not available.

Conditions of Instability: Not available.

Incompatibility with various substances: Slightly reactive to reactive with oxidizing agents.

Corrosivity: Not available.

Special Remarks on Reactivity: Not available.

Special Remarks on Corrosivity: Not available.

Polymerization: No.

Section 11: Toxicological Information

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

Toxicity to Animals:
LD50: Not available.
LC50: Not available.

Chronic Effects on Humans: Not available.

Other Toxic Effects on Humans: Slightly hazardous in case of skin contact (irritant).

Special Remarks on Toxicity to Animals: Not available.

Special Remarks on Chronic Effects on Humans: Not available.

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

Section 12: Ecological Information

Ecotoxicity: Not available.

BOD5 and COD: Not available.

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

Toxicity of the Products of Biodegradation: The product itself and its products of degradation are not toxic.

Special Remarks on the Products of Biodegradation: Not available.

Section 13: Disposal Considerations

Waste Disposal:

Section 14: Transport Information

DOT Classification: Not a DOT controlled material (United States).

Identification: Not applicable.

Special Provisions for Transport: Not applicable.

Section 15: Other Regulatory Information

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

Other Regulations: Not available..

Other Classifications:

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

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

HMIS (U.S.A.):

Health Hazard: 1

Fire Hazard: 1

Reactivity: 0

Personal Protection: E

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

Health: 1

Flammability: 1

Reactivity: 0

Specific hazard:

Protective Equipment:
Gloves.
Lab coat.
Dust respirator. Be sure to use an
approved/certified respirator or
equivalent.
Safety glasses.

Section 16: Other Information

References: Not available.

Other Special Considerations: Not available.

Created: 10/09/2005 05:26 PM

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

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Material Safety Data Sheet

Airgas

Carbon Dioxide

Section 1. Chemical product and company identification

Product Name : Carbon Dioxide

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

Product use : Synthetic/Analytical chemistry.

MSDS# : 001013

Date of Preparation/Revision : **4/11/2005.**

In case of emergency : 1-800-949-7937

Section 2. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Carbon Dioxide	124-38-9	100	**ACGIH TLV (United States, 9/2004).** STEL: 54000 mg/m^3 15 minute(s). Form: All forms STEL: 30000 ppm 15 minute(s). Form: All forms TWA: 9000 mg/m^3 8 hour(s). Form: All forms TWA: 5000 ppm 8 hour(s). Form: All forms **NIOSH REL (United States, 6/2001).** STEL: 54000 mg/m^3 15 minute(s). Form: All forms STEL: 30000 ppm 15 minute(s). Form: All forms TWA: 9000 mg/m^3 10 hour(s). Form: All forms TWA: 5000 ppm 10 hour(s). Form: All forms **OSHA PEL (United States, 6/1993).** TWA: 9000 mg/m^3 8 hour(s). Form: All forms TWA: 5000 ppm 8 hour(s). Form: All forms

Section 3. Hazards identification

Physical state : Gas.

Emergency overview : Warning!

CONTENTS UNDER PRESSURE.
CAUSES DAMAGE TO THE FOLLOWING ORGANS: LUNGS, CARDIOVASCULAR SYSTEM, SKIN, EYES, CENTRAL NERVOUS SYSTEM, EYE, LENS OR CORNEA.
MAY CAUSE RESPIRATORY TRACT, EYE AND SKIN IRRITATION.

Avoid contact with skin and clothing. Avoid breathing gas. Do not puncture or incinerate container. Keep container closed. Use only with adequate ventilation. Wash thoroughly after handling.

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

Routes of entry : Inhalation,Dermal,Eyes

Potential acute health effects

Eyes : Moderately irritating to the eyes.

Skin : Moderately irritating to the skin.

Inhalation : Moderately irritating to the respiratory system.

Ingestion : Ingestion is not a normal route of exposure for gases

Potential chronic health effects : **CARCINOGENIC EFFECTS** Not available.
MUTAGENIC EFFECTS Not available.
TERATOGENIC EFFECTS: Not available.

Medical conditions aggravated by overexposure : Acute or chronic respiratory conditions may be aggravated by overexposure to this gas.

See toxicological Information (section 11)

Section 4. First aid measures

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

Eye contact : In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Get medical attention immediately.

Skin contact : In case of contact, immediately flush skin with plenty of water. Remove contaminated clothing and shoes. Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention.

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. If breathing is difficult, give oxygen. Get medical attention.

Ingestion : Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Get medical attention if symptoms appear.

Section 5. Fire fighting measures

Flammability of the product : Non-flammable.

Fire fighting media and instructions : Use an extinguishing agent suitable for surrounding fires.

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

No specific hazard.

Special protective equipment for fire-fighters : Fire fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full facepiece 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.

Section 7. Handling and storage

Handling : Avoid contact with eyes, skin and clothing. Keep container closed. Use only with adequate ventilation. Do not puncture or incinerate container. Wash thoroughly after handling. High pressure gas. 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 : Keep container tightly closed. Keep container in a cool, well-ventilated area. 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 airborne levels below recommended exposure 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 or gauntlets 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 : A self-contained breathing apparatus should be used to avoid inhalation of the product.

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight : 44.01 g/mole

Molecular formula : $CO2$

Boiling/condensation point : -78.55°C (-109.4°F)

Melting/freezing point : Sublimation temperature: -78.5°C (-109.3°F)

Critical temperature : 30.9°C (87.6°F)

Vapor pressure : 830 psig

Vapor density : 1.53 (Air = 1)

Specific Volume (ft^3/lb) : 8.77193

Gas Density (lb/ft^3) : 0.114

Physical chemical comments : Not available.

Section 10. Stability and reactivity

Stability and reactivity : The product is stable.

Section 11. Toxicological information

Toxicity data

IDLH : 40000 ppm

Chronic effects on humans : Causes damage to the following organs: lungs, cardiovascular system, skin, eyes, central nervous system (CNS), eye, lens or cornea.

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

Products of degradation	: These products are carbon oxides (CO, CO_2).
Toxicity of the products of biodegradation	: The product itself and its products of degradation are not toxic.
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	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).		-

Section 15. Regulatory information

United States

U.S. Federal regulations : TSCA 8(b) inventory: Carbon Dioxide

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

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

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

Clean air act (CAA) 112 accidental release prevention: No products were found.

Clean air act (CAA) 112 regulated flammable substances: No products were found.

Clean air act (CAA) 112 regulated toxic substances: No products were found.

State regulations : Pennsylvania RTK: Carbon Dioxide: (generic environmental hazard)
Massachusetts RTK: Carbon Dioxide
New Jersey: Carbon Dioxide

Canada

WHMIS (Canada) : Class A: Compressed gas.

CEPA DSL: Carbon Dioxide

Section 16. Other information

United States

Label Requirements : CONTENTS UNDER PRESSURE.
CAUSES DAMAGE TO THE FOLLOWING ORGANS: LUNGS, CARDIOVASCULAR SYSTEM, SKIN, EYES, CENTRAL NERVOUS SYSTEM, EYE, LENS OR CORNEA.
MAY CAUSE RESPIRATORY TRACT, EYE AND SKIN IRRITATION.

Canada

Label Requirements : Class A: Compressed gas.

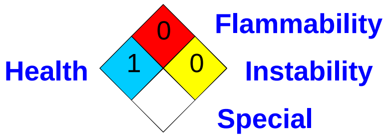
Hazardous Material Information System (U.S.A.) :

Health	*	1
Fire hazard		0
Reactivity		0
Personal protection		C

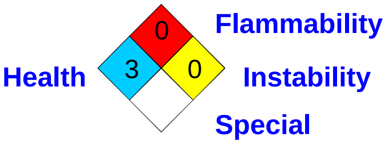
liquid:

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

Carbon Monoxide

Section 1. Chemical product and company identification

Product name : Carbon Monoxide

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

Product use : Synthetic/Analytical chemistry.

Synonym : carbone (oxyde de) (french); carbonic oxide; carbonio (ossido di) (italian); carbon monoxide ; carbon oxide (co); exhaust gas; flue gas; kohlenmonoxid (german); koolmonoxyde (dutch); oxyde de carbone (french); wegla tlenek (polish)

MSDS # : 001014

Date of Preparation/Revision : **6/8/2009.**

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

Section 2. Hazards identification

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

Emergency overview : WARNING!

FLAMMABLE GAS.
MAY CAUSE FLASH FIRE.
HARMFUL IF INHALED.
MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA.
CONTENTS UNDER PRESSURE.

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

Contact with rapidly expanding gases can cause frostbite.

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

Routes of entry : Inhalation

Potential acute health effects

- **Eyes** : Contact with rapidly expanding gas may cause burns or frostbite.
- **Skin** : Contact with rapidly expanding gas may cause burns or frostbite.
- **Inhalation** : Toxic by inhalation.
- **Ingestion** : Ingestion is not a normal route of exposure for gases

Potential chronic health effects : **CARCINOGENIC EFFECTS**: Not available.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.

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

See toxicological information (section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Carbon Monoxide	630-08-0	100	**ACGIH TLV (United States, 1/2008).** TWA: 29 mg/m³ 8 hour(s). TWA: 25 ppm 8 hour(s). **NIOSH REL (United States, 6/2008).** CEIL: 229 mg/m³ CEIL: 200 ppm TWA: 40 mg/m³ 10 hour(s). TWA: 35 ppm 10 hour(s). **OSHA PEL (United States, 11/2006).** TWA: 55 mg/m³ 8 hour(s). TWA: 50 ppm 8 hour(s). **OSHA PEL 1989 (United States, 3/1989).** CEIL: 229 mg/m³ CEIL: 200 ppm TWA: 40 mg/m³ 8 hour(s). TWA: 35 ppm 8 hour(s).

Section 4. First aid measures

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

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

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

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

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

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

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 608.89°C (1128°F)

Flammable limits : Lower: 12.5% Upper: 74.2%

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

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

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

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

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

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

Section 6. Accidental release measures

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

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

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

Section 7. Handling and storage

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

Storage : Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame). Segregate from oxidizing materials. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Section 8. Exposure controls/personal protection

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

Personal protection

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

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

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

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

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

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

Product name

Carbon monoxide

ACGIH TLV (United States, 1/2008).
TWA: 29 mg/m^3 8 hour(s).
TWA: 25 ppm 8 hour(s).
NIOSH REL (United States, 6/2008).
CEIL: 229 mg/m^3
CEIL: 200 ppm
TWA: 40 mg/m^3 10 hour(s).
TWA: 35 ppm 10 hour(s).
OSHA PEL (United States, 11/2006).
TWA: 55 mg/m^3 8 hour(s).

TWA: 50 ppm 8 hour(s).

OSHA PEL 1989 (United States, 3/1989).

CEIL: 229 mg/m³
CEIL: 200 ppm
TWA: 40 mg/m³ 8 hour(s).
TWA: 35 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 28.01 g/mole
Molecular formula	: C-O
Boiling/condensation point	: -191.7°C (-313.1°F)
Melting/freezing point	: -198.9°C (-326°F)
Critical temperature	: -140.1°C (-220.2°F)
Vapor density	: 0.97 (Air = 1)
Specific Volume (ft ^{3}/lb)	: 13.8889
Gas Density (lb/ft ^{3})	: 0.072

Section 10. Stability and reactivity

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

Section 11. Toxicological information

Toxicity data

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

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

Specific effects

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

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

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

Section 13. Disposal considerations

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

Section 14. Transport information

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

Carbon Monoxide

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

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

Section 15. Regulatory information

United States

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

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

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

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

Clean Air Act (CAA) 112 accidental release prevention: No products were found.

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

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

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

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

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

Canada

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

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

Section 16. Other information

United States

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

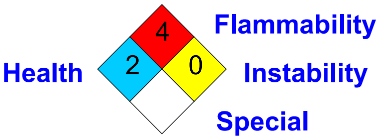
Canada

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

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

Health	*	2
Flammability		4
Physical hazards		0

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



Notice to reader

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

Material Safety Data Sheet

Hydrogen Sulfide

Section 1. Chemical product and company identification

Product Name : Hydrogen Sulfide

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 :

MSDS# : 001029

Date of Preparation/Revision : **2/12/2008.**

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

Section 2. Hazards identification

Physical state : Gas. (COLORLESS LIQUEFIED COMPRESSED GAS WITH A ROTTEN EGG ODOR, BUT ODORLESS AT POISONOUS CONCENTRATIONS. [NOTE: SENSE OF SMELL BECOMES RAPIDLY FATIGUED AND CAN NOT BE RELIED UPON TO WARN OF THE CONTINUOUS PRESENCE OF H2S.])

Emergency overview : Danger!

MAY BE FATAL IF INHALED.
FLAMMABLE GAS.
CONTENTS UNDER PRESSURE.
CAUSES DAMAGE TO THE FOLLOWING ORGANS: LUNGS, RESPIRATORY TRACT, EYES, CENTRAL NERVOUS SYSTEM, EYE, LENS OR CORNEA.
VAPOR MAY CAUSE FLASH FIRE.
MAY CAUSE EYE AND SKIN IRRITATION.

Avoid contact with skin and clothing. Do not breathe gas. Keep away from heat, sparks and flame. Do not puncture or incinerate container. Keep container closed. Use only with adequate ventilation. Wash thoroughly after handling.

Contact with rapidly expanding gases can cause frostbite.

Routes of entry : Inhalation,Dermal,Eyes

Potential acute health effects

- **Eyes** : Moderately irritating to the eyes.
- **Skin** : Moderately irritating to the skin.
- **Inhalation** : Very toxic by inhalation.
- **Ingestion** : Ingestion is not a normal route of exposure for gases

Potential chronic health effects : **CARCINOGENIC EFFECTS:** Not available.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.

Medical conditions aggravated by overexposure : Repeated exposure to a highly toxic material may produce general deterioration of health by an accumulation in one or many human organs.

See toxicological Information (section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits

Hydrogen Sulfide			
Hydrogen Sulfide	7783-06-4	100	**ACGIH TLV (United States, 9/2004). Notes: Substances for which the TLV is higher than the OSHA Permissible Exposure Limit (PEL) and/or the NIOSH Recommended Exposure Limit (REL). See CFR 58(124) :36338-33351, June 30, 1993, for revised OSHA PEL.** STEL: 21 mg/m^3 15 minute(s). Form: All forms STEL: 15 ppm 15 minute(s). Form: All forms TWA: 14 mg/m^3 8 hour(s). Form: All forms TWA: 10 ppm 8 hour(s). Form: All forms **NIOSH REL (United States, 6/2001).** CEIL: 15 mg/m^3 10 minute(s). Form: All forms CEIL: 10 ppm 10 minute(s). Form: All forms **OSHA PEL Z2 (United States, 6/2002).** AMP: 50 ppm 10 minute(s). Form: All forms CEIL: 20 ppm Form: All forms

Section 4. First aid measures

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

Eye contact	:	In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Get medical attention immediately.
Skin contact	:	In case of contact, immediately flush skin with plenty of water. Remove contaminated clothing and shoes. Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention.
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. If breathing is difficult, give oxygen. Get medical attention immediately.
Ingestion	:	Do NOT induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Get medical attention if symptoms appear.

Section 5. Fire fighting measures

Flammability of the product	:	Flammable.
Auto-ignition temperature	:	259.85°C (499.7°F)
Flammable limits	:	Lower: 4% Upper: 44%
Products of combustion	:	These products are sulfur oxides (SO_2, SO_3...).
Fire fighting media and instructions	:	In case of fire, use water spray (fog), foam, dry chemicals, or CO_2. If involved in fire, shut off flow immediately if it can be done without risk. Apply water from a safe distance to cool container and protect surrounding area. Extremely flammable. Gas may accumulate in confined areas, travel considerable distance to source of ignition and flash back causing fire or explosion.
Special protective equipment for fire-fighters	:	Fire fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full facepiece 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.

Section 7. Handling and storage

Handling	: Avoid contact with eyes, skin and clothing. Keep container closed. Use only with adequate ventilation. Keep away from heat, sparks and flame. To avoid fire, minimize ignition sources. Use explosion-proof electrical (ventilating, lighting and material handling) equipment. Do not puncture or incinerate container. Wash thoroughly after handling. High pressure gas. 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.
Storage	: Keep container tightly closed. Keep container in a cool, well-ventilated area. 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 airborne levels below recommended exposure limits. The engineering controls also need to keep gas, vapor or dust concentrations below any 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 or gauntlets 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	: Full chemical resistant suit and self-contained breathing apparatus only by trained and authorized persons.

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 34.08 g/mole
Molecular formula	: H2S
Boiling/condensation point	: -59.99°C (-76°F)
Melting/freezing point	: -82.77°C (-117°F)
Critical temperature	: 100.5°C (212.9°F)
Vapor pressure	: 252 psig
Vapor density	: 1.19 (Air = 1)
Specific Volume (ft^3/lb)	: 11.236
Gas Density (lb/ft^3)	: 0.089

Section 10. Stability and reactivity

Stability and reactivity : The product is stable.

Incompatibility with various substances : Extremely reactive or incompatible with oxidizing agents.

Section 11. Toxicological information

Toxicity data

Ingredient name	Test	Result	Route	Species
Hydrogen Sulfide	LC50	712 ppm (1 hour (s))	Inhalation	Rat
	LC50	634 ppm (1 hour (s))	Inhalation	Mouse

IDLH : 100 ppm

Chronic effects on humans : Causes damage to the following organs: lungs, upper respiratory tract, eyes, central nervous system (CNS), eye, lens or cornea.

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

Ingredient name	Species	Period	Result
Hydrogen Sulfide	Pimephales promelas (LC50)	96 hour(s)	0.007 mg/l
	Oncorhynchus mykiss (LC50)	96 hour(s)	0.007 mg/l
	Pimephales promelas (LC50)	96 hour(s)	0.0071 mg/l
	Lepomis macrochirus (LC50)	96 hour(s)	0.009 mg/l
	Pimephales promelas (LC50)	96 hour(s)	0.0107 mg/l
	Oncorhynchus mykiss (LC50)	96 hour(s)	0.012 mg/l

Products of degradation : These products are sulfur oxides (SO_2, SO_3...).

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

Environmental fate : Not available.

Environmental hazards : Very toxic to aquatic organisms.

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	UN1053	HYDROGEN SULFIDE	2.3	Not applicable (gas).	 	**Reportable quantity** 100 lbs. (45.36 kg) **Limited quantity** Yes.

						Packaging instruction **Passenger Aircraft** Quantity limitation: Forbidden. **Cargo Aircraft** Quantity limitation: Forbidden. **Special provisions** 2, B9, B14
TDG Classification	UN1053	HYDROGEN SULFIDE; OR HYDROGEN SULPHIDE	2.3	Not applicable (gas).	 	**Explosive Limit and Limited Quantity Index** 0 **ERAP Index** 0 **Passenger Carrying Ship Index** Forbidden **Passenger Carrying Road or Rail Index** Forbidden
Mexico Classification	UN1053	HYDROGEN SULFIDE	2.3	Not applicable (gas).	 	-

Section 15. Regulatory information

United States

U.S. Federal regulations : TSCA 8(b) inventory: Hydrogen Sulfide

SARA 302/304/311/312 extremely hazardous substances: Hydrogen Sulfide
SARA 302/304 emergency planning and notification: Hydrogen Sulfide
SARA 302/304/311/312 hazardous chemicals: Hydrogen Sulfide
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: Hydrogen Sulfide: Fire hazard, Sudden Release of Pressure, Immediate (Acute) Health Hazard, Delayed (Chronic) Health Hazard

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

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

Clean air act (CAA) 112 accidental release prevention: Hydrogen Sulfide

Clean air act (CAA) 112 regulated flammable substances: No products were found.

Clean air act (CAA) 112 regulated toxic substances: Hydrogen Sulfide

SARA 313

	Product name	CAS number	Concentration
Form R - Reporting requirements :	Hydrogen Sulfide	7783-06-4	100
Supplier notification :	Hydrogen Sulfide	7783-06-4	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 : Pennsylvania RTK: Hydrogen Sulfide: (environmental hazard, generic environmental hazard)
Massachusetts RTK: Hydrogen Sulfide
New Jersey: Hydrogen Sulfide

Canada

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

CEPA DSL: Hydrogen Sulfide

Section 16. Other information

United States

Label Requirements : MAY BE FATAL IF INHALED.
FLAMMABLE GAS.
CONTENTS UNDER PRESSURE.
CAUSES DAMAGE TO THE FOLLOWING ORGANS: LUNGS, RESPIRATORY TRACT, EYES, CENTRAL NERVOUS SYSTEM, EYE, LENS OR CORNEA.
VAPOR MAY CAUSE FLASH FIRE.
MAY CAUSE EYE AND SKIN IRRITATION.

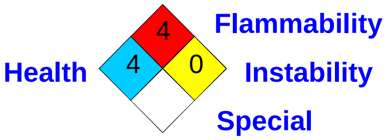
Canada

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

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

Health	*	4
Fire hazard		4
Reactivity		0
Personal protection		C

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



Notice to reader

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Material Safety Data Sheet

Hydrogen

Section 1. Chemical product and company identification

Product name : Hydrogen

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 : Dihydrogen; o-Hydrogen; p-Hydrogen; Molecular hydrogen; H2; UN 1049; UN 1966; Liquid hydrogen (LH2 or LH2)

MSDS # : 001026

Date of Preparation/Revision : **3/26/2010.**

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.

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.

Potential chronic health effects : **CARCINOGENIC EFFECTS**: Not available.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.

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
Hydrogen	1333-74-0	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 : 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 : Flammable.

Auto-ignition temperature : 399.85 to 573.75°C (751.7 to 1064.8°F)

Flammable limits : Lower: 4% Upper: 75%

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: oxidizing 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. 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	
hydrogen	Oxygen Depletion [Asphyxiant]

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight : 2.02 g/mole

Molecular formula : H2

Boiling/condensation point : -253.2°C (-423.8°F)

Melting/freezing point : -259.2°C (-434.6°F)

Critical temperature : -240.1°C (-400.2°F)

Vapor density : 0.07 (Air = 1)   Liquid Density@BP: 4.43 lb/ft3 (70.96 kg/m3)

Specific Volume (ft ^{3}/lb) : 14.0845

Gas Density (lb/ft ^{3}) : 0.071

Section 10. Stability and reactivity

Stability and reactivity : The product is stable.

Incompatibility with various substances : Extremely reactive or incompatible with the following materials: oxidizing materials.

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

Hazardous polymerization : Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

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

Specific effects

Carcinogenic effects : No known significant effects or critical hazards.

Mutagenic effects : No known significant effects or critical hazards.

Reproduction toxicity : No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

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	UN1049 UN1966	HYDROGEN, COMPRESSED Hydrogen, refrigerated liquid	2.1	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: Forbidden. **Cargo aircraft** Quantity limitation: 150 kg
TDG Classification	UN1049 UN1966	HYDROGEN, COMPRESSED Hydrogen, refrigerated liquid	2.1	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **ERAP Index** 3000 **Passenger Carrying Ship Index** Forbidden **Passenger**

						Carrying Road or Rail Index Forbidden
Mexico Classification	UN1049 UN1966	HYDROGEN, COMPRESSED Hydrogen, refrigerated liquid	2.1	Not applicable (gas).		-

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

Section 15. Regulatory information

United States

U.S. Federal regulations : TSCA 8(a) IUR: hydrogen
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: hydrogen
SARA 311/312 MSDS distribution - chemical inventory - hazard identification: hydrogen: Fire hazard, Sudden release of pressure

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

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

Clean Air Act (CAA) 112 accidental release prevention: hydrogen

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

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

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

Canada

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

CEPA Toxic substances: This material is not listed.
Canadian ARET: This material is not listed.
Canadian NPRI: This material is 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.
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.

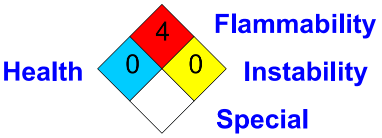
Hazardous Material Information System (U.S.A.) :

Health	0
Flammability	4
Physical hazards	0

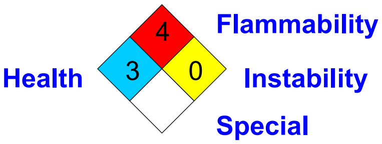
liquid:

Health	3
Fire hazard	4
Reactivity	0
Personal protection	

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



liquid:



Notice to reader

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

MATERIAL SAFETY DATA SHEET

SECTION 1. PRODUCT IDENTIFICATION

PRODUCT NAME: **Methane** **FORMULA:** CH_4
CHEMICAL NAME: Methane, Saturated Alphatic Hydrocarbon, Alkane
SYNONYMS: Methyl Hydride, Marsh Gas, Fire Damp

MANUFACTURER: **Air Products and Chemicals, Inc.**
7201 Hamilton Boulevard
Allentown, PA 18195 - 1501

PRODUCT INFORMATION : (800) 752-1597

MSDS NUMBER: 1070 **REVISION:** 6
REVIEW DATE: July 1999 **REVISION DATE:** July 1999

SECTION 2. COMPOSITION / INFORMATION ON INGREDIENTS

Methane is packaged as pure product (>99%).

CAS NUMBER: 74-82-8

EXPOSURE LIMITS:
OSHA: None established **ACGIH:** Simple Asphyxiant **NIOSH:** None established

SECTION 3. HAZARD IDENTIFICATION

EMERGENCY OVERVIEW

Methane is a flammable, colorless, odorless, compressed gas packaged in cylinders under high pressure. It poses an immediate fire and explosion hazard when mixed with air at concentrations exceeding 5.0%. High concentrations that can cause rapid suffocation are within the flammable range and should not be entered.

EMERGENCY TELEPHONE NUMBERS
800 - 523 - 9374 in Continental U.S. , Canada and Puerto Rico
610 - 481 - 7711 outside U.S.

ACUTE POTENTIAL HEALTH EFFECTS:
ROUTES OF EXPOSURE:
EYE CONTACT: No harmful affect.
INGESTION: Not applicable
INHALATION: Methane is nontoxic. It can, however, reduce the amount of oxygen in the air necessary to support life. Exposure to oxygen-deficient atmospheres (less than 19.5 %) may produce dizziness, nausea, vomiting, loss of consciousness, and death. At very low oxygen concentrations (less than 12 %) unconsciousness and death may occur without warning. It should be noted that before suffocation could occur, the lower flammable limit for Methane in air will be exceeded; causing both an oxygen deficient and an explosive atmosphere.
SKIN CONTACT: No harmful affect.
POTENTIAL HEALTH EFFECTS OF REPEATED EXPOSURE:
ROUTE OF ENTRY: None
SYMPTOMS: None

TARGET ORGANS: None
MEDICAL CONDITIONS AGGRAVATED BY OVEREXPOSURE: None
CARCINOGENICITY: Methane is not listed as a carcinogen or potential carcinogen by NTP, IARC, or OSHA Subpart Z.

SECTION 4. FIRST AID MEASURES

EYE CONTACT: No treatment necessary.
INGESTION: Not applicable
INHALATION: Remove person to fresh air. If not breathing, administer artificial respiration. If breathing is difficult, administer oxygen. Obtain prompt medical attention.
SKIN CONTACT: No treatment necessary.
NOTES TO PHYSICIAN: Treatment of overexposure should be directed at the control of symptoms and the clinical condition.

SECTION 5. FIRE FIGHTING MEASURES

FLASH POINT:	AUTOIGNITION:	FLAMMABLE RANGE:
-306 °F (-187.8 °C)	999 °F (537 °C)	5.0% - 15%

EXTINGUISHING MEDIA: Dry chemical, carbon dioxide, or water.
SPECIAL FIRE FIGHTING INSTRUCTIONS: Evacuate all personnel from area. If possible, without risk, shut off source of methane, then fight fire according to types of materials burning. Extinguish fire only if gas flow can be stopped. This will avoid possible accumulation and re-ignition of a flammable gas mixture. Keep adjacent cylinders cool by spraying with large amounts of water until the fire burns itself out. Self-contained breathing apparatus (SCBA) may be required.

UNUSUAL FIRE AND EXPLOSION HAZARDS: Most cylinders are designed to vent contents when exposed to elevated temperatures. Pressure in a cylinder can build up due to heat and it may rupture if pressure relief devices should fail to function.
HAZARDOUS COMBUSTION PRODUCTS: Carbon monoxide

SECTION 6. ACCIDENTAL RELEASE MEASURES

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED: Evacuate immediate area. Eliminate any possible sources of ignition, and provide maximum explosion-proof ventilation. Use a flammable gas meter (explosimeter) calibrated for Methane to monitor concentration. Never enter an area where Methane concentration is greater than 1.0% (which is 20% of the lower flammable limit). An immediate fire and explosion hazard exists when atmospheric Methane concentration exceeds 5.0%. Use appropriate protective equipment (SCBA and fire resistant suit). Shut off source of leak if possible. Isolate any leaking cylinder. If leak is from container, pressure relief device or its valve, contact your supplier. If the leak is in the user's system, close the cylinder valve, safely vent the pressure, and purge with an inert gas before attempting repairs.

SECTION 7. STORAGE AND HANDLING

STORAGE: Store cylinders in a well-ventilated, secure area, protected from the weather. Cylinders should be stored upright with valve outlet seals and valve protection caps in place. There should be no sources of ignition. All electrical equipment should be explosion-proof in the storage areas. Storage areas must meet National Electrical Codes for class 1 hazardous areas. Flammable storage areas must be separated from oxygen and other oxidizers by a minimum distance of 20 ft. or by a barrier of non-combustible material at least 5 ft. high having a fire resistance rating of at least _ hour. Post "No Smoking or Open Flames" signs in the storage or use areas. Do not allow storage temperature to exceed 125 °F (52 °C). Storage should be away from heavily traveled areas and emergency exits. Full and empty cylinders should be segregated. Use a first-in first-out inventory system to prevent full containers from being stored for long periods of time.

HANDLING: Do not drag, roll, slide or drop cylinder. Use a suitable hand truck designed for cylinder movement. Never attempt to lift a cylinder by its cap. Secure cylinders at all times while in use. Use a pressure reducing regulator to safely discharge gas from cylinder. Use a check valve to prevent reverse flow into cylinder. Never apply flame or localized heat directly to any part of the cylinder. Do not allow any part of the cylinder to exceed 125 °F (52 °C). Use piping and equipment adequately designed to withstand pressures to be encountered. Once cylinder has been connected to properly purged and inerted process, open cylinder valve slowly and carefully. If user experiences any difficulty operating cylinder valve, discontinue use and contact supplier. Never insert an object (e.g., wrench, screwdriver, etc.) into valve cap openings. Doing so may damage valve causing a leak to occur. Use an adjustable strap-wrench to remove over-tight or rusted caps. All piped systems and associated equipment must be grounded. Electrical equipment should be non-sparking or explosion-proof.

SPECIAL PRECAUTIONS: Always store and handle compressed gas cylinders in accordance with Compressed Gas Association, Inc. (telephone 703-412-0900) pamphlet CGA P-1, ***Safe Handling of Compressed Gases in Containers***. Local regulations may require specific equipment for storage or use.

SECTION 8. EXPOSURE CONTROLS/PERSONAL PROTECTION

ENGINEERING CONTROLS:

VENTILATION: Provide adequate natural or explosion-proof ventilation to prevent accumulation of gas concentrations above 1.0% Methane (20% of LEL).

RESPIRATORY PROTECTION:

Emergency Use: Do not enter areas where Methane concentration is greater than 1.0% (20% of the LEL). Exposure to concentrations below 1.0% do not require respiratory protection.

EYE PROTECTION: Safety glasses and/or face shield.
SKIN PROTECTION: Leather gloves for handling cylinders. Fire resistant suit and gloves in emergency situations.
OTHER PROTECTIVE EQUIPMENT: Safety shoes are recommended when handling cylinders.

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

APPEARANCE, ODOR AND STATE: Colorless, odorless, flammable gas.
MOLECULAR WEIGHT: 16.04
BOILING POINT (1 atm): -258.7 °F (-161.5 °C)
SPECIFIC GRAVITY (Air = 1): 0.554
FREEZING POINT / MELTING POINT: -296. 5 °F (-182.5 °C)
VAPOR PRESSURE (At 70 _F (21.1 _C)): Permanent, noncondensable gas.
GAS DENSITY (At 70 _F (21.1 _C) and 1 atm): 0.042 lb/ft^3
SOLUBILITY IN WATER (vol/vol): 3.3 ml gas / 100 ml

SECTION 10. STABILITY AND REACTIVITY

CHEMICAL STABILITY: Stable
CONDITIONS TO AVOID: Cylinders should not be exposed to temperatures in excess of 125 °F (52 °C).
INCOMPATIBILITY (Materials to Avoid): Oxygen, Halogens and Oxidizers
REACTIVITY:

A) HAZARDOUS DECOMPOSITION PRODUCTS: None
B) HAZARDOUS POLYMERIZATION: Will not occur

SECTION 11. TOXICOLOGICAL INFORMATION

LC_{50} (Inhalation): Not applicable. Simple asphyxiant.
LD_{50} (Oral): Not applicable
LD_{50} (Dermal): Not applicable

SKIN CORROSIVITY: Methane is not corrosive to the skin.
ADDITIONAL NOTES: None

SECTION 12. ECOLOGICAL INFORMATION

AQUATIC TOXICITY: Not determined
MOBILITY: Not determined
PERSISTENCE AND BIODEGRADABILITY: Not determined
POTENTIAL TO BIOACCUMULATE: Not determined
REMARKS: This product does not contain any Class I or Class II ozone depleting chemicals.

SECTION 13. DISPOSAL CONSIDERATIONS

UNUSED PRODUCT / EMPTY CONTAINER: Return container and unused product to supplier. Do not attempt to dispose of residual or unused quantities.

DISPOSAL INFORMATION: Residual product in the system may be burned if a suitable burning unit (flair incinerator) is available on site. This shall be done in accordance with federal, state, and local regulations. Wastes containing this material may be classified by EPA as hazardous waste by characteristic (i.e., Ignitability, Corrosivity, Toxicity, Reactivity). Waste streams must be characterized by the user to meet federal, state, and local requirements.

SECTION 14. TRANSPORT INFORMATION

DOT SHIPPING NAME: Methane, compressed
HAZARD CLASS: 2.1
IDENTIFICATION NUMBER: UN1971
SHIPPING LABEL(s): Flammable gas
PLACARD (When required): Flammable gas

SPECIAL SHIPPING INFORMATION: Cylinders should be transported in a secure upright position in a well-ventilated truck. Never transport in passenger compartment of a vehicle. Ensure cylinder valve is properly closed, valve outlet cap has been reinstalled, and valve protection cap is secured before shipping cylinder.

CAUTION: Compressed gas cylinders shall not be refilled except by qualified producers of compressed gases. Shipment of a compressed gas cylinder which has not been filled by the owner or with the owner's written consent is a violation of Federal law (49 CFR 173.301).

NORTH AMERICAN EMERGENCY RESPONSE GUIDEBOOK NUMBER (NAERG #): 115

SECTION 15. REGULATORY INFORMATION

U.S. FEDERAL REGULATIONS:

EPA - ENVIRONMENTAL PROTECTION AGENCY

CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (40 CFR Parts 117 and 302)
Reportable Quantity (RQ): None

SARA TITLE III: Superfund Amendment and Reauthorization Act

SECTIONS 302/304: Emergency Planning and Notification (40 CFR Part 355)
Extremely Hazardous Substances: Methane is not listed.
Threshold Planning Quantity (TPQ): None
Reportable Quantity (RQ): None

SECTIONS 311/312: Hazardous Chemical Reporting (40 CFR Part 370)

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

SECTION 313: Toxic Chemical Release Reporting (40 CFR Part 372)
Methane does not require reporting under Section 313.

CLEAN AIR ACT:

SECTION 112 (r): Risk Management Programs for Chemical Accidental Release (40 CFR PART 68)

Methane is listed as a regulated substance.
Threshold Planning Quantity (TPQ): 10,000 lbs

TSCA: Toxic Substance Control Act

Methane is listed on the TSCA inventory.

OSHA - OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION:

29 CFR Part 1910.119: Process Safety Management of Highly Hazardous Chemicals

Methane is not listed in Appendix A as a highly hazardous chemical. However, any process that involves a flammable gas on site in one location, in quantities of 10,000 pounds
(4,553 kg) or greater is covered under this regulation unless it is used as fuel.

STATE REGULATIONS:

CALIFORNIA:

Proposition 65: This product is not a listed substance which the State of California requires warning under this statute.

SECTION 16. OTHER INFORMATION

NFPA RATINGS:		**HMIS RATINGS:**	
HEALTH:	= 1	HEALTH:	= 0
FLAMMABILITY:	= 4	FLAMMABILITY:	= 4
REACTIVITY:	= 0	REACTIVITY:	= 0
SPECIAL:	= SA*		

*SA denotes “Simple Asphyxiant” per Compressed Gas Association recommendation.

Material Safety Data Sheet

Propane

Section 1. Chemical product and company identification

Product name : Propane

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

Product use : Synthetic/Analytical chemistry.

Synonym : n-Propane; Dimethylmethane; Freon 290; Liquefied petroleum gas; Lpg; Propyl hydride; R 290; C3H8; UN 1075; UN 1978; A-108; Hydrocarbon propellant.

MSDS # : 001045

Date of Preparation/Revision : **4/7/2009.**

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

Section 2. Hazards identification

Physical state : Gas. [COLORLESS LIQUEFIED COMPRESSED GAS; ODORLESS BUT MAY HAVE SKUNK ODOR ADDED.]

Emergency overview : WARNING!

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

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

Contact with rapidly expanding gases can cause frostbite.

Target organs : May cause damage to the following organs: the nervous system.

Routes of entry : Inhalation

Potential acute health effects

- **Eyes** : Contact with rapidly expanding gas may cause burns or frostbite.
- **Skin** : Contact with rapidly expanding gas may cause burns or frostbite.
- **Inhalation** : Acts as a simple asphyxiant.
- **Ingestion** : Ingestion is not a normal route of exposure for gases

Potential chronic health effects : **CARCINOGENIC EFFECTS**: Not available.
MUTAGENIC EFFECTS: Not available.
TERATOGENIC EFFECTS: Not available.

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

See toxicological information (section 11)

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits

Propane			
Propane	74-98-6	100	**ACGIH TLV (United States, 1/2008).** TWA: 1000 ppm 8 hour(s). **NIOSH REL (United States, 6/2008).** TWA: 1800 mg/m³ 10 hour(s). TWA: 1000 ppm 10 hour(s). **OSHA PEL (United States, 11/2006).** TWA: 1800 mg/m³ 8 hour(s). TWA: 1000 ppm 8 hour(s). **OSHA PEL 1989 (United States, 3/1989).** TWA: 1800 mg/m³ 8 hour(s). TWA: 1000 ppm 8 hour(s).

Section 4. First aid measures

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

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

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

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

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

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

Section 5. Fire-fighting measures

Flammability of the product : Flammable.

Auto-ignition temperature : 449.85°C (841.7°F)

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

Flammable limits : Lower: 2.1% Upper: 9.5%

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

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

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

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

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

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

Section 6. Accidental release measures

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

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

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

Section 7. Handling and storage

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

Storage : Keep container in a cool, well-ventilated area. Keep container tightly closed and sealed until ready for use. Avoid all possible sources of ignition (spark or flame). Segregate from oxidizing materials. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Section 8. Exposure controls/personal protection

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

Personal protection

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

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

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

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

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

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

Product name

propane

ACGIH TLV (United States, 1/2008).
TWA: 1000 ppm 8 hour(s).
NIOSH REL (United States, 6/2008).
TWA: 1800 mg/m³ 10 hour(s).
TWA: 1000 ppm 10 hour(s).
OSHA PEL (United States, 11/2006).
TWA: 1800 mg/m³ 8 hour(s).
TWA: 1000 ppm 8 hour(s).
OSHA PEL 1989 (United States, 3/1989).
TWA: 1800 mg/m³ 8 hour(s).

TWA: 1000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	44.11 g/mole
Molecular formula	C3-H8
Boiling/condensation point	-41.8°C (-43.2°F)
Melting/freezing point	-185.9°C (-302.6°F)
Critical temperature	96.6°C (205.9°F)
Vapor pressure	109 (psig)
Vapor density	1.6 (Air = 1)
Specific Volume (ft ^{3}/lb)	8.6206
Gas Density (lb/ft ^{3})	0.116

Section 10. Stability and reactivity

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

Section 11. Toxicological information

Toxicity data

IDLH	2100 ppm
Chronic effects on humans	May cause damage to the following organs: the nervous system.
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	UN1978	PROPANE SEE ALSO PETROLEUM GASES, LIQUEFIED	2.1	Not applicable (gas).		**Limited quantity** Yes. **Packaging instruction** **Passenger aircraft** Quantity limitation: Forbidden. **Cargo aircraft** Quantity limitation: 150 kg **Special provisions** 19, T50
TDG Classification	UN1978	PROPANE	2.1	Not applicable (gas).		**Explosive Limit and Limited Quantity Index** 0.125 **ERAP Index** 3000 **Passenger Carrying Ship Index** 65 **Passenger Carrying Road or Rail Index** Forbidden **Special provisions** 29, 42
Mexico Classification	UN1978	PROPANE SEE ALSO PETROLEUM GASES, LIQUEFIED	2.1	Not applicable (gas).		-

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

Section 15. Regulatory information

United States

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

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

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

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

Clean Air Act (CAA) 112 accidental release prevention: propane

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

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

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

Canada

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

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

Section 16. Other information

United States

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

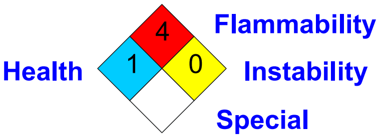
Canada

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

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

Health	*	1
Flammability		4
Physical hazards		0

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



Notice to reader

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