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Electrical Energy Storage Using Fuel Cell Technology

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Abstract
The goal of this project was to design three different energy storage systems utilizing reversible solid oxide fuel cells. Two of the systems use gaseous feed stocks and require storage for the gas produced by electrolysis. In the third design, molten antimony oxide is reduced to pure antimony during electrolysis rather than storing the energy in a gas. The three systems discussed in this report use electric power during off-peak demand hours to electrolyze a chemical feedstock. The resulting products are then stored for use during peak demand time in fuel cell operation. The systems were designed to store 1 MW of electrical power over a 12 hour period of off-peak demand and release power during a 12 hour period of peak demand. In the two gaseous systems, the fuel cell is made of an yttria-stabilized-zirconia (YSZ) electrolyte with porous nickel at the anode and YSZ-$LaMnO_3$ composite at the cathode.

In the electrolysis of steam to form hydrogen, the hydrogen is stored in pressurized vessels at 100 psi. During fuel cell mode, the hydrogen gas is oxidized in the fuel cell to form water, which is again stored for use in electrolysis the following day. The operating temperature for both electrolysis and fuel cell operation is 1472°F. The overall efficiency for the hydrogen system is 52.4%, with the main losses occurring as heat supplied to the electrolyzer.

The second design electrolyzes a mixture of steam to hydrogen and carbon dioxide to carbon monoxide at 1292°F and 147 psia. The resulting syngas is fed through a methanation reactor to produce a methane rich stream. The overall efficiency of the methane-based system is 55.7%, with the main losses coming from compression and heating for electrolysis mode.

The molten antimony fuel cell uses an equimolar mixture of antimony and antimony trioxide as the feedstock for electrolysis. The electric current in the electrolyzer reduces the antimony trioxide to form a stream of pure molten antimony. Both the electrolyzer and fuel cell operate isothermally at 1292°F and 14.7 psia. The overall efficiency for the antimony design is 53.7%, with the main losses coming from heat supplied to the electrolyzer.

For profitability analysis, off peak electricity was priced at $0.06/kWh and peak power was priced at $0.20/kWh. Under these optimistic assumptions, the return on investment (ROI) for the hydrogen design was calculated to be -26.1%. For the methane system, the ROI was calculated to be -19.2%. For the antimony case, the ROI was found to be -34.2%. These designs serve as a framework for future work with electrical energy storage. However, we believe that with improvements in system efficiency and reductions in the initial capital investment, future reversible fuel cell systems will be profitable and competitive with other forms of electrical energy storage.

UNIVERSITY OF PENNSYLVANIA

Electrical Energy Storage Using Fuel Cell Technology

Senior Design Project Written Report

Erica Harkins, Mark Pando, and David Sobel

4/12/2011

Faculty Advisor: Dr. Raymond J. Gorte

Professor Leonard A. Fabiano

Department of Chemical and Biomolecular Engineering
University of Pennsylvania
220 South 33rd Street
Philadelphia, PA 19104

April 12, 2011

Dear Mr. Fabiano, and Dr. Gorte,

This spring, our design team was presented with the task of designing three different processes for electrical energy storage using reversible solid oxide fuel cells (SOFCs). The project called for the design of a system that would store 1 MW of energy from either a renewable source or nuclear power plant. The reversible SOFC would run in electrolysis mode during off peak hours, converting the 1 MW of energy to a fuel that could be used to produce energy during peak hours by running the SOFC in fuel cell mode. To evaluate the feasibility of such a process, the economics and efficiencies of each system were examined.

The first system uses hydrogen as a fuel, producing only water in fuel cell mode. The second system uses both hydrogen and methane as fuels, converting them to carbon dioxide and water. A methanator is used in electrolysis mode to generate methane from carbon monoxide. The third system uses molten antimony as a fuel, converting it to antimony oxide in fuel cell mode. The profit for this process is generated by the difference in price of off peak and peak electricity.

Analysis of the systems indicates that at the current state of technology for reversible SOFCs and an electricity price difference of $0.14/kWh, for our specific designs given the time constraints, none of the three systems is profitable. The capital costs are too high compared to the small profit margin, and the yearly costs are greater than the revenues generated from electricity sales. Additionally, efficiencies achieved are all below 60%. The majority of losses are caused by fuel cell inefficiencies and heat requirements, factors that can only be improved by advancement in technology, no matter the process design surrounding the cell. The process designs, economic analyses, and recommendations are further discussed in this report.

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David Sobel

Table of Contents

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Introduction and Project Charter

The inspiration for this design project was a paper by Bierschenk et al.[1] that suggested using reversible solid oxide fuel cells as the basis for an efficient energy storage system. The basic concept behind the three design cases investigated in this project is the conversion of electrical into chemical energy through oxidation and reduction reactions. Bierschenk offers a variety of options for operating conditions, and the data presented in this paper was used as the foundation for two of the three fuel cell design options, the hydrogen and methane cases, presented in this report. The third option offers a completely novel method for using fuel cells reversibly; in this case, electrical energy is used to convert molten antimony into antimony oxide, eliminating this need for gas storage tanks. These three proposals could be used to store electricity generated by renewable energy technologies, or these systems could be used simply to store excess electricity from the grid. The goal of this design project was to determine the overall efficiency and cost of each of these systems.

Project Charter

Project Charter—Electrical Energy Storage Using Fuel Cell Technology

Project Champion: Dr. Raymond J. Gorte
Project Members: Erica Harkins, Mark Pando, and David Sobel
Specific Goals

- Design an energy storage system based on a reversible fuel cell system with a porous nickel anode capable of storing 1 MW of electrical energy
- Design an energy storage system based on a reversible fuel cell system with a molten antimony oxide anode capable of storing 1 MW of electrical energy
- Determine a cost of energy storage ($/kWh) for both systems

Project Scope

In Scope

- Storage capacity of 12 MWh off-peak electricity for use during peak demand
- Design storage tanks for molten Sb/Sb_2O_3
- Determine whether pure, stored oxygen or oxygen from ambient air is more economically advantageous
- Cost comparison of the three fuel cell designs

Out of Scope

- Cost comparison to other energy storage devices
- Explore possibility of using the high temperature exit gas to drive gas turbines
- Explore possibility of using a heat exchanger to transfer waste heat to steam for additional power generation

Deliverables

- Fully specified process designs for each energy storage system
- Process flow diagrams
- Successful ASPEN models

Business Feasibility

- Does the increase in capacity during peak demand from stored electricity justify the cost of these systems?

Time Line

- The project will be completed by April 12, 2011 and presented on April 21, 2011.

Fuel Cells

A fuel cell is an apparatus that produces power through an electrochemical reaction rather than combustion. In this regard, a fuel cell is like a battery, but it allows for a continuous supply of fuel and electricity. The absence of combustion in fuel cells translates to a substantial decrease in emissions when compared to traditional methods of power generation, so these technologies are more environmentally-responsible than fossil fuel combustion or burning coal. Furthermore, there are many different types of fuel cells that cater to many different aspects of energy management. From energy storage for intermittent renewable energy sources like solar and wind to primary power generation, fuel cells are an innovative technology that could prove to be an integral part of future energy portfolios.

The basic concept behind any fuel cell design is as follows: The side of the cell that houses the fuel is the anode, and the side that contains oxygen is the cathode. At the anode, the fuel is oxidized, producing electrons. The electrons then pass through an external circuit, extracting them from the system. At the cathode, the oxygen is reduced by addition of electrons. The two reactants are separated by an electrolyte barrier, through which ions, but not electrons, can pass.

Solid oxide fuel cells (SOFCs) are a particular type of fuel cell that use a solid ceramic electrolyte. SOFCs are often more efficient than other types of fuel cells due to the high operating temperature. The high operating temperature of SOFCs can also be advantageous for combined heat and power generation, which uses the "waste" heat to heat a fluid to turn a turbine, increasing the efficiency of the entire system. The elimination of liquid materials from operations can also extend the life of SOFCs since corrosion, the chemical degradation of components, cannot occur in a solid electrolyte. Also, SOFCs can process a wider range of chemicals than other types of fuel cells. In standard fuel cells, pure hydrogen is necessary for operation. The fuel for SOFCs is typically a mixture of hydrogen and carbon monoxide, both of which can be produced internally within the fuel cell from natural gas and water. Since the fuel can be reformed internally, external reformers for the fuel, which can be quite expensive, are not required. These simplifications can allows for more economically advantageous designs than one possible with other types of fuel cells, allowing SOFCs to expand into regions of the market dominated by more traditional means of power production. In order for an alternative energy source to replace combustion and fossil fuels, it needs to be able to carry a similar energy load as well as be financially competitive. Research demonstrates that SOFCs may be able to compete on this level.

Reversible Fuel Cells for Energy Storage

In addition to the option of using fuel cells for primary power generation, they can also be used reversibly for energy storage. In this process, excess electricity is used to electrolyze water and/or carbon dioxide to produce fuel for later consumption. This excess electricity can come from a renewable source, such as wind or solar, or it can be excess grid electricity during off-peak hours.

This project explores the possibility of utilizing SOFCs for energy storage. Three base cases, as described below, have been proposed, and each has been modeled and analyzed for overall efficiency and profitability. Each of the cases operates on a reversible SOFC with a YSZ electrolyte. During off-peak hours while operating as an electrolyzer, the fuel cell converts 1

MW of electricity into stored chemical energy. When demand levels increase during the day, that stored chemical energy is converted back into electricity. The hydrogen and methane cases store chemical energy in the form of a gas, and the work of Beirschenk et al. was used as the foundation. Alternatively, the molten antimony uses electricity to convert Sb_3O_2 to Sb, and no storage gas is needed. These three cases are detailed below.

Hydrogen Base Case

During electrolysis, liquid water from storage is vaporized and fed to the fuel cell, producing hydrogen that goes to storage and oxygen that is exhausted to the environment. In fuel cell mode, hydrogen is consumed and the liquid water is stored. These reactions are shown below in Table 1 in the Key Reactions section. In electrolysis mode, the operating voltage and current density are 1.07 V and -0.5 A/cm^2 respectively, and in fuel cell mode, they are 0.86 V and 0.55 A/cm^2. A turnover period of 30 minutes was assumed between each process. For the design presented in this report, an overall efficiency of 52% was achieved.

Methane Case

For this case, methane is internally reformed in the anode during fuel cell operation and the syngas that is produced is used as the fuel, producing water and carbon dioxide. These products are then reacted to syngas during electrolysis. These reactions can be seen in Table 2 of the Key Reactions section.

The presence of carbon dioxide in the electrolysis process allows for more flexibility in the fuel composition during fuel cell operation. Another advantage to the carbon dioxide base case is that the syngas can be further reacted to produce methane and reduce the storage vessel volume. This methanation reaction, Equation 1 , is performed over a nickel catalyst.

$$3H_2 + CO \overset{Ni}{\leftrightarrow} CH_4 + H_2O$$

Equation 1

The number of moles of gas for storage is reduced by a factor of four when the water is condensed out of the gas stream, significantly reducing storage costs. Furthermore, the additional cost of the methanation reactor is not significant. In electrolysis mode, the operating voltage and current density are 1.06 V and -0.5 A/cm^2 respectively, and in fuel cell mode, they are 0.923 V and 0.55 A/cm^2. A turnover period of 30 minutes was assumed between each process. For the design presented in this report, an overall efficiency of 55.7% was achieved.

Antimony Case

For the antimony case, the feed to for electrolysis mode is a molten, equimolar mixture of antimony and antimony trioxide. The antimony trioxide in the mixture is completely reduced in the electrolyzer, to produce an effluent stream of pure molten antimony. These reactions can be seen below in Table 3 of the Key Reactions section. Molten antimony is a conductor of electrons acts as both a product and the electrode. The molten nature of the anode allows for electrons to be easily transported throughout the mixture, which minimizes inefficiencies of typical fuel cells associated with transport of the reactants to the electrodes.

The pure antimony stream that is produced in electrolysis is stored for use as the fuel when operation shifts to fuel cell mode. The principle advantage of the antimony-based system is the significant reduction in fuel storage volume since the molten metal is much denser than the product gases for the hydrogen and methane systems. In electrolysis mode, the operating voltage and current density are 0.83 V and -0.20 A/cm^2 respectively, and in fuel cell mode, they are 0.662 V and 0.22 A/cm^2. A turnover period of 30 minutes was assumed between each process. For the design presented in this report, an overall efficiency of 55.7% was achieved.

Key Reactions

Table 1 - Hydrogen System Reactions

Electrolysis	Fuel Cell
$Cathode: H_2O + 2e^- \rightarrow H_2 + O^{2-}$	$Cathode: \frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$
$Anode: O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$	$Anode: H_2 + O^{2-} \rightarrow H_2O + 2e^-$
$Overall: H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$Overall: H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Table 2 - Methane System Reactions

Electrolysis	Fuel Cell
$Cathode: \begin{matrix} CO_2 + 2e^- \rightarrow CO + O^{2-} \\ H_2O + 2e^- \rightarrow H_2 + O^{2-} \end{matrix}$	$Cathode: O_2 + 4e^- \rightarrow 2O^{2-}$
$Anode: 2O^{2-} \rightarrow O_2 + 4e^-$	$Anode: \begin{matrix} H_2 + O^{2-} \rightarrow H_2O + 2e^- \\ CO + O^{2-} \rightarrow CO_2 + 2e^- \end{matrix}$
$Overall: CO_2 + H_2O \rightarrow CO + H_2$	$Overall: H_2 + CO + O_2 \rightarrow H_2O + CO_2$

Table 3 - Antimony System Reactions

Electrolysis	Fuel Cell
$Cathode: Sb_2O_3 \rightarrow 2Sb + 3O^{2-}$	$Cathode: \frac{3}{2}O_2 + 3e^- \rightarrow 3O^{2-}$
$Anode: 3O^{2-} \rightarrow \frac{3}{2}O_2 + 6e^-$	$Anode: 2Sb + 3O^{2-} \rightarrow Sb_2O_3$
$Overall: Sb_2O_3 \rightarrow 2Sb + \frac{3}{2}O_2$	$Overall: 2Sb + \frac{3}{2}O_2 \rightarrow Sb_2O_3$

Market and Competitive Analyses

SOFC devices can be used in both centralized and distributed applications since the designs are modular and can be scaled up easily. Additionally, the high operating temperature of SOFCs leads to a large amount of waste heat that can be used for combined heat and power generation systems in larger, centralized installations. SOFCs can achieve very high efficiencies without the use of expensive, precious metals like platinum. In addition, SOFCs can run off of fuels already widely available, allowing them to become integrated into the market with ease.

Energy storage is a young market that is likely to expand in the coming years as fuel prices continue to rise and carbon dioxide emissions become increasingly regulated. Responsible energy storage, increased use of renewable energy sources, and improved control infrastructures are all essential components of the Smart Grid, and the implementation of these could save vast amounts of resources and money. Energy prices will continue to increase in the coming years, and increases in efficiency will generate increasing saving as prices rise. Energy storage systems are essential to improving the efficiency of the grid, and fuel cell systems are particularly attractive due to their high efficiency, flexible design, and site independence. Fuel cells do not depend on natural resources such as wind or water reservoirs, so they can be implemented in wide range of sites. Current energy storage systems include pumped water storage, flywheels, advanced batteries, high-temperature solar thermal storage, and salt ponds. Other energy storage systems are being implemented, but some of these technologies are site-specific. For example, excess electricity generated during off-peak hours can be used to pump water uphill into a reservoir, but this method of energy storage requires a large amount of land and water.

Customer Requirements

Efficient Energy Storage

Energy storage to balance demand loads is a major component of the Smart Grid strategy proposed by the United States Department of Energy[2], and there are many creative engineering solutions being investigated for large-scale energy storage. Many of these technologies are still in the development stage, and market-proven solutions are needed. Low-cost energy storage will also improve the economic outlook for intermittent, renewable forms of energy, such as wind and solar power.

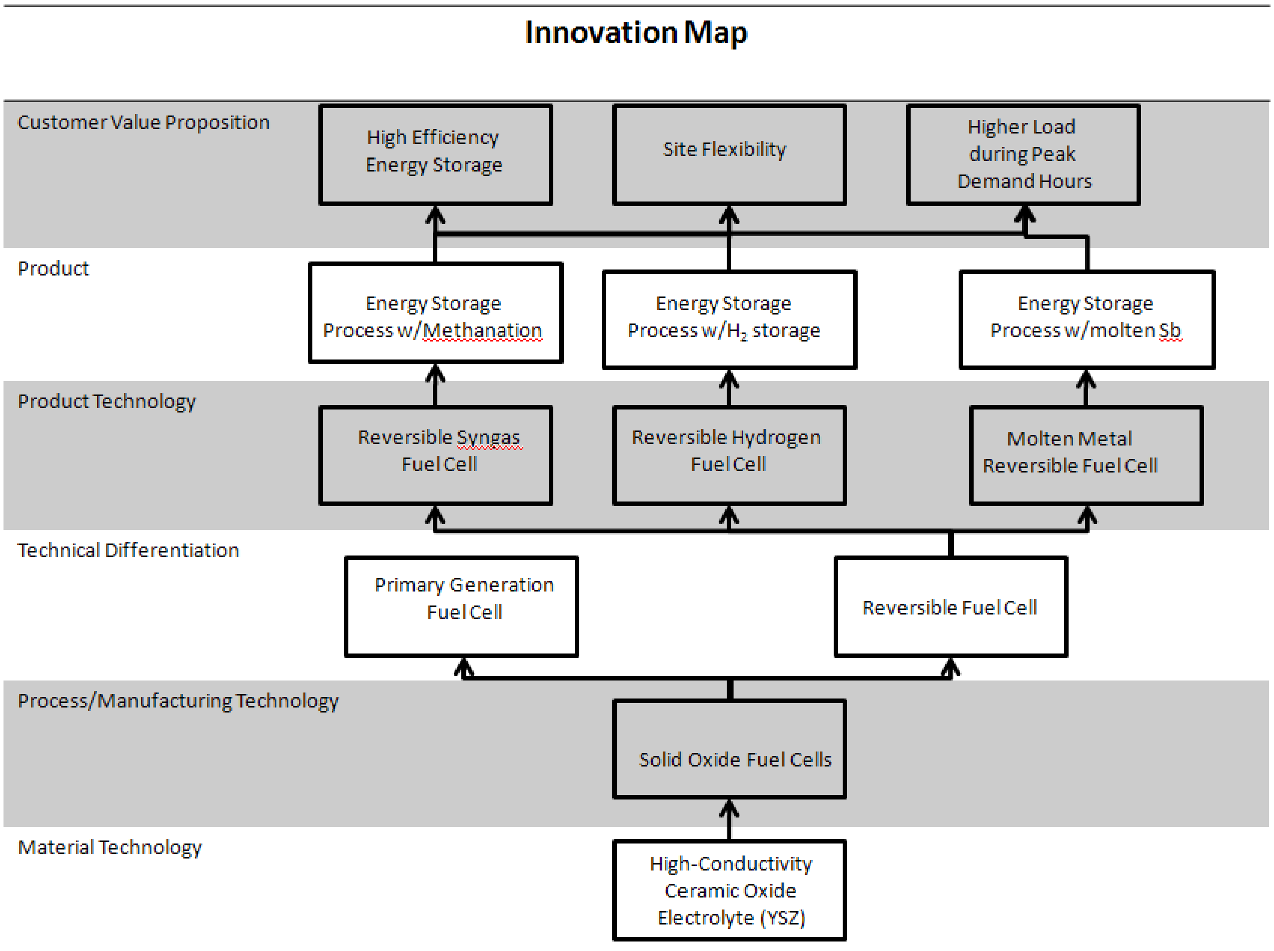
These fuel cell systems will be competing against a host of advanced technology energy storage solutions, yet fuel cells have unique characteristics that allow them to be suitable for a wide range of sites. The U.S. Department of Energy hopes to achieve a capital cost target of $1,250/kW and efficiency ratings about 80% for energy storage technologies over the next several years. These targets are ambitious, and they are long-term goals. Some energy storage options have already been deployed in large-scale installations, and the costs of these technologies will serve as points of comparison for future energy storage projects.

Pumped-hydro storage is a well-established energy storage technology that uses off-peak electricity to pump water uphill into a reservoir. During times of high demand, the water is allowed to flow downhill through turbines, regenerating electricity. These systems are typically 76-85% efficient[3]. However, these systems are only appropriate for sites with large amounts of available land and a natural rise in elevation.

Technology-Readiness Assessment

Innovation Map

Figure 1: Innovation Map



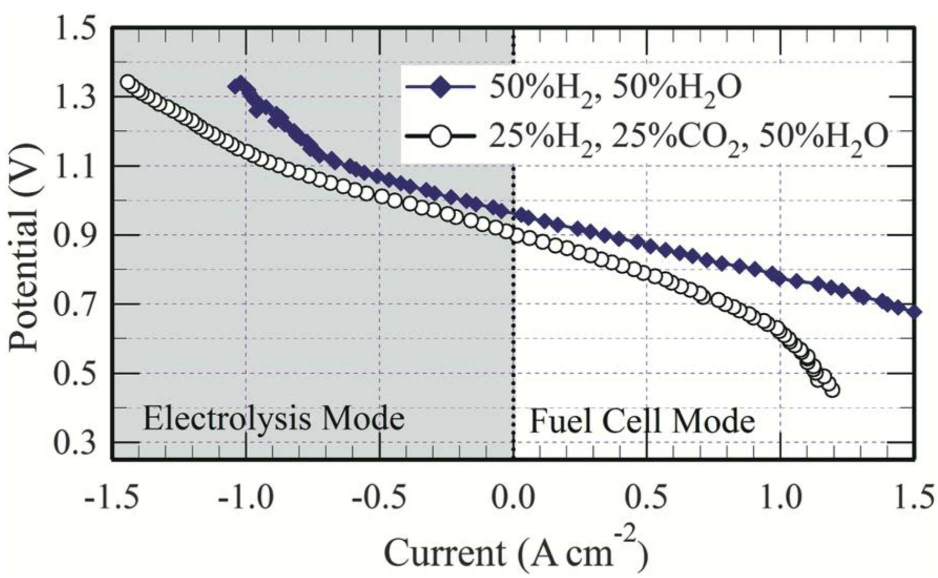
The YSZ electrolyte is the material technology that allows this process to yield high efficiency energy storage. This electrolyte can withstand extremely high temperatures, which leads to high ionic conductivity and improves cell efficiency. The process technology that implements the electrolyte is the solid oxide fuel cell. SOFCs can be part of fuel cell systems for both primary generation and reversible systems for energy storage. There are several different types of reversible fuel cell systems. The three examined in this use report utilize three different fuels, hydrogen, syngas and molten metal. The two gas-based fuel cell systems and the molten antimony system all produce the same product, energy storage of low-value off-peak electricity. Each system has its pros and cons, but each one allows the customer to increase power output during peak demand hours, increase plant flexibility and to efficiently store energy.

Preliminary Process Synthesis

Thermodynamics

The amount of chemical energy that can be converted into electricity depends on the Gibbs free energy of the system. The operating voltages and corresponding current densities were selected from the V-i curves in the papers by Bierschenk et al. and Gorte and Gross[4]. Figure 2 is the experimental V-i curve compiled by Bierschenk et al. This graph provides the fundamental electrical data for the hydrogen and methane cases. As seen below, the open cell voltage is observed at a current density of zero.

Figure 2: V-i Curve from Bierschenk et. al. for



The Nernst potential can be calculated using Equation 2, in which ΔG^o is the standard Gibbs free energy change of the reaction, n is the number of moles of electrons transferred in the reaction, and F is Faraday's constant.

$$E^o = -\frac{\Delta G^o}{nF}$$

Equation 2

The open circuit voltage can then be calculated using Equation 3, using partial pressures, where the i species are the reactants and the j species are the products.

$$E = E^o + \frac{RT}{nF} ln\left(\frac{\prod_i p_i^{v_i}}{\prod_j p_j^{v_j}}\right)$$

Equation 3

Ideally, the fuel cell operates at the open circuit potential, but voltage must be applied to drive the reactions. This additional voltage leads to heat losses due to cell inefficiencies, and the heat generated by the overpotential difference can be calculated using , in which V is the operating voltage, V_{OC} is the open cell voltage, i is the current density, and A is the cell area.

$$Heat = |V - V_{OC}| \times i \times A$$

Equation 4

These equations were taken from the Department of Energy Fuel Cell Handbook[5].

Electrolysis Mode

During electrolysis mode, electrical energy is converted into stored chemical energy as previously discussed. These reactions are endothermic, so heat must be supplied to the fuel cell during electrolysis mode in order to maintain a constant operating temperature. Some of the necessary heat is provided by the difference in operating voltage and open cell voltage, as demonstrated in Equation 4, but the remainder of this heat must be supplied from external sources. This heat can be supplied in a variety of ways. The fuel cell can be run at the thermoneutral voltage, or the feed stream can be heated above the operating temperature. A combination of these two methods of supplying heat can also be used. Regardless of how the heat is supplied to the system, this need for additional energy is a major contributor to the system efficiency. Another major consideration in electrolysis mode is storage. Each of the three cases in this project store different chemicals, and the cost of storage is significant in each case.

Fuel Cell Mode

Fuel cell mode is when electricity is reconverted from stored chemical energy. The reactions in this mode are highly exothermic, and heat is also produced by the difference in operating voltage and open cell voltage as in electrolysis mode. Large amounts of heat must be removed from the system as a result of these two factors. This can be accomplished by running excess air through the fuel cell.

Hydrogen Base Case

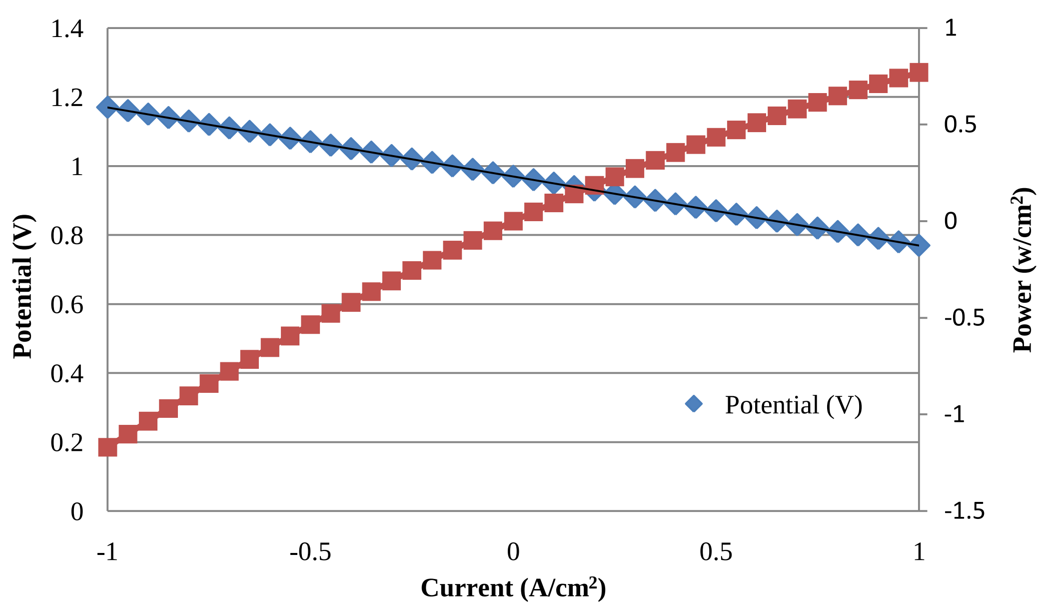
Concept Stage

The design of the hydrogen reversible fuel cell system can be divided into three major parts: determination of operating conditions, heat integration, and storage. The operating voltage and current must be decided before performing the mass and energy balances. Heat integration is especially vital to this system due to the high operating temperature of the fuel cell, and the outlet, high-temperature streams are used to preheat the inlet streams. The third element of the process design is the storage of the product streams in electrolysis mode. The pressure at which the gases are stored strongly affects the capital costs of the system.

Operating Conditions of the Fuel Cell

The operating conditions for our design were based on data from the Bierschenk et al. for a 50%/50% feed of water and hydrogen as seen in Figure 2. A linear approximation of this curve was calculated, shown below in Figure 3. As seen in the figure, the linear approximation held for the range of current densities from -1.0 A/cm^2 to 1.0 A/cm^2. A high conversion was desired for the process; therefore our design used a feedstock composition of 90% water and 10% hydrogen. Since the concentration of the feed does not have a large effect on open cell voltage for this case, the data from the linearized curve was used as the basis for the new feed composition.

Figure 3: V-i Curve for Hydrogen SOFC



A variety of factors affected the selection of the operating voltages and corresponding current densities. The operating times of electrolysis and fuel cell modes were determined first. The operating time of electrolysis was specified as 12 hours; we chose to include a down time between each change in mode to allow for changes in equipment, including valve control and thermal control. The U.S. Department of Energy has set a target of 20 minutes for start-up time by the year 2020[6], and we added 10 extra minutes onto this target. The result of this decision is that fuel cell mode operates 11 hours a day. In order to react all of the hydrogen being stored in the 12 hours of electrolysis mode, the current density of fuel cell mode had to be increased due to the reduction in operating time. This resulted in a slight loss of efficiency since the voltage had to be decreased to raise the current density, but it was decided that fully utilizing the storage gas justified this loss.

For the hydrogen case, the open circuit voltage is 0.97 V for the conditions of our system. However, to carry out electrolysis, a higher potential must be applied, with losses proportional to the difference between the actual voltage and the Nernst potential. Based on these reasons and the suggestions given in Bierschenk et al., 1.07 V and -0.5 A/cm^2 were chosen as the operating conditions for electrolysis. To allow for the operating time difference, 0.55 A/cm^2 and 0.87 V were selected for the operating conditions for fuel cell mode. The efficiency of the cell when run at these conditions was calculated to be 80.4%.

Heat Integration

The next component in the design of the hydrogen system was heat integration. The heating and cooling loads of each stream were matched in heat exchangers for maximum efficiency and the lowest utility load. In electrolysis mode, the feed stream entered the cell above the operating temperature since the electrolysis reaction is endothermic and requires heating during operation. The outlet streams from the electrolyzer did not have enough energy to completely vaporize and heat the inlet water stream, so additional heat had to be added to the system. The most significant energy sink for the inlet streams was the vaporization of water. Therefore, two options were examined to determine which would yield the lowest additional energy input.

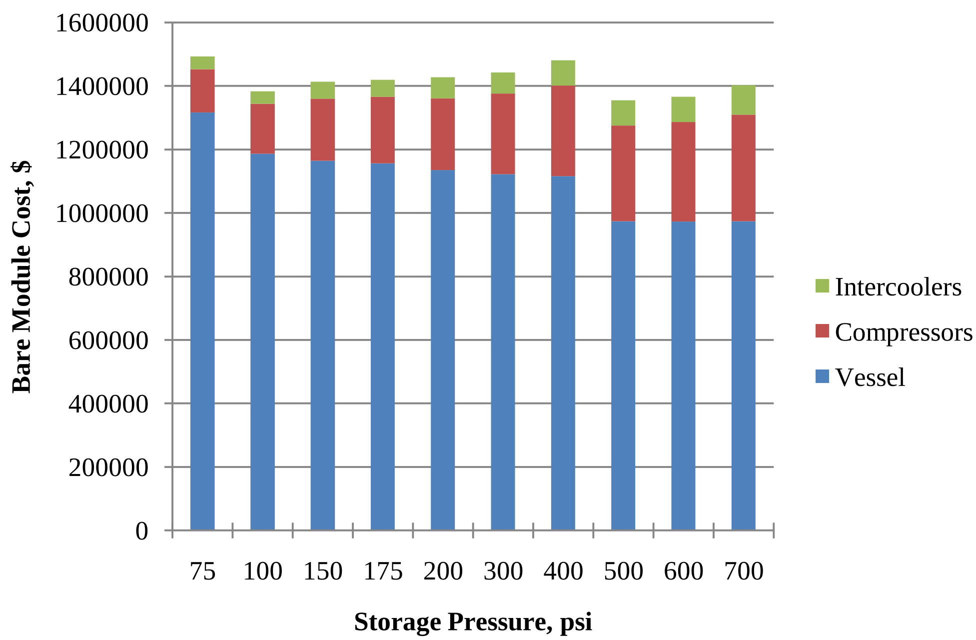
The first option was using a normal kettle vaporizer to boil all of the water. The water would be pumped at a pressure slightly above operating pressure and then vaporized to steam before entering the heat exchangers where it would be heated by the hot outlet streams. The second option was to use a flash vessel, incorporating a pressure swing along with heat. In this option, the water would be pumped to a high pressure, heated to the saturation temperature by an outlet stream, and then vaporized in a flash vessel that both increased the temperature and lowered the pressure of the feed. The flash method required less energy and was therefore chosen for the process.

Storage Pressure Selection

The third important component of the hydrogen system is the storage pressure of the product gases. There was a tradeoff in price between storage volume and wall thickness of the vessel. However, since vessels of a given diameter need to have a minimum wall thickness so that they can support their own weight, the most costly storage tanks are those with relatively low storage pressures, large volumes, and large diameters. Additionally, the aspect ratio (L/D) of the sample storage tanks was varied to determine which dimensions would yield the lowest price at each storage pressure.

Even though higher storage pressures result in smaller tanks, the cost of the hydrogen compression had to be considered in the sensitivity analysis. As suggested by one of the industrial consultants, the hydrogen should not exceed 250°F during compression for safety reasons. Therefore, intercoolers using cooling water were included between each compression stage, cooling the compressed hydrogen to 100°F before entering the next intercooler. Based on these specifications, the bare module cost of both compressors and intercoolers was determined, using an average value of U=14 Btu/ft^2-hr-°F for the intercooler heat transfer coefficients and carbon steel as the materials. Figure 9 shows the minimum bare module cost of vessel, compressors, and intercoolers for storage pressures from 75 psi to 700 psi.

Figure 4: Summary of Bare Module Cost for the Compression System



From the above graph, the minimum total bare module cost of $1,354,524 occurs at a storage pressure of 500 psi. At pressures above 500 psi, the costs of compression and cooling water exceed the vessel cost savings. However, the bare module cost for the storage pressure of 100 psi is $1,383,042. Because this is quite close to the cost at 500 psi, the difference in power required by the compressors and cooling water required by the intercoolers was examined.

Since the cooling water is inexpensive, its cost is negligible compared to the cost of the storage vessel. The difference in required power, however, affects both the cost and the overall efficiency of the system. The power required for compression to 100 psi is 34.0 kW, and the required power to compress to 500 psi is 64.5 kW. This 30.5 kW difference in compression power over the course of one year, at a rate of $0.06/kWh, is approximately $7,250. Therefore, over the lifetime of the equipment, the 100 psi storage system will be both less expensive and more efficient because it consumes less energy. Sample calculations for costs of these units can be seen in the Appendix on page 180 for the vessel, page 179 for compressors, and page 178 for intercoolers.

Process Flow Diagrams and Material Balances - Electrolysis

Figure 5: Process Flow Diagram for Electrolysis Mode of the Hydrogen Case

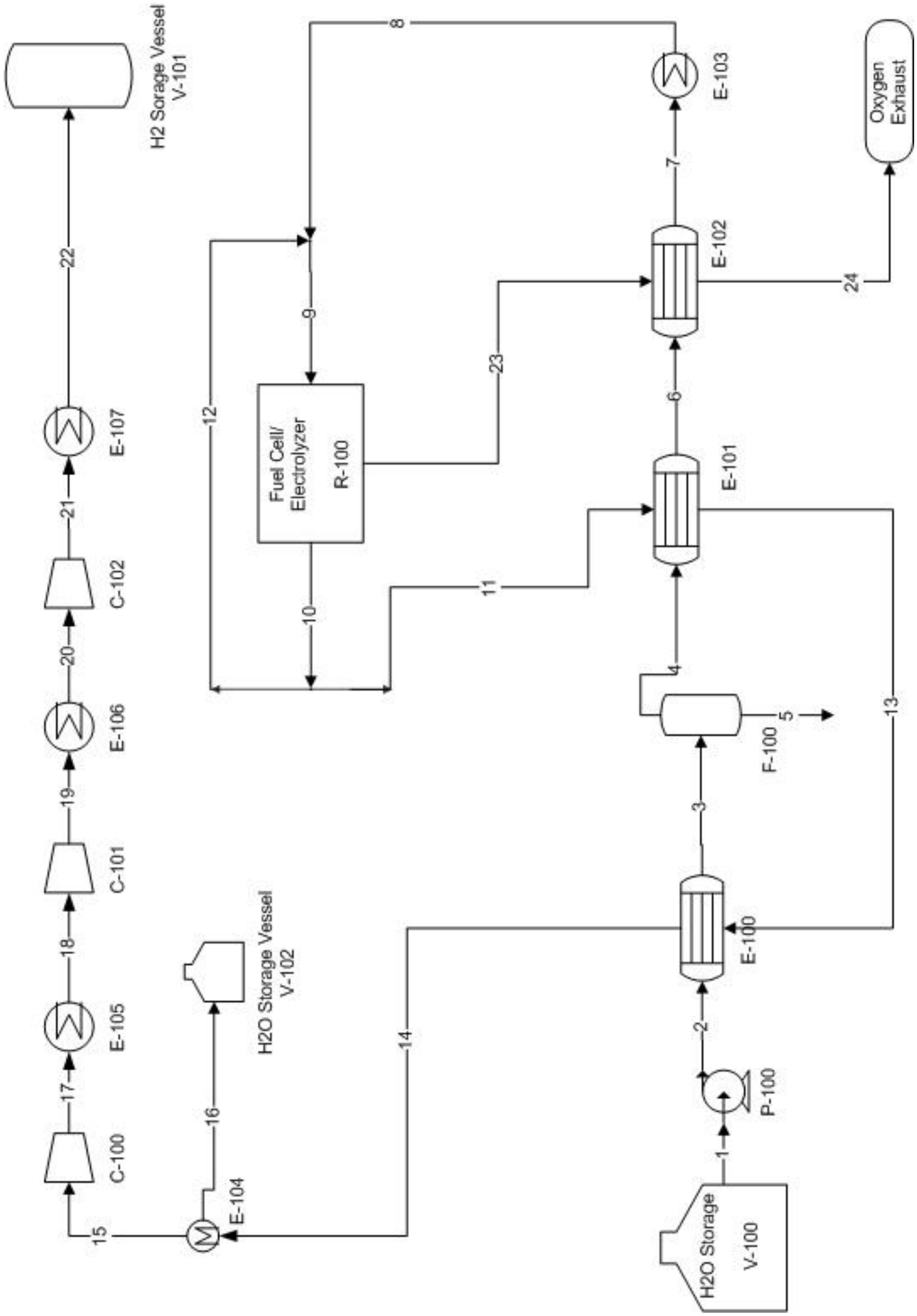


Table 4: Stream Summaries fo r Electrolysis Mode of the Hydrogen Case

		1	2	3	4	5	6	7	8
From			P-100	E-100	F-100	F-100	E-101	E-102	E-103
To		P-100	E-100	F-100	E-101		E-102	E-103	M-100
Substream: MIXED									
Phase:		Liquid	Liquid	Liquid	Vapor	Missing	Vapor	Vapor	Vapor
Component Mole Flow									
WATER	LBMOL/HR	42.71	42.71	42.71	42.71	0.00	42.71	42.71	42.71
HYDROGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Component Mass Flow									
WATER	LB/HR	769.38	769.38	769.38	769.38	0.00	769.38	769.38	769.38
HYDROGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole Flow	LBMOL/HR	42.71	42.71	42.71	42.71	0.00	42.71	42.71	42.71
Mass Flow	LB/HR	769.38	769.38	769.38	769.38	0.00	769.38	769.38	769.38
Volume Flow	CUFT/HR	12.39	12.39	13.89	13238.09	0.00	30783.36	36136.33	46771.24
Temperature	F	75.00	76.21	263.33	242.19		918.86	1133.99	1500.00
Pressure	PSIA	14.70	214.70	214.70	24.00	24.00	20.50	20.20	19.20
Vapor Fraction		0.00	0.00	0.00	1.00		1.00	1.00	1.00
Liquid Fraction		1.00	1.00	1.00	0.00		0.00	0.00	0.00
Molar Enthalpy	BTU/LBMOL	-1.24E+05	-1.24E+05	-1.20E+05	-1.03E+05		-9.68E+04	-9.48E+04	-9.12E+04
Mass Enthalpy	BTU/LB	-6.90E+03	-6.90E+03	-6.68E+03	-5.70E+03		-5.37E+03	-5.26E+03	-5.06E+03
Enthalpy Flow	BTU/HR	-5.31E+06	-5.31E+06	-5.14E+06	-4.38E+06		-4.13E+06	-4.05E+06	-3.89E+06
Molar Entropy	BTU/LBMOL-R	-40.97051	-40.92901	-34.67038	-9.443277		-3.30626	-1.923016	0.206747
Mass Entropy	BTU/LB-R	-2.274209	-2.271905	-1.924499	-5.24E-01		-1.84E-01	-1.07E-01	1.15E-02
Molar Density	LBMOL/CUFT	3.44805	3.445809	3.075152	3.23E-03		1.39E-03	1.18E-03	9.13E-04
Mass Density	LB/CUFT	6.21E+01	6.21E+01	5.54E+01	5.81E-02		2.50E-02	2.13E-02	1.64E-02

		9	10	11	12	13	14	15	16
From		M-100	FC-SPLIT	S-100	S-100	E-101	E-100	E-104	E-104
To		R-100	S-100	E-101	M-100	E-100	E-104	C-100	
Substream: MIXED									
Phase:		Vapor	Vapor	Vapor	Vapor	Vapor	Mixed	Vapor	Liquid
Component Mole Flow									
WATER	LBMOL/HR	43.24	4.81	4.28	0.53	4.28	4.28	0.03	4.25
HYDROGEN	LBMOL/HR	4.80	43.23	38.43	4.80	38.43	38.43	38.43	0.00
OXYGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Component Mass Flow									
WATER	LB/HR	779.01	86.70	77.07	9.63	77.07	77.07	0.54	76.53
HYDROGEN	LB/HR	9.68	87.15	77.47	9.68	77.47	77.47	77.47	0.00
OXYGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole Flow	LBMOL/HR	48.04	48.04	42.71	5.34	42.71	42.71	38.46	4.25
Mass Flow	LB/HR	788.69	173.85	154.54	19.31	154.54	154.54	78.01	76.53
Volume Flow	CUFT/HR	52556.08	51883.90	46119.60	5764.30	27165.38	14327.14	12461.37	1.23
Temperature	F	1497.54	1472.00	1472.00	1472.00	672.00	131.00	100.00	100.00
Pressure	PSIA	19.20	19.20	19.20	19.20	19.10	18.85	18.55	18.55
Vapor Fraction		1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00
Liquid Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Molar Enthalpy	BTU/LBMOL	-8.11E+04	-305.7493	-305.7493	-3.06E+02	-6.18E+03	-1.01E+04	7.80E+01	-1.22E+05
Mass Enthalpy	BTU/LB	-4.94E+03	-84.49623	-84.49623	-8.45E+01	-1.71E+03	-2.79E+03	3.84E+01	-6.80E+03
Enthalpy Flow	BTU/HR	-3.90E+06	-14689.68	-13057.65	-1632.023	-2.64E+05	-4.31E+05	2998.521	-5.20E+05
Molar Entropy	BTU/LBMOL-R	1.676249	8.270702	8.270702	8.270702	4.364414	-0.334624	-0.169587	-38.21244
Mass Entropy	BTU/LB-R	1.02E-01	2.285674	2.285674	2.29E+00	1.21E+00	-9.25E-02	-8.36E-02	-2.12E+00
Molar Density	LBMOL/CUFT	9.14E-04	9.26E-04	9.26E-04	9.26E-04	1.57E-03	2.98E-03	3.09E-03	3.441537
Mass Density	LB/CUFT	1.50E-02	3.35E-03	3.35E-03	3.35E-03	5.69E-03	1.08E-02	6.26E-03	6.20E+01

		17	18	19	20	21	22	23	24
From		C-100	E-105	C-101	E-106	C-102	E-107	FC-SPLIT	E-102
To		E-105	C-101	E-106	C-102	E-107		E-102	
Substream: MIXED									
Phase:		Vapor	Vapor	Vapor	Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow									
WATER	LBMOL/HR	0.03	0.03	0.03	0.03	0.03	0.03	0.00	0.00
HYDROGEN	LBMOL/HR	38.43	38.43	38.43	38.43	38.43	38.43	0.00	0.00
OXYGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	0.00	19.21	19.21
Component Mass Flow									
WATER	LB/HR	0.54	0.54	0.54	0.54	0.54	0.54	0.00	0.00
HYDROGEN	LB/HR	77.47	77.47	77.47	77.47	77.47	77.47	0.00	0.00
OXYGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00	614.84	614.84
Mole Flow	LBMOL/HR	38.46	38.46	38.46	38.46	38.46	38.46	19.21	19.21
Mass Flow	LB/HR	78.01	78.01	78.01	78.01	78.01	78.01	614.84	614.84
Volume Flow	CUFT/HR	8922.77	7295.89	5176.72	4193.01	2908.87	2319.09	20751.94	15076.57
Temperature	F	231.42	100.00	235.32	100.00	244.95	100.00	1472.00	929.00
Pressure	PSIA	32.00	31.70	55.51	55.21	100.30	100.00	19.20	19.00
Vapor Fraction		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Liquid Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molar Enthalpy	BTU/LBMOL	9.90E+02	7.84E+01	1.02E+03	7.93E+01	1087.337	80.83992	1.09E+04	6.39E+03
Mass Enthalpy	BTU/LB	4.88E+02	3.87E+01	5.02E+02	3.91E+01	536.0707	39.85509	3.39E+02	2.00E+02
Enthalpy Flow	BTU/HR	38073.77	3016.34	39158.34	3048.22	41818.09	3109.037	2.09E+05	1.23E+05
Molar Entropy	BTU/LBMOL-R	0.2100873	-1.233909	-0.8446195	-2.336089	-1.923533	-3.516454	9.235022	6.54463
Mass Entropy	BTU/LB-R	1.04E-01	-6.08E-01	-4.16E-01	-1.15E+00	-0.948326	-1.733656	2.89E-01	2.05E-01
Molar Density	LBMOL/CUFT	4.31E-03	5.27E-03	7.43E-03	9.17E-03	0.0132213	0.0165837	9.26E-04	1.27E-03
Mass Density	LB/CUFT	8.74E-03	1.07E-02	0.0150691	1.86E-02	0.0268174	0.0336376	2.96E-02	4.08E-02

Process Description

This section discusses the electrolysis mode of the hydrogen system, which operates for 12 hours per day during off-peak electricity demand. In electrolysis mode, 42.71 lbmol/hr of water is fed into the system from a storage tank. After being vaporized and preheated by the electrolyzer outlet streams, it is fed to the cathode of the electrolyzer which uses 1 MW of energy supplied from the power plant to convert it to hydrogen and oxygen. The hydrogen product stream is stored in a pressurized vessel after giving heat to the inlet streams. The oxygen formed at the anode is cooled and then discarded to the atmosphere.

The water feed (Stream 1) is pumped (P-100) from its storage tank to a pressure of 214.7 psi and then heated by the product stream (Stream 13) in a double pipe heat exchanger (E-100) to 263°F. This high pressure liquid water stream then goes into a flash vessel (F-100) where it is flashed into a vapor at 24 psi. By pumping the liquid, heating it, and then flashing it, the overall energy required by the system is less than if a standard boiler had been used. Additionally, pumping a liquid is less energy intensive than compressing a gas, saving the system energy.

After being flashed, the vapor stream (Stream 4) passes through another double pipe heat exchanger (E-101) where it gains heat from the same product stream (Stream 11), exiting at 919°F. Next, the stream passes through a final double pipe exchanger (E-102) where it gets heated by the oxygen product stream (Stream 23) to 1134°F before passing through a fired heater (E-103) to reach its final temperature, 1500°F (Stream 8). It is then combined with the product recycle (Stream 12) and fed into the electrolyzer at 1498°F (Stream 9).

The electrolyzer (R-100) operates at 1472°F and 19.2 psi. The hydrogen-rich product stream (Stream 10) exits at 1472°F and gets split into the recycle and product streams (Streams 12 & 1). The oxygen product stream (Stream 23) exits the electrolyzer at 1472° F and is then exhausted to the environment after giving heat to the feed stream as described above. The hydrogen product stream passes through multiple heat exchangers as described above and exits the final feed preheater at 131°F (Stream 14). In a double pipe partial condenser (E-104), 4.25 lbmol/hr of water is condensed out (Stream 16) using cooling water and stored in a tank (V-102), leaving a dry hydrogen stream at 100°F (Stream 15) to be stored. This stream of 38.43 lbmol/hr of hydrogen and 0.03 lbmol/hr of water then goes through multistage compression with intercooling (C-100-2 and E-105-7). It exits the final cooler at 100°F and 100 psi and is stored in a large pressure vessel (V-101).

Energy Balance and Utility Requirements

The energy and utility requirements for the hydrogen system in electrolysis mode are listed below in Table 5. The annual costs are based on the 12 hours of operation per day throughout the operating year.

Table 5: Utility and Energy Requirements for Electrolysis

Cooling Water					
Equipment	**Unit No.**	**Flow Rate (lb/hr)**	**Annual Flowrate (lb)**	**Price ($/lb)**	**Annual Cost**
Partial Condenser	E-104	2884.2	11,421,432	9.01E-06	$102.86
Intercooler 1	E-105	1172.7	4,643,892	9.01E-06	$41.82
Intercooler 2	E-106	1260	4,989,600	9.01E-06	$44.94
Intercooler3	E-107	1324.8	5,246,208	9.01E-06	$47.25
Total Cooling Water		**6641.7**	**26,301,132**		**$236.87**

Low Pressure Steam					
Equipment	**Unit No.**	**Flow Rate (lb/hr)**	**Annual Flowrate (lb)**	**Price**	**Annual Cost**
Flash Vessel	F-100	828.5	3,280,911	$ 3.00/1000 lb	$9,842.732

Natural Gas					
Equipment	**Unit No.**	**Heat Duty (Btu/hr)**	**Flow Rate (SCF/hr)**	**Cost**	**Annual Cost**
Fired Heater	E-103	152,339	159.5	$3.20/1000 SCF	$2,021.40

Electricity					
Equipment	Unit No.	Power (kW)	Annual consumption (kWh)	Price (off peak)	Annual Cost
Storage Compressor 1	C-100	10.28	40,721	$.06/kWh	$2,443.26
Storage Compressor 2	C-101	11.05	43,763	$.06/kWh	$2,625.78
Storage Compressor 3	C-102	11.63	46,037	$.06/kWh	$2,762.22
Water Pump	P-100	0.46	1,801	$.06/kWh	$108.06
Electrolyzer	R-100	1000	3,960,000	$.06/kWh	$237,600.00
Total Electricity		**1,033.4**	**4,092,323**	**$.06/kWh**	**$245,539.30**

Additional Heat to Electrolyzer					
Equipment	**Unit No.**	**Heat Duty (Btu/hr)**	**Electricity (kW)**	**Annual Heat (Btu)**	**Annual Electricity (kWh)**
Electrolyzer	R-100	678,143	198.7	2,685,445,001	787,026

The major utilities used in electrolysis mode are cooling water, low pressure steam, natural gas, and electricity. Since this process will occur at a power plant, all of these utilities will be readily available and inexpensive.

Cooling water is used to condense the water product and cool the hydrogen in the intercoolers during compression. The flow rates of water needed were calculated using a temperature increase of 90°F to 120°F in ASPEN and the cost of cooling water is from Table 23.1 of *Product and Process Design Principles*[7].

Low pressure steam supplies the heat used to vaporize the water in the flash vessel (F-100). The flow rate needed was calculated by ASPEN and the cost is also from Table 23.1 of *Product and Process Design Principles*.

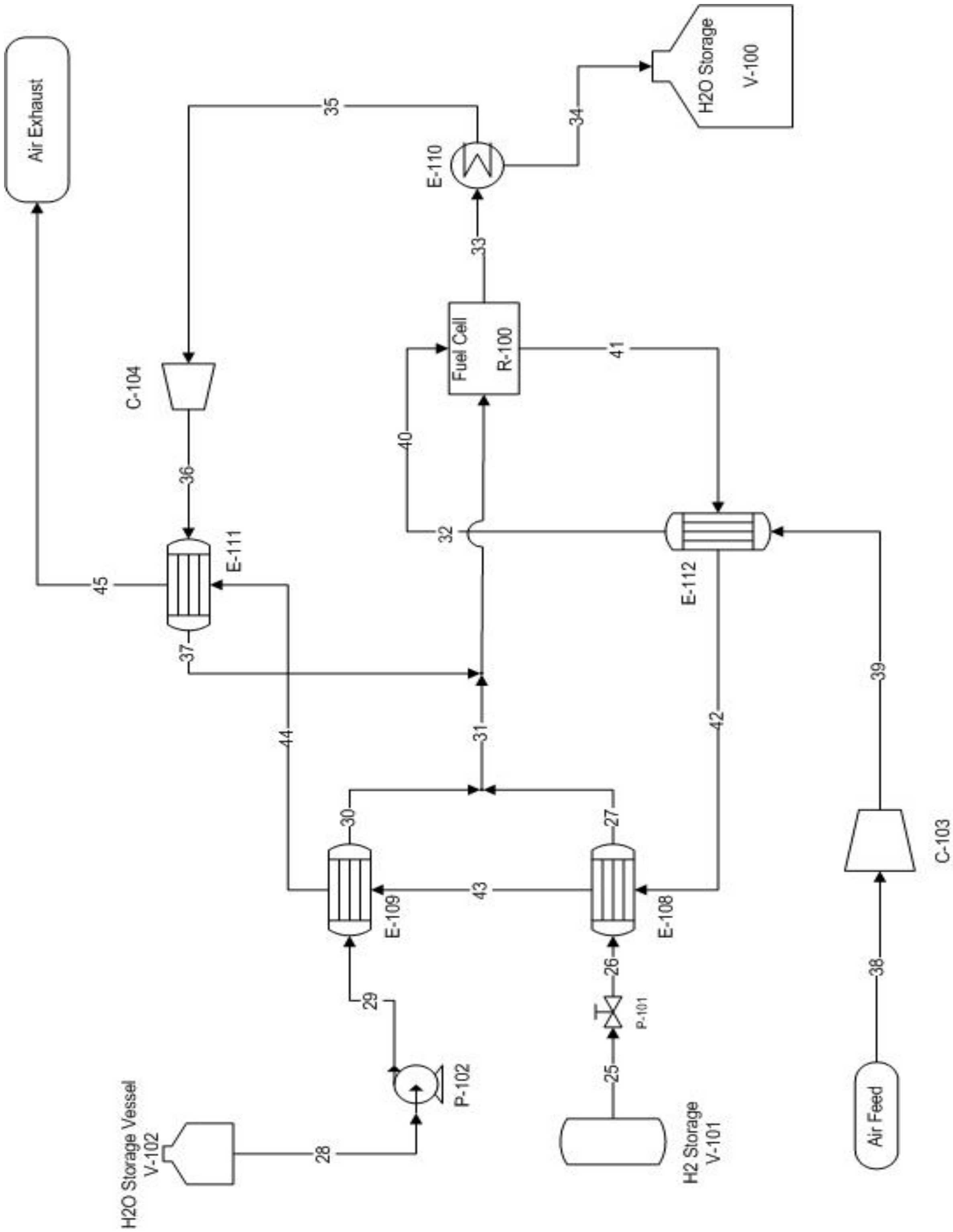
Natural gas is used to supply the heat for the fired heater (E-103) that heats the water feed to operating temperature. The LHV of natural gas was used, obtained from Table 23.2 of *Product and Process Design Principles*. The cost of natural gas was taken from Table 23.1 of the same source.

The electricity needed for this process comes directly from the power plant and is purchased at the off-peak, wholesale price. This price is $0.06/kWh, found in Table 23.1 of *Product and Process Design Principles.* The electrolyzer runs on 1 MW of power, while the pumps and compressors throughout the system require 33.4 kW. Of this 1 MW of power, 93.46 kW is waste heat that heats the electrolyzer as discussed in the thermodynamics section of this report on page 15.

However, in addition to this heat, as shown above in Table 5, 678,143 Btu/hr or 198.7 kW need to be supplied to keep the electrolyzer running at 1472°F. This heat can be supplied in two ways: as more overvoltage or as additional heat to the feed stream. To be supplied as more heat, the inlet stream must be 831°F hotter, or to be supplied as overvoltage, the operating voltage must be increased by 0.11 V. While these two options are the extremes, the most feasible solution would be a combination of both. A discussion of how these two options effect efficiency will be discussed later on page 82 of this report.

Process Flow Diagram and Material Balances - Fuel Cell Mode

Figure 6: Process Flow Diagram for Fuel Cell Mode of the Hydrogen Case



		25	26	27	28	29	30	31	32
From			P-101	E-108		P-102	E-109	M-101	M-102
To		P-101	E-108	M-101	P-102	E-109	M-101	M-102	R-100
Substream: MIXED									
Phase:		Vapor	Vapor	Vapor	Liquid	Liquid	Vapor	Vapor	Vapor
Component Mole Flow									
WATER	LBMOL/HR	0.00	0.00	0.00	4.70	4.70	4.70	4.70	5.29
HYDROGEN	LBMOL/HR	42.28	42.28	42.28	0.00	0.00	0.00	42.28	47.56
NITROGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Component Mass Flow									
WATER	LB/HR	0.00	0.00	0.00	84.64	84.64	84.64	84.64	95.23
HYDROGEN	LB/HR	85.23	85.23	85.23	0.00	0.00	0.00	85.23	95.88
NITROGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OXYGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mole Flow	LBMOL/HR	42.28	42.28	42.28	4.70	4.70	4.70	46.98	52.85
Mass Flow	LB/HR	85.23	85.23	85.23	84.64	84.64	84.64	169.87	191.11
Volume Flow	CUFT/HR	2435.873	14546.97	22140.09	1.362652	1.362665	2431.35	24590.15	27893.7
Temperature	F	75	75.4035	3.50E+02	7.50E+01	7.50E+01	3.50E+02	3.50E+02	3.56E+02
Pressure	PSIA	100	16.7	1.66E+01	1.47E+01	1.77E+01	1.67E+01	1.66E+01	1.66E+01
Vapor Fraction		1	1	1	0.00E+00	0.00E+00	1.00E+00	1.00E+00	1.00E+00
Liquid Fraction		0	0	0	1.00E+00	1.00E+00	0	0	0
Molar Enthalpy	BTU/LBMOL	-10.41634	-1.04E+01	1.90E+03	-1.24E+05	-1.24E+05	-1.02E+05	-8.47E+03	-8.42E+03
Mass Enthalpy	BTU/LB	-5.167143	-5.17E+00	9.42E+02	-6900.115	-6900.085	-5648.883	-2.34E+03	-2.33E+03
Enthalpy Flow	BTU/HR	-440.3871	-440.3871	80254.38	-5.84E+05	-5.84E+05	-4.78E+05	-3.98E+05	-4.45E+05
Molar Entropy	BTU/LBMOL-R	-3.835697	-0.274671	2.614683	-40.97051	-40.96989	-7.525772	2.246091	2.304926
Mass Entropy	BTU/LB-R	-1.902741	-0.136254	1.297043	-2.274209	-2.274174	-0.417744	0.621138	0.6374136
Molar Density	LBMOL/CUFT	0.0173566	2.91E-03	1.91E-03	3.44805	3.448016	1.93E-03	1.91E-03	1.89E-03
Mass Density	LB/CUFT	0.0349888	5.86E-03	3.85E-03	6.21E+01	6.21E+01	3.48E-02	6.91E-03	6.85E-03

		33	34	35	36	37	38	39	40
From		FCSPLIT	E-110		C-104	E-111	MULTIPLY	C-103	E-112
To		E-110		C-104	E-111	M-102	C-103	E-112	R-100
Substream: MIXED									
Phase:		Vapor	Liquid	Vapor	Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow									
WATER	LBMOL/HR	47.56	46.98	0.59	0.59	0.59	0.00	0.00	0.00
HYDROGEN	LBMOL/HR	5.29	0.00	5.29	5.29	5.29	0.00	0.00	0.00
NITROGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	147.83	147.83	147.83
OXYGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00	39.30	39.30	39.30
Component Mass Flow									
WATER	LB/HR	856.88	846.33	10.58	10.58	10.58	0.00	0.00	0.00
HYDROGEN	LB/HR	10.66	0.00	10.66	10.66	10.66	0.00	0.00	0.00
NITROGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	4141.26	4141.26	4141.26
OXYGEN	LB/HR	0.00	0.00	0.00	0.00	0.00	1257.45	1257.45	1257.45
Mole Flow	LBMOL/HR	52.85	46.98	5.87	5.87	5.87	187.13	187.13	187.13
Mass Flow	LB/HR	867.54	846.33	21.24	21.24	21.24	5398.71	5398.71	5398.71
Volume Flow	CUFT/HR	65599.27	13.97502	2655.583	2507.152	3283.582	73049.38	55974.66	85834.1
Temperature	F	1472	180.5008	1.81E+02	2.04E+02	4.10E+02	7.50E+01	1.73E+02	450
Pressure	PSIA	16.7	15.2	1.52E+01	1.67E+01	1.67E+01	1.47E+01	2.27E+01	21.29595
Vapor Fraction		1	0	1.00E+00	1.00E+00	1	1	1	1
Liquid Fraction		0	1	0	0.00E+00	0	0	0	0
Molar Enthalpy	BTU/LBMOL	-81342.89	-1.21E+05	-9.67E+03	-9.50E+03	-8.04E+03	-1.68E+01	6.65E+02	2.63E+03
Mass Enthalpy	BTU/LB	-4955.37	-6717.692	-2674.102	-2627.512	-2.22E+03	-5.84E-01	2.31E+01	90.99591
Enthalpy Flow	BTU/HR	-4.30E+06	-5.69E+06	-5.68E+04	-5.58E+04	-47208.22	-3151.911	1.25E+05	4.91E+05
Molar Entropy	BTU/LBMOL-R	1.825084	-35.79586	0.7570315	0.8284207	2.746903	0.9894893	1.298281	3.992828
Mass Entropy	BTU/LB-R	0.1111832	-1.986972	0.2093665	0.2291101	0.7596903	0.0342972	0.0450004	0.1383977
Molar Density	LBMOL/CUFT	8.06E-04	3.361601	2.21E-03	2.34E-03	1.79E-03	2.56E-03	3.34E-03	2.18E-03
Mass Density	LB/CUFT	0.0132248	60.56018	8.00E-03	8.47E-03	6.47E-03	7.39E-02	9.64E-02	0.062897

		41	42	43	44	45
From		NOTREAL	E-112	E-108	E-109	E-111
To		E-112	E-108	E-109	E-111	
Substream: MIXED						
Phase:		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
WATER	LBMOL/HR	0.00	0.00	0.00	0.00	0.00
HYDROGEN	LBMOL/HR	0.00	0.00	0.00	0.00	0.00
NITROGEN	LBMOL/HR	147.83	147.83	147.83	147.83	147.83
OXYGEN	LBMOL/HR	18.16	18.16	18.16	18.16	18.16
Component Mass Flow						
WATER	LB/HR	0.00	0.00	0.00	0.00	0.00
HYDROGEN	LB/HR	0.00	0.00	0.00	0.00	0.00
NITROGEN	LB/HR	4141.26	4141.26	4141.26	4141.26	4141.26
OXYGEN	LB/HR	581.02	581.02	581.02	581.02	581.02
Mole Flow	LBMOL/HR	165.99	165.99	165.99	165.99	165.99
Mass Flow	LB/HR	4722.28	4722.28	4722.28	4722.28	4722.28
Volume Flow	CUFT/HR	1.62E+05	1.54E+05	1.52E+05	1.57E+05	1.61E+05
Temperature	F	1.47E+03	1.19E+03	1127.942	1044.674	1.04E+03
Pressure	PSIA	21.3	1.91E+01	18.6	17.1	1.66E+01
Vapor Fraction		1.00E+00	1.00E+00	1	1	1.00E+00
Liquid Fraction		0	0	0	0	0
Molar Enthalpy	BTU/LBMOL	1.03E+04	8.12E+03	7633.238	6995.196	6.94E+03
Mass Enthalpy	BTU/LB	363.0571	285.397	268.3089	245.8817	244.0627
Enthalpy Flow	BTU/HR	1.71E+06	1.35E+06	1.27E+06	1.16E+06	1.15E+06
Molar Entropy	BTU/LBMOL-R	9.288209	8.269167	8.021578	7.775835	7.800313
Mass Entropy	BTU/LB-R	0.3264813	0.2906619	0.2819591	0.2733212	0.2741816
Molar Density	LBMOL/CUFT	1.03E-03	1.08E-03	1.09E-03	1.06E-03	1.03E-03
Mass Density	LB/CUFT	0.0292197	3.07E-02	0.0310447	0.0301214	2.94E-02

Process Description

This section discusses the fuel cell mode of the hydrogen system, which operates for 10.9 hours per day during peak electricity demand. 42.28 lbmol/hr of hydrogen (Stream 25) from storage is expanded through a valve (P-101) to lower its pressure from 100 psi to 16.7 psi (Stream 26). It is heated in a preheater (E-108) by the air exhaust stream (Stream 42) to 350°F (Stream 27). Parallel to the hydrogen stream, 4.70 lbmol/hr of water (Stream 28) from storage is pumped (P-102) and then vaporized and heated by the air exhaust (Stream 43) in a heat exchanger (E-109) to 350°F (Stream 30). The hydrogen and water streams are combined in a mixer (Stream 31) and then combined with the product recycle (Stream 37) in another mixer before being sent into the anode of the fuel cell at 356°F (Stream 32). Additionally, air at 1.86 times excess, 187.13 lbmol/hr, (Stream 38) is compressed (C-103) and then preheated to 450°F (Stream 40) by the exhaust air stream (Stream 41) in a heat exchanger (E-112) before entering the cathode of the fuel cell.

The difference between operating temperature and inlet stream temperature in this system is the same as in the Siemens Westinghouse 4.5 MW SOFC system on page 8-58 of *The Fuel Cell Handbook*. Since the fuel cell itself is exothermic, some of this extra heat went towards heating the inlet streams to operating temperature. The rest of the heat generated was absorbed by the excess air. A sensitivity analysis was run on the amount of excess air vs. cooling load needed on the fuel cell, and with a 186% air excess, the cooling load was equal to zero.

The fuel cell (R-100) operates at 1472°F. A pressure gradient exists across the electrolyte, with the fuel being fed at 16.6 psi and the air entering at 21.3 psi. Since the electrolyte is a ceramic material, this strain is allowed. The air exhaust stream (Stream 41) is used to preheat the three inlet streams as stated above, exiting from the third preheater at 1045°F (Stream 44). The exhaust then enters one final heat exchanger (E-111) where it reheats the recycle stream (Stream 36) and is then discarded to the environment (Stream 45). The product stream from the fuel cell (Stream 33) enters a partial condenser (E-110), and the water product of 46.98 lbmol/hr at 180.5°F (Stream 34) is sent to storage (V-100). The vapor recycle (Stream 35) passes through the recycle blower (C-104) before being reheated to 410°F (Stream 37) and being combined with the water and hydrogen feeds to be sent into the fuel cell.

Energy Balance and Utility Requirements

The energy and utility requirements for the hydrogen system in fuel cell mode are listed below in Table 6. The annual costs are based on the 10.9 hours of operation per day throughout the operating year.

Table 6: Equipment Summary for Fuel Cell Mode of the Hydrogen Case

Cooling Water					
Equipment	**Unit**	**Flow Rate (lb/hr)**	**Annual Flowrate (lb)**	**Price**	**Annual Cost**
Product Stream Partial Condenser	E-110	48,264	173,606,354	9.01E-06	$1563.50

Electricity					
Equipment	**Unit**	**Power (kW)**	**Annual consumption (kWh)**	**Price (peak)**	**Annual Cost**
Inlet Air Blower	C-103	37.41922	134,597	$0.20/kWh	$26,919.40
Recycle Blower	C-104	0.2900773	1,043	$0.20/kWh	$208.60
Feed Pump	P-102	0.0007457	3.00	$0.20/kWh	$0.60
Fuel Cell	R-100	(884.116)	(3,180,129)	$0.20/kWh	($636,025.80)
Total Electricity		846.40	3,044,486	$0.20/kWh	

The major utilities used in fuel cell mode are cooling water, and electricity. Since this process will occur at a power plant, both of these utilities will be readily available and inexpensive.

Cooling water is used to condense the water from the fuel cell product stream. The flow rate of water needed was calculated using a temperature increase of 90°F to 120°F in ASPEN and the cost of cooling water is from Table 23.1 of *Product and Process Design Principles*.

In fuel cell operation, electricity is produced, and therefore the electricity required by pumps and compressors is provided by the fuel cell. Fuel cell operation produces a net 846.4 kW which is sold at the peak, commercial cost per kilowatt-hour of $0.20/kWh[8].

Just as electrolysis mode generated waste heat to counter the endothermic reaction in the system, the fuel cell produces waste heat in addition to being exothermic, meaning that heat needs to be removed to keep it operating at 1472°F. This heat is removed by the inlet streams entering the cell at a lower than operating temperature, and additionally, as mentioned above, by excess air. The temperatures of the inlets and excess air in this system absorb all the heat, leaving no heat duty on the cell.

Equipment List and Unit Descriptions

Electrolysis Mode

Table 7: Equipment List for Hydrogen System Electrolysis

Unit No.	Unit Type	Function	Size	Material	Oper. T (°F)	Oper. P (psi)
C-100	Storage Compressor 1	Increase the pressure of H_2 product stream	P_C = 13.79 hp	Carbon Steel	231.4	32.0
C-101	Storage Compressor 2	Increase the pressure of H_2 product stream	P_C = 14.82 hp	Carbon Steel	241.1	55.5
C-102	Storage Compressor 3	Increase the pressure of H_2 product stream	P_C = 15.59 hp	Carbon Steel	248.3	100.3
E-100*	Water Preheater 1	Preheat the liquid water before being flashed	A = 18.19 ft^2 Q = 167,094 Btu/hr	Stainless Steel	263.3	214.7
E-101*	Water Preheater 2	Preheat the water vapor stream	A = 25.28 ft^2 Q = 250,848 Btu/hr	Stainless Steel	918.9	24.0
E-102*	Water Preheater 3	Preheat the water vapor stream	A = 189.63 ft^2 Q = 85,822 Btu/hr	Stainless Steel	1134	20.5
E-103*	Fired heater	Preheat the water vapor stream	Q = 153,570 Btu/hr	Stainless Steel	1500	19.2
E-104*	Product Partial Condenser	Remove water from the product stream prior to compression	A = 201.05 ft^2 Q = 86,234	Stainless Steel	100	18.55
E-105*	Intercooler for C-100	Keep the H_2 stream from getting too hot	A =61.01 ft^2 Q =35,058 Btu/hr	Stainless Steel	100	31.0
E-106*	Intercooler for C-101	Keep the H_2 stream from getting too hot	A = 60.89 ft^2 Q = 37,673 Btu/hr	Stainless Steel	100	54.51
E-107*	Intercooler for C-102	Keep the H_2 stream from getting too hot	A = 60.11 ft^2 Q = 38,709 Btu/hr	Stainless Steel	100	45.4
F-100	Flash Vessel	To vaporize the water using heat and a pressure swing	A = 55.29 ft^2 Q = 755265 Btu/hr	Stainless Steel	243.3	24.0
P-100	Water Feed Pump	Raise the pressure of the inlet water stream	P_C = 0.61 hp	Stainless Steel	75	214.7
R-100	Electrolyzer/ Fuel Cell	Convert Water to Hydrogen using electricity	I = 0.5 A/cm^2 V = 1.07 V Area = 1.869E+06 cm^2	YSZ, porous Nickel, $LaMnO_3$	1472	17.6
V-100	Large Water Storage Tank	Large storage vessel for water	V = 1105.3 gal	Stainless Steel	75	14.7
V-101	Hydrogen Storage Tank	Pressurized storage tank for H_2	D=11.8 ft L = 236.0 ft	Carbon Steel	75	100
V-102	Small Water Storage Tank	Small storage vessel for water	V = 110.5 gal	Stainless Steel	75	14.7

* To be consistent in our calculations of heat exchanger area and price, all heat exchangers were designed in ASPEN Heat Exchange Design[9], and the heat transfer coefficient and pressure drops calculated were transferred into the ASPEN flow sheet.

Storage Compressor 1 (C-100)

The first compressor in the three stage compression of hydrogen is a screw compressor with an electric drive, constructed out of carbon steel. As stated above, the temperature of the hydrogen during compression could not exceed 250°F. This limited the amount of compression that could occur in each compressor. In this first compressor, the hydrogen is compressed to 32 psi. The net work of the compressor is 13.79 hp, with a bare module cost of $48,552.86. Please refer to the Specification Sheet on page 37 and sample calculations on page 179.

Storage Compressor 2 (C-101)

The second compressor in the three stage compression of hydrogen is also a screw compressor with an electric drive, constructed out of carbon steel. The hydrogen is compressed from 31.7 psi to 55.51 psi. The net work of the compressor is 14.82 hp, with a bare module cost of $51,121.70. Please refer to the Specification Sheet on page 38 and sample calculations on page 179.

Storage Compressor 3 (C-102)

The third and final compressor in the three stage compression of hydrogen is also a screw compressor with an electric drive, constructed out of carbon steel. The hydrogen is compressed from 55.21 psi to 100.3 psi to account for the pressure drop across the intercooler. It is then put into the storage tank. The net work of this compressor is 15.59 hp, with a bare module cost of $53,032.05. Please refer to the Specification Sheet on page 39 and sample calculations on page 179.

Water Preheater 1 (E-100)

The first water preheater increases the temperature of the high pressure liquid feed prior to flashing and evaporating. The temperature of the water stream is to rise from 76.21°F to 263.33°F by heat transfer with the hot product stream. ASPEN was unable to give accurate heat transfer coefficients and pressure drops. Therefore, the hot and cold stream inlet and outlet conditions were input into ASPEN Heat Exchange Design, and the calculated pressure drop and heat transfer coefficient were input into ASPEN, giving more accurate areas for heat exchange and pressure drops across heat exchangers. The calculated area for this unit was small, and therefore this heat exchanger is a double pipe heat exchanger, with stainless steel as both the inner and outer pipe material. The bare module cost of this unit is $10,900.23. Please refer to the Specification Sheet on page 40 and sample calculations on page 178.

Water Preheater 2 (E-101)

The second water preheater heats the steam feed stream by using the electrolyzer product stream. The temperature of the steam rises from 242°F to 919°F. The same procedure as stated in Water Preheater 1 was used to obtain an accurate area for heat transfer. Once again, a small area was calculated and double pipe geometry was used. For a stainless steel inner and outer tube construction, the bare module cost of the exchanger is $11,489.44. Please refer to the Specification Sheet on page 41 and the sample calculations on page 178.

Water Preheater 3 (E-102)

The third water preheater heats the steam from 919°F to 1134°F using the oxygen product stream produced at the cathode of the electrolyzer. Using the same method as the previous two preheaters, a larger heat transfer area was calculated, but still within the double pipe geometry range. With stainless steel inner and outer tubes, the bare module cost of the unit is $15,863.66. Please refer to the Specification Sheet on page 42 and the sample calculations on page 178.

Fired Heater (E-103)

The fourth and final water preheater is a fired heater that uses natural gas as a fuel. The natural gas consumption of this unit can be found in the Energy and Utilities section on page 26. The heater increases the temperature of the feed from 1134°F to 1500° F, slightly above the operating temperature of the electrolyzer. Based on a stainless steel, shop fabricated unit, the bare module cost is $48,304.46. Please refer to the Specification Sheet on page 43 and the sample calculations on page 179.

Product Partial Condenser (E-104)

This partial condenser is used to remove almost all of the water from the product stream, as well as cool the hydrogen product stream prior to compression. The cold utility used for is cooling water, bringing the product stream from 131°F to 100°F. The details of the cooling water flow rate can be found in the Energy and Utilities section on page 26. Based on the same heat transfer area calculation method as stated above, the geometry of this heat exchanger is a double pipe. With stainless steel as the material for both the inner and outer pipes, the bare module cost is $16,010.00. Please refer to the Specification Sheet on page 44 and the sample calculations on page 178.

Intercooler for C-100 (E-105)

This intercooler cools the hydrogen product stream after it passes through its first stage of compression. It is cooled from 231.4°F to 100°F using cooling water, keeping it from reaching the 250°F threshold mentioned previously. For details on cooling water flow rates, please refer to page 26, in the Energy and Utilities section. Using the same methods as previously described, the area for heat transfer calculated allowed for double pipe geometry. For stainless steel construction, the bare module cost of this unit is $13,228.98. Please refer to the Specification Sheet on page 45 and the sample calculations on page 178.

Intercooler for C-101 (E-106)

This intercooler cools the hydrogen product stream after it passes through the second stage of compression. It is cooled from 235°F to 100°F using cooling water. For details on cooling water flow rates, please refer to page 26, in the Energy and Utilities section. Using the same methods for heat transfer area calculation, the area for heat transfer calculated allowed for double pipe geometry. For stainless steel construction, the bare module cost of this unit is $13,224.76. Please refer to the Specification Sheet on page 46 and the sample calculations on page 178.

Intercooler for C-102 (E-107)

This intercooler cools the hydrogen product stream after it passes through its final stage of compression, prior to entering the storage vessel. It is cooled from 245°F to 100°F using cooling water. For details on cooling water flow rates, please refer to page 26, in the Energy and Utilities section. Using the same methods for heat transfer area calculation, the area for heat transfer calculated allowed for double pipe geometry. For stainless steel construction, the bare module cost of this unit is $13,231.22. Please refer to the Specification Sheet on page 48 and the sample calculations on page 178.

Flash Vessel (F-100)

To evaporate the inlet water stream, rather than using a heater, a flash vessel is used. This allows for a pressure swing to work along with a heat duty, vaporizing the water at a lower total energy cost. The water is flashed from 214.7 psi to 24.0 psi, and the heat duty required by the unit is provided by 50 psig steam. The amount of steam required can be found in the Energy and Utilities section on page 26. For a stainless steel construction, the total bare module factor of this unit is $13,022.33. Please refer to the Specification Sheet on page 49 and the sample calculations on page 178.

Water Feed Pump (P-100)

The water feed pump is a small, low power pump used to raise the pressure of the inlet water stream from out of the storage tank at atmospheric pressure to 200 psig, providing enough pressure to perform a good flash and still move through the system. The size of this unit is too small for the correlations in *Product and Process Design Principles*. We therefore found a price for a comparable pump online. Based on the cost of a Wel-Bit Cast Iron Clear water pump[10] multiplied by a materials factor for stainless steel of two, the bare module cost of this unit is $398.00. Please refer to the Water Feed Pump Specification Sheet on page 50.

Fuel Cell/Electrolyzer (Electrolysis)

This unit is a reversible SOFC, made of YSZ with a porous nickel catalyst at the anode and $LaMnO_3$-doped YSZ catalyst at the cathode. In electrolysis mode, this unit takes in 1.0 MW of electricity and converts water to hydrogen and oxygen. Based on data from Bierschenk[1], an operating voltage of 1.07 V and current density of 0.5 A/cm^2 was selected. Based on these values, the electrode area required was determined to be $1.8692*10^6$ cm^2. The feed stream to the cell enters at 1500°F, slightly above the operating temperature. Since the electrolyzer operates endothermically, this slightly higher temperature of the inlet helps to keep it at operating temperature. As mentioned previously, the electrolyzer is assumed to be a CSTR for ease of calculations, and therefore all streams exit at the operating temperature, 1472°F. Based on DOE targets for fuel cell factory costs in 2020[2], this unit had a bare module cost of $450,000. A bare module factor of 1 was assumed for this unit since fuel cells come from the factory ready for use. Please refer to the Specification Sheet on page 51.

Large Water Storage Tank (V-100)

The water feed for electrolysis mode and water product from fuel cell operation is stored in this tank. The water for this process must be pure, and therefore stainless steel is used as the material of construction. The tank is designed to hold an extra 200 gallons of water in case additional water needs to be stored or added to the system. Based on a cone roof liquid storage tank design, the bare module cost of this unit is $10,264.95. Please refer to the Specification Sheet on page 52.

Hydrogen Storage Tank (V-101)

This pressure vessel is for storing the hydrogen product from electrolysis mode and feed for fuel cell operation. As described previously on page 17, the storage pressure was chosen to be 100 psi by an economic optimization of the compression and storage system. The vessel is a horizontal, carbon steel cylinder with an aspect ratio of 20. It has a bare module cost $1,383,042. Please refer to the Specification Sheet on page 53 and sample calculations on page 180.

Small Water Storage Tank (V-102)

This tank is used to store the water in the product stream during electrolysis operation and provide water for the feed in fuel cell operation. The tank is designed to hold an extra 20 gallons in case additional water needs to be stored or added to the system. Based on a cone roof liquid storage tank design of stainless steel, the bare module cost of this unit is $3,172.17. Please refer to the Specification Sheet on page 54.

Electrolysis Specification Sheets

The following lists the page number of the specification sheets detailing the different units within electrolysis operation, followed by the specification sheets.

Storage Compressor 1

Identification

Item	Compressor	Date	4/5/11
Item No.	C-100	By	EH/MP/DS
No. Required	1		

Function: Increase the pressure of H_2 product stream for storage

Operation: 12 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	15	17
Quantity (lb/hr)	78.01	78.01
Composition:		
Water	0.54	0.54
Hydrogen	77.47	77.47
Temperature (°F)	100	231.4
Pressure (psi)	18.55	32
Vapor Fraction	1	1

Design Data

Type	Screw Compressor
Material	Carbon Steel
Net Work (HP)	13.79
Efficiency	0.72

C_P	$	22,568.77
C_{BM}	$	48,522.86

Storage Compressor 2

Identification

Item	Compressor	Date	4/5/11
Item No.	C-101	By	EH/MP/DS
No. Required	1		

Function: Increase the pressure of H_2 product stream for storage

Operation: 12 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	18	19
Quantity (lb/hr)	78.01	78.01
Composition:		
Water	0.54	0.54
Hydrogen	77.47	77.47
Temperature (°F)	100	235.3
Pressure (psi)	31.7	55.51
Vapor Fraction	1	1

Design Data

Type	Screw Compressor
Material	Carbon Steel
Net Work (HP)	14.82
Efficiency	0.72

C_P	$	23,777.54
C_{BM}	$	51,121.70

Storage Compressor 3

Identification

Item	Compressor	Date	4/5/11
Item No.	C-102	By	EH/MP/DS
No. Required	1		

Function: Increase the pressure of H_2 product stream for storage

Operation: 12 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	20	21
Quantity (lb/hr)	78.01	78.01
Composition:		
Water	0.54	0.54
Hydrogen	77.47	77.47
Temperature (°F)	100	244.95
Pressure (psi)	55.21	100.3
Vapor Fraction	1	1

Design Data

Type	Screw Compressor
Material	Carbon Steel
Net Work (HP)	15.59
Efficiency	0.72

C_P	$	24,666.07
C_{BM}	$	53,032.05

Water Preheater 1

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-100	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature of the inlet liquid water stream

Operation: 12 hours, daily

Materials Handled		**Hot**		**Cold**	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		13	14	2	3
Quantity (lb/hr)		154.54	154.54	769.40	769.40
Composition:					
	Water	77.07	77.07	769.40	769.40
	Hydrogen	77.47	77.47	0.00	0.00
Temperature (°F)		672	131	76.21	263.33
Pressure (psi)		19.1	18.85	214.7	214.7
Vapor Fraction		1	1	0	0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	167,094
Heat Transfer Coefficient (Btu/hr-ft^2-F)	52.16
Heat Transfer Area (ft^2)	18.19

C_P	$	6,055.68
C_{BM}	$	10,900.23

Water Preheater 2

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-101	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature of the steam feed stream

Operation: 12 hours, daily

Materials Handled		**Hot**		**Cold**	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		11	13	4	6
Quantity (lb/hr)		154.54	154.54	769.40	769.40
Composition:					
	Water	77.07	77.07	769.40	769.40
	Hydrogen	77.47	77.47	0.00	0.00
Temperature (°F)		1472	672	242.2	918.9
Pressure (psi)		19.2	19.1	24	20.5
Vapor Fraction		1	1	1	1

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	250,848
Heat Transfer Coefficient (Btu/hr-ft^2-F)	20.30
Heat Transfer Area (ft^2)	25.28

C_P	$	6,383.02
C_{BM}	$	11,489.44

Water Preheater 3

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-102	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature of the steam feed stream

Operation: 12 hours, daily

Materials Handled		**Hot**		**Cold**	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		23	24	6	7
Quantity (lb/hr)		614.84	614.84	769.40	769.40
Composition:					
	Water	0.00	0.00	769.40	769.40
	Hydrogen	0.00	0.00	0.00	0.00
	Oxygen	614.84	614.84	0.00	0.00
Temperature (°F)		1472.0	929.0	918.9	1134.0
Pressure (psi)		19.2	19.0	20.5	20.2
Vapor Fraction		1	1	1	1

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	85,822
Heat Transfer Coefficient (Btu/hr-ft^2-F)	4.84
Heat Transfer Area (ft^2)	189.6

C_P	$	8,813.94
C_{BM}	$	15,863.66

Fired Heater

Identification

Item	Fired Heater	Date	4/5/11
Item No.	E-103	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature of the steam feed stream

Operation: 12 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	7	8
Quantity (lb/hr)	769.40	769.40
Composition:		
Water	769.40	769.40
Temperature (°F)	1134.0	1500.0
Pressure (psi)	20.2	19.2
Vapor Fraction	1	1

Design Data

Type	Fired Heater
Material	Stainless Steel
Bare-Module Type	Shop Fabricated
Heat Transfer (Btu/hr)	153,569

C_P	$	22,056.83
C_{BM}	$	48,304.46

Product Partial Condenser

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-104	By	EH/MP/DS
No. Required	1		

Function: Cool hydrogen product stream and condense water product

Operation: 12 hours, daily

Materials Handled

		Inlet	Outlet	Condensate
Stream ID		14	15	16
Quantity (lb/hr)		154.54	78.01	76.53
Composition:				
	Water	77.07	0.54	76.53
	Hydrogen	77.47	77.47	0
Temperature (°F)		131.0	100.0	100.0
Pressure (psi)		19.1	18.9	18.9
Vapor Fraction		1	1	0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	86,234
Heat Transfer Coefficient (Btu/hr-ft^2-F)	40.88
Heat Transfer Area (ft^2)	201.05
Cold Utility	Cooling Water

C_P	$	8,894.44
C_{BM}	$	16,010.00

Intercooler for C-100

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-105	By	EH/MP/DS
No. Required	1		

Function: Cool the hydrogen product stream in between compressors

Operation: 12 hours, daily

Materials Handled

	Inlet	Outlet
Stream ID	17	18
Quantity (lb/hr)	78.01	78.01
Composition:		
Water	0.54	0.54
Hydrogen	77.47	77.47
Temperature (°F)	231.4	100.0
Pressure (psi)	32.0	31.7
Vapor Fraction	1	1

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	35,057
Heat Transfer Coefficient (Btu/hr-ft^2-F)	13.66
Heat Transfer Area (ft^2)	61.01
Cold Utility	Cooling Water

C_P	$	7,349.43
C_{BM}	$	13,228.98

Intercooler for C-101

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-106	By	EH/MP/DS
No. Required	1		

Function: Cool the hydrogen product stream in between compressors

Operation: 12 hours, daily

Materials Handled

	Inlet	Outlet
Stream ID	19	20
Quantity (lb/hr)	78.01	78.01
Composition:		
Water	0.54	0.54
Hydrogen	77.47	77.47
Temperature (°F)	235.3	100.0
Pressure (psi)	55.5	55.2
Vapor Fraction	1	1

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	36,110
Heat Transfer Coefficient (Btu/hr-ft^2-F)	13.77
Heat Transfer Area (ft^2)	60.89
Cold Utility	Cooling Water

C_P	$	7,347.09
C_{BM}	$	13,224.76

Intercooler for C-102

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-107	By	EH/MP/DS
No. Required	1		

Function: Cool the hydrogen product stream after the final compressor

Operation: 12 hours, daily

Materials Handled

	Inlet	**Outlet**
Stream ID	21	22
Quantity (lb/hr)	78.01	78.01
Composition:		
Water	0.54	0.54
Hydrogen	77.47	77.47
Temperature (°F)	245.0	100.0
Pressure (psi)	100.3	100.0
Vapor Fraction	1	1

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	38,709
Heat Transfer Coefficient (Btu/hr-ft^2-F)	13.92
Heat Transfer Area (ft^2)	60.11
Cold Utility	Cooling Water

C_P	$	7,350.68
C_{BM}	$	13,231.22

Flash Vessel

Identification

Item	Flash Vessel	Date	4/5/11
Item No.	F-100	By	EH/MP/DS
No. Required	1		

Function: To vaporize water using heat and a pressure swing

Operation: 12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID			
Quantity (lb/hr)		769.40	769.40
Composition:			
	Water	769.40	769.40
Temperature (°F)		263.33	242.19
Pressure (psi)		214.7	24
Vapor Fraction		0	1

Design Data

Type	Kettle Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	755,265
Heat Transfer Coefficient (Btu/hr-ft^2-F)	300
Heat Transfer Area (ft^2)	55.29

C_P	$	7,234.63
C_{BM}	$	13,022.33

Water Feed Pump

Identification

	Item	Pump	Date	4/5/11
	Item No.	P-100	By	EH/MP/DS
	No. Required	1		

Function: Increase the pressure of the water feed pump

Operation: 12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		15	17
	Quantity (lb/hr)	769.40	769.40
	Composition:		
	Water	769.40	769.40
	Temperature (°F)	75	76.21
	Pressure (psi)	14.7	214.7
	Vapor Fraction	0	0

Design Data

	Type	Wel-Bilt Cast Iron Clear Water Pump
	Material	Stainless Steel
	Net Work (HP)	0.61
	Efficiency	0.4

C_P	$	120.00
C_{BM}	$	396.00

Fuel Cell/Electrolyzer (Electrolysis)

Identification

Item	Electrolyzer	Date	4/5/11
Item No.	R-100	By	EH/MP/DS
No. Required	1		

Function: Reduces water to hydrogen and oxygen with supplied electricity

Operation: 12 hours, daily

Materials Handled		**Inlet**	**Outlet**	
Stream ID		9	10	23
Quantity (lb/hr)		788.69	173.85	614.84
Composition:				
	Water	779.01	86.70	0.00
	Hydrogen	9.68	87.15	0.00
	Oxygen	0.00		614.84
Temperature (°F)		1497.5	1472	1472
Pressure (psi)		19.2	19.2	19.2
Vapor Fraction		1	1	1

Design Data

Type	Reversible Fuel Cell
Material	YSZ, porous Nickel, $LaMnO_3$
Heat Duty (Btu/hr)	3.189E+05
Electricity Supplied (kW)	1000
Operating T (°F)	1472
Operating P (psi)	19.2
Voltage (V)	1.07
Current (A/cm^2)	0.5
Electrode Area (cm^2)	1.8692E+06

C_P	$	450,000.00
C_{BM}	$	450,000.00

Large Water Storage Tank

Identification

Item	Storage Tank	Date	4/5/11
Item No.	V-100	By	EH/MP/DS
No. Required	1		

Function: Store the water produced from fuel cell mode

Operation: Continuous

Materials Handled	**Inlet (fuel cell)**	**Outlet (electrolysis)**
Stream ID	34	1
Quantity (lb/hr)	846.33	769.34
Composition:		
Water	846.33	769.34
Temperature (°F)	75	75
Pressure (psi)	14.7	14.7
Vapor Fraction	0	0

Design Data

Type	Cone Roof
Material	Stainless Steel
Liquid Volume (gal)	1105.3
Tank Volume (gal)	1300

C_P	$	10,264.95
C_{BM}	$	10,264.95

Hydrogen Storage Tank

Identification

Item	Storage Tank	Date	4/5/11
Item No.	V-101	By	EH/MP/DS
No. Required	1		

Function: Store the hydrogen produced in electrolysis mode

Operation: Continuous

Materials Handled	**Inlet (electrolysis)**	**Outlet (fuel cell)**
Stream ID	22	25
Quantity (lb/hr)	78.01	769.34
Composition:		
Water	0.54	0.59
Hydrogen	77.47	85.23
Temperature (°F)	75	75
Pressure (psi)	100	100
Vapor Fraction	1	1

Design Data

Type	Horizontal Vessel
Material	Stainless Steel
Gas Volume (ft^3)	26665.86349
Diameter (ft)	7.5
Length (ft)	600
Wall Thickness (ft)	0.032821367

C_P	$	453,456.39
C_{BM}	$	$1,383,042

Small Water Storage Tank

Identification

Item	Storage Tank	Date	4/5/11
Item No.	V-102	By	EH/MP/DS
No. Required	1		

Function: Store the excess water from electrolysis mode

Operation: Continuous

Materials Handled	**Inlet (electrolysis)**	**Outlet (fuel cell)**
Stream ID	16	28
Quantity (lb/hr)	76.53	84.64
Composition:		
Water	76.53	84.64
Temperature (°F)	75	75
Pressure (psi)	14.7	14.7
Vapor Fraction	0	0

Design Data

Type	Cone Roof
Material	Stainless Steel
Liquid Volume (gal)	110.5
Tank Volume (gal)	130

C_P	$	3,172.17
C_{BM}	$	3,172.17

Fuel Cell Mode

Table 8: Equipment List for Fuel Cell Mode of the Hydrogen Case

Unit No.	Unit Type	Function	Size	Material	Oper. T (°F)	Oper. P (psi)
C-103	Inlet Air Blower	Increase the pressure of the air inlet stream to pass through system	P_C = 50.18 hp	Cast Iron	75	14.7
C-104	Recycle Blower	Blow the recycle stream back to the fuel cell feed	P_C = 0.39 hp	Cast Iron	181	16.7
E-108	Hydrogen Preheater	Increase the temperature of the hydrogen feed stream	A = 9.48 ft^2 Q = 80,695 Btu/hr	Stainless Steel	350	16.6
E-109	Water Vaporizer and Preheater	Vaporize and increase the temperature of water feed	A = 5.9 ft^2 Q = 10,590 Btu/hr	Stainless Steel	350	16.7
E-110	Product Stream Partial Condenser	Cool fuel cell product and condense product water	A = 25.77 ft^2 Q = 352,393 Btu/hr	Stainless Steel	180.5	15.2
E-111	Recycle Heater	Increase the temperature of the recycle stream	A = 1.66 ft^2 Q = 8,589 Btu/hr	Stainless Steel	410	16.7
E-112	Air Preheater	Heat the air feed stream prior to entering the fuel cell	A = 50.78 ft^2 Q = 366,733 Btu/hr	Stainless Steel	450	20
P-102	FC Water Feed Pump	Increase the pressure of the water feed stream	P_C = 0.001 hp	Stainless Steel	75	17.7
R-100	Fuel Cell/Electrolyzer	Oxidizes hydrogen to water, producing electricity	I = 0.55 A/cm^2 V = 0.86 V Area = 1.869E+06 cm^2	YZS, porous nickel, $LaMnO_3$	1472	16.6
V-100	Large Water Storage Tank	Large storage vessel for water	V = 1105.3 gal	Stainless Steel	75	14.7
V-101	Hydrogen Storage Tank	Pressurized storage tank for H_2	D=7.5 ft L = 600 ft	Carbon Steel	75	100
V-102	Small Water Storage Tank	Small storage vessel for water	V = 110.5 gal	Stainless Steel	75	14.7

Inlet Air Blower (C-103)

This blower provides the air with enough pressure head to pass through the entire system and exit at atmospheric pressure. The air inlet stream leaves the blower at 22.7 psi, just enough pressure to pass through all of the units in its flow path and exit at 14.7 psi. Based on a rotary straight-lobe blower made of cast iron with cast aluminum blades, the bare module cost of this unit is $46,839.67. Please refer to the Specification Sheet on page 60 and sample calculations on page 179.

Recycle Blower (C-104)

This small blower is used to move a small fraction of the product stream back to the entrance of the fuel cell to mix with the inlet streams. It supplies enough pressure, 1.5 psi, to move the stream through the single heat exchanger it must pass through. Using a torayry straight-lobe deisgn with cast iron and cast aluminum blades, the bare module cost of this unit is $1,197.61. Please refer to the Specification Sheet on page 61 and sample calculations on page 179.

Hydrogen Preheater (E-108)

The hydrogen preheater uses the exhaust air stream to heat the hydrogen feed from 75.4°F to 350°F before being combined with the water feed stream. Using the same heat transfer coefficient calculation method as for the preheaters in electrolysis mode, a small area of heat transfer was calculated, allowing for a double pipe exchanger. Using stainless steel for both the inner and outer pipes, a bare module cost of $9,821.48 was calculated. Please refer to the Specification Sheet on page 62 and sample calculations on page 178.

Water Vaporizer and Preheater (E-109)

The function of this heat exchanger is to increase the temperature of the inlet water, vaporize it, and then increase the temperature further, from 75°F liquid to 350°F steam. Using the same method of heat transfer coefficient calculation as in previous heat exchangers, a small area was obtained, and double pipe geometry could be used. For a stainless steel construction, the bare module cost of this unit is $9,103.97. Please refer to the Specification Sheet on page 63 and sample calculations on page 178.

Product Stream Partial Condenser (E-110)

The product stream partial condenser uses cooling water to cool the fuel cell product stream from 1472°F to 180.5°F, causing water to condense out for storage. For details on cooling water flow rates, please refer to page 24 in the Energy and Utilities section. Using the same method of heat transfer coefficient calculation, a small area was calculated and double pipe geometry could be used. For stainless steel pipes, the bare module cost of this unit is $11,525.05. Please refer to the Specification Sheet on page 64 and sample calculations on page 178.

Recycle Heater (E-111)

The recycle heater uses the air exhaust stream to reheat the recycle stream after the water has been condensed out. Its temperature rises from 204°F to 410°F before being combined with the feed streams. Using the same method of heat transfer coefficient calculation to find an area, a small heat transfer area was required. Therefore, a double pipe geometry could be used. For stainless steel pipes, the bare module cost of this unit is $7,432.88. Please refer to the Specification Sheet on page 65 and sample calculations on page 178.

Air Preheater (E-112)

The air preheater heats the blown air feed stream from 173°F to 450°F using the air exhaust as the heat source. Using the same method of heat transfer coefficient calculation, a small heat transfer area was obtained, and a double pipe geometry could be used. For stainless steel construction, the bare module cost of this unit is $12,846.26. Please refer to the Specification Sheet on page 66 and sample calculations on page 178.

Fuel Cell Water Feed Pump (P-102)

The water feed pump for fuel cell operation requires 0.001 hp for operation since the pressure of the water stream only needs to increase by 3 psi. Since the size of this unit is far below the correlations within *Product and Process Design Principles*, a cost for this pump was determined by a Wel-Bit cast iron clear water pump[7] multiplied by the material factor for stainless steel. Therefore, the bare module cost of this unit is $398.00. Please refer to the Specification Sheet on page 67.

Fuel Cell/Electrolyzer (Fuel Cell)

As was stated before, this unit is a reversible fuel cell made of YSZ with a porous nickel at the anode and $LaMnO_3$ at the cathode. It operates at 0.55 A/cm^2 so that there is time during the day for turnover between fuel cell and electrolysis mode. Based on data from Bierschenk et al.**Error! ookmark not defined.**, this current density corresponds to a voltage of 0.86 V, and at the same area as stated previously, produces 884 kW over the course of the 10.9 hours during each operating day. It operates slightly above atmospheric pressure and at 1472°F. As stated before, the bare module cost of this unit is $450,000 based on Department of Energy targets. Please refer to the Specification Sheet on page 68.

Fuel Cell Specification Sheets

The following pages list the page number of the specification sheets detailing the different units within fuel cell operation.

Table 9: Equipment Summary for Fuel Cell Mode of the Hydrogen Case

Page	Unit No.	Unit Type
60	C-103	Inlet Air Blower
61	C-104	Recycle Blower
62	E-108	Hydrogen Preheater
63	E-109	Water Vaporizer and Preheater
64	E-110	Product Stream Partial Condenser
65	E-111	Recycle Heater
66	E-112	Air Preheater
67	P-102	FC Water Feed Pump
68	R-100	Fuel Cell/Electrolyzer
52	V-100	Large Water Storage Tank
53	V-101	Hydrogen Storage Tank
54	V-102	Small Water Storage Tank

Inlet Air Blower

Identification

Item	Blower	Date	4/5/11
Item No.	C-103	By	EH/MP/DS
No. Required	1		

Function: Increase the pressure of the inlet air stream

Operation: 10.9 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	38	39
Quantity (lb/hr)	5398.70	5398.70
Composition:		
Oxygen	1257.45	1257.45
Nitrogen	4141.26	4141.26
Temperature (°F)	75	173
Pressure (psi)	14.7	22.7
Vapor Fraction	1	1

Design Data

Type	Rotary Straight-Lobe
Material	Cast Iron, Cast Aluminum Blades
Net Work (HP)	50.18
Efficiency	0.72

C_P	$	21,785.89
C_{BM}	$	46,839.67

Recycle Blower

Identification

Item	Blower		Date	4/5/11
Item No.	C-104		By	EH/MP/DS
No. Required	1			

Function: Blow the recycle stream to the entrance of the fuel cell

Operation: 10.9 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		35	36
Quantity (lb/hr)		21.24	21.24
Composition:			
	Water	10.58	10.58
	Hydrogen	10.66	10.66
Temperature (°F)		181	204
Pressure (psi)		15.2	16.7
Vapor Fraction		1	1

Design Data

Type	Rotary Straight-Lobe
Material	Cast Iron, Cast Aluminum Blades
Net Work (HP)	0.39
Efficiency	0.72

C_P	$	557.03
C_{BM}	$	1,197.61

Hydrogen Preheater

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-108	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature of the hydrogen feed stream

Operation: 10.9 hours, daily

Materials Handled		**Hot**		**Cold**	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		42	43	26	27
Quantity (lb/hr)		4722.28	4722.26	85.23	85.23
Composition:					
	Hydrogen	0.00	0.00	85.23	85.23
	Nitrogen	4141.26	4141.26	0.00	0.00
	Oxygen	581.02	581.02	0.00	0.00
Temperature (°F)		1190	1128	75.4	350
Pressure (psi)		19.1	18.6	16.7	16.6
Vapor Fraction		1	1	0	0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	80,695
Heat Transfer Coefficient (Btu/hr-ft^2-F)	9.03
Heat Transfer Area (ft^2)	9.48

C_P	$	5,456.38
C_{BM}	$	9,821.48

Water Vaporizer and Preheater

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-109	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature and vaporize water inlet

Operation: 10.9 hours, daily

Materials Handled

		Hot		Cold	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		43	44	29	30
Quantity (lb/hr)		4722.28	4722.26	84.64	84.64
Composition:					
	Water	0.00	0.00	84.64	84.64
	Nitrogen	4141.26	4141.26	0.00	0.00
	Oxygen	581.02	581.02	0.00	0.00
Temperature (°F)		1128	1044.67	75.4	350
Pressure (psi)		18.6	17.1	17.7	16.7
Vapor Fraction		1	1	0	1

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	105,908
Heat Transfer Coefficient (Btu/hr-ft^2-F)	20.62
Heat Transfer Area (ft^2)	5.9

C_P	$	5,057.76
C_{BM}	$	9,103.97

Product Stream Partial Condenser

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-110	By	EH/MP/DS
No. Required	1		

Function: Cool fuel cell product stream to condense product water

Operation: 10.9 hours, daily

Materials Handled

	Inlet	**Outlet**	**Condensate**
Stream ID	33	35	34
Quantity (lb/hr)	867.54	21.24	846.33
Composition:			
Water	856.88	10.58	846.33
Hydrogen	10.66	10.66	0.00
Temperature (°F)	1472	180.5	180.5
Pressure (psi)	16.7	15.2	15.2
Vapor Fraction	1	1	0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	352,393
Heat Transfer Coefficient (Btu/hr-ft^2-F)	29.31
Heat Transfer Area (ft^2)	25.77
Cold Utility	Cooling Water

C_P	$	6,402.81
C_{BM}	$	11,525.05

Recycle Heater

Identification			
Item	Heat Exchanger	Date	4/5/11
Item No.	E-111	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature of the recycle stream

Operation: 10.9 hours, daily

Materials Handled		**Hot**		**Cold**	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		44	45	36	37
Quantity (lb/hr)		4722.28	4722.26	85.23	85.23
Composition:					
	Hydrogen	0.00	0.00	10.66	10.66
	Water	0.00	0.00	10.58	10.58
	Nitrogen	4141.26	4141.26	0.00	0.00
	Oxygen	581.02	581.02	0.00	0.00
Temperature (°F)		1045	1038	204	410
Pressure (psi)		17.1	16.6	16.7	16.7
Vapor Fraction		1	1	1	1

Design Data	
Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	8,589
Heat Transfer Coefficient (Btu/hr-ft^2-F)	7.08
Heat Transfer Area (ft^2)	1.66

C_P	$	4,129.38
C_{BM}	$	7,432.88

Air Preheater

Identification

Item	Heat Exchanger	Date	4/5/11
Item No.	E-112	By	EH/MP/DS
No. Required	1		

Function: Increase the temperature of the air feed stream

Operation: 10.9 hours, daily

Materials Handled

		Hot		Cold	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		41	42	39	40
Quantity (lb/hr)		4722.28	4722.26	5398.71	5398.71
Composition:					
	Nitrogen	4141.26	4141.26	4141.26	4141.26
	Oxygen	581.02	581.02	1257.45	1257.45
Temperature (°F)		1472	1191	173	450
Pressure (psi)		17.1	16.6	22.7	21.3
Vapor Fraction		1	1	1	1

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	366,733
Heat Transfer Coefficient (Btu/hr-ft^2-F)	7.08
Heat Transfer Area (ft^2)	50.78

C_P	$	7,136.81
C_{BM}	$	12,846.26

FC Water Feed Pump

Identification

Item	Pump	Date	4/5/11
Item No.	P-102	By	EH/MP/DS
No. Required	1		

Function: Slightly increase the pressure of the water feed

Operation: 10.9 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	28	29
Quantity (lb/hr)	84.64	84.64
Composition:		
Water	84.64	84.64
Temperature (°F)	75	75
Pressure (psi)	14.7	17.7
Vapor Fraction	0	0

Design Data

Type	Wel-Bilt Cast Iron Clear Water Pump
Material	Stainless Steel
Net Work (HP)	0.001
Efficiency	0.4

C_P	$	120.00
C_{BM}	$	398.00

Fuel Cell/Electrolyzer (Fuel Cell)

Identification

Item	Fuel Cell	Date	4/5/11
Item No.	R-100	By	EH/MP/DS
No. Required	1		

Function: Oxidizes hydrogen to water to produce electricity

Operation: 10.9 hours, daily

Materials Handled	**Inlet**		**Outlet**	
Stream ID	32	40	33	41
Quantity (lb/hr)	191.11	5398.71	867.54	4722.28
Composition:				
Water	95.23	0.00	856.88	0.00
Hydrogen	95.88	0.00	10.66	0.00
Oxygen	0.00	1257.45	0.00	581.02
Nitrogen	0.00	4141.26	0.00	4141.26
Temperature (°F)	356	450	1472	1472
Pressure (psi)	16.6	21.3	16.6	21.3
Vapor Fraction	1	1	1	1

Design Data

Type	Reversible Fuel Cell
Material	YSZ, porous Nickel, $LaMnO_3$
Heat Duty (Btu/hr)	0.00
Electricity Produced (kW)	884.11
Operating T (°F)	1472
Operating P (psi)	16.6
Voltage (V)	0.87
Current (A/cm^2)	0.55
Electrode Area (cm^2)	1.8692E+06

C_P	$	450,000
C_{BM}	$	450,000

Equipment Cost Summary

Table 10: Summary of Purchase Cost and Bare Module Cost for All Units

Unit No.	Unit Name	Purchase Cost	Bare Module Factor	Bare Module Cost
C-100	Storage Compressor 1	$22,569	2.15	$48,523
C-101	Storage Compressor 2	$23,778	2.15	$51,122
C-102	Storage Compressor 3	$24,666	2.15	$53,032
E-100	Water Preheater 1	$6,056	1.80	$10,900
E-101	Water Preheater 2	$6,383	1.80	$11,489
E-102	Water Preheater 3	$8,814	1.80	$15,865
E-103	Fired Heater	$22,057	2.19	$48,304
E-104	Product Partial Condenser	$8,894	1.80	$16,010
E-105	Intercooler for C-100	$7,349	1.80	$13,229
E-106	Intercooler for C-101	$7,347	1.80	$13,225
E-107	Intercooler for C-102	$7,351	1.80	$13,231
F-100	Flash Vessel	$7,235	1.80	$13,022
P-100	Water Feed Pump	$120	3.30	$396
R-100	Fuel Cell/Electrolyzer	$450,000	1.00	$450,000
V-100	Large Water Storage Tank	$10,265	1.00	$10,265
V-101	Hydrogen Storage Tank	$453,456	3.05	$1,383,041
V-102	Small Water Storage Tank	$3,172	1.00	$3,172
Electrolysis Subtotal		**$1,069,511**		**$2,154,827**
		Fuel Cell Equipment		
Unit No.	**Unit Name**	**Purchase Cost**	**Bare Module Factor**	**Bare Module Cost**
C-103	Inlet Air Blower	$21,786	2.15	$46,840
C-14	Recycle Blower	$557	2.15	$1,198
E-108	Hydrogen Preheater	$5,456	1.80	$9,821
E-109	Water Vaporizer & Preheater	$5,058	1.80	$9,104
E-110	Product Stream Partial Condenser	$6,403	1.80	$11,525
E-111	Recycle Heater	$4,129	1.80	$7,433
E-112	Air Preheater	$7,137	1.80	$12,846
P-10	FC-Water Feed Pump	$120	3.30	$396
Fuel Cell Subtotal		**$50,646**		**$99,163**
	System Total	**$1,120,157**		**$2,253,990**

Table 10 shows the equipment cost summary for each piece of major equipment in the hydrogen system, both electrolysis and fuel cell modes. The purchase cost is the cost to buy the physical equipment, and the bare module cost is the purchase cost including installation costs. The bare module factors are a function of the specific type of equipment and can be found listed in Table 22.11 of *Product and Process Design Principles*. The purchase cost of most of these units has been estimated using correlations throughout Chapter 22 of *Product and Process Design Principles*.

Table 11: Fixed Capital Investment Summary for Hydrogen Process

C_{BM}	Equipment Bare Module Costs			$	857,512
C_{store}	Storage Vessel Bare Module costs			$	1,396,478
			C_{TBM}	**$**	**2,253,990**
Direct Permanent Investment					
C_{TBM}	Total Bare Module Cost			$	2,253,990
C_{site}	Site Preparation			$	112,700
C_{serv}	ServiceFacilities			$	112,700
C_{alloc}	Allocated Costs for Utility Plants			$	0
			C_{DPI}	**$**	**2,479,389**
Total Depreciable Capital					
C_{DPI}	Direct Permanent Investment			$	2,479,389
C_{cont}	Contingencies and Contractors Fees			$	446,290
			C_{TDC}	**$**	**2,925,679**
Total Permanent Investment					
C_{TDC}	Total Depreciable Capital			$	2,925,679
C_{land}	Land			$	0
C_{roylty}	Royalty			$	0
$C_{startup}$	Plant Startup			$	292,568
		(unadjusted)	C_{TPI}	$	3,218,247
			F_{site}		1.1
			C_{TPI}	**$**	**3,540,072**
Total Capital Investment					
C_{TPI}	Total Permanent Investment			$	3,540,072
C_{WC}	Working Capital			$	143,126
			C_{TCI}	**$**	**3,683,198**

The Fixed Capital Investment Summary in Table 11 lists the various capital investments estimated for the hydrogen system. The direct permanent investment, C_{DPI}, includes the total bare module cost of all equipment for the process, the cost of site preparation, and the cost of service facilities. As shown above, the total bare module cost of all equipment is $2,253,990, while the cost of services and site preparations are estimated at 5% of total bare module costs. Since the energy storage system will be located at a previously established plant, no additional allocated cost for utilities is required. All utilities will already exist at established price levels, provided by the power plant. The total depreciable capital, C_{TDC}, is calculated by adding the contractors and contingencies fees, 18% of C_{TDC}, to C_{DPI}.

The total permanent investment, C_{TPI}, is the sum of total depreciable capital and other non-depreciable investments, such as the cost of land, royalties, and plant startup. Since the system will be implemented at an existing power plant, there is no cost for the land, and no royalties need to be paid. Startup, however, was estimated as 10% of C_{TDC}. To account for the plant being located in the North East, a site factor of 1.1 was used, taken from Table 22.13 in *Product and Process Design Principles*. Adding working capital to this adjusted C_{TPI} yields a total capital investment, C_{TCI}, of $3,683,198. All approximations for costs are taken from Chapter 22 of *Product and Process Design Principles*.

Other Important Considerations

Environmental and Safety Problems and Concerns

While there are no toxic materials used in the hydrogen system, many streams throughout the system will be very hot. Therefore, the system needs to be either enclosed in some sort of insulation as to protect the surrounding environment or fenced off a safe distance away. Additionally, as the system is currently designed, the exhaust streams leave at very high temperatures. These streams would need to be further cooled before being exhausted to the environment.

The temperature at which the system operates is well above the auto-ignition point of hydrogen. This means that there is the chance of an explosion if a spark goes off or oxygen is accidentally mixed with the hydrogen. Therefore, care needs to be taken to make sure all seals are perfect and there are no leaks of oxygen into the hydrogen pipes.

Additionally, the presence of hydrogen with metals can lead to hydrogen embrittlement. This is when hydrogen, ue to its small size, will dissolve into the metal and cause it to weaken and be more prone to fracturing. In the pipes throughout the system, since the gas will be moving at high velocity, this is not a big problem. However, in the storage vessel, where the hydrogen is stored at high pressure for longer periods of time, this can become a serious issue, weakening the structure and possibly leading to safety hazards. To help relieve this problem, we found a hydrogen-shielding polymer that could line the inside of the vessel and reduce the hydrogen contact with the metal, allowing the structure to last much longer. This polymer is EVAL™ M100[11], seen at the end of the appendix of this report. With a thickness of 0.1 mm, this polymer significantly hinders hydrogen permeability. Based on a cost received from the company of $5 per liter, and the amount of polymer needed, approx. 10 L, the cost of the polymer becomes negligible compared to the rest of the process.

Startup and Shutdown

At the initial startup of the system, very pure water must be purchased and used in electrolysis mode to generate hydrogen, starting the cycle. The amount needed, approximately 1100 gallons, could be purchased for a total cost of $0.75 based on the cost of process water listed in Table 23.1 of *Product and Process Design Principles*. After this water has been purchased, since the process is cyclical, no additional feeds need to be purchased.

Additionally, the system will have to startup two times each day, once for electrolysis mode and once for fuel cell operation. The flow rates of each cycle were designed such that a 30-minute period exists for turnover. During this time period, the operators can turn equipment on, allowing them to heat up to operating temperature. However, because the heat exchangers that preheat the inlet streams use heat from the exhaust streams of the reversible fuel cell, additional heat will be needed during startup when no streams exit the cell. This would most likely require an additional fired heater that can provide enough energy to vaporize and heat all inlet streams, used in both fuel cell and electrolysis operation. This fired heater would be more expensive, and would require a lot more fuel than the fired heater currently in the process design, adding to the overall variable and equipment costs of the process.

Operating Costs

This section describes the operating costs of the hydrogen reversible fuel cell system. The Variable Costs are listed below in Table 12.

Table 12: Variable Cost Summary of Hydrogen System

			Annual Cost
General Expenses			
	Selling / Transfer Expenses:	$	41,200.44
	Direct Research:	$	0.00
	Allocated Research:	$	0.00
	Administrative Expense:	$	27,466.96
	Management Incentive Compensation:	$	17,166.85
	Total General Expenses	$	85,834.25
Raw Materials		$	0.00
Byproducts		$	0.00
Utilities			
	Low P Steam	$	9,842.73
	Cooling Water	$	1,800.37
	Electricity	$	319,889.46
	Natural Gas	$	2,021.40
	Total Utilities		333,553.96
Total Variable Costs		**$**	**419,388.21**

The variable costs of this process include utilities and other general expenses. Under general expenses, since there is no research associated with the system, the research costs are $0. Additionally, there are no raw materials or byproducts produced in this system, and therefore both of these costs are also $0. The utilities include all electrolysis and fuel cell inputs, including the additional heating to the electrolyzer (accounted for as electricity above). The general costs are estimations based on values from Chapter 23 of *Product and Process Design Principles*. As seen in Table 12, the total variable costs are $419,388.21 per year. The fixed costs for the hydrogen system are summarized below in Table 13.

Table 13: Fixed Costs for the Hydrogen Case

		Annual Cost
Operations		
	Direct Wages and Benefits	$327,600
	Direct Salaries and Benefits	$49,140
	Operating Supplies and Services	$19,656
	Total Operations	**$396,396**
Maintenance		
	Wages and Benefits	$131,656
	Salaries and Benefits	$32,914
	Materials and Services	$131,656
	Maintenance Overhead	$6,583
	Total Maintenance	**$302,808**
Operating Overhead		
	General Plant Overhead:	$38,433
	Mechanical Department Services:	$12,991
	Employee Relations Department:	$31,937
	Business Services:	$40,057
	Total Operating Overhead	**$123,419**
Property Taxes and Insurance		**$58,514**
Total Fixed Costs		**$881,136**

The annual fixed costs for the hydrogen system are the costs incurred regardless of the production of electricity. As seen in Table 13, these costs include operating costs, maintenance costs, operating overhead, and property taxes and insurance. These values have all been determined as a percentage of total depreciable capital as suggested in Section 23.2 of *Product and Process Design Principles*[3]. The total operating costs are calculated with the assumption that the process is responsible for the payment of 1.5 operators per shift, since some power plant operators will already be present. Maintenance costs include costs for keeping equipment clean and in acceptable order, personnel salaries, and maintenance overhead. The operating overhead costs include the costs of providing services that are not directly related to plant operation, such as first aid and medical services, fire protection, warehousing, and other costs. As seen above, the total annual fixed costs add up to $881,136.

Overall Economic Analysis

The overall profitability of the hydrogen system has been evaluated using the Profitability Analysis Spreadsheet (see page 192 of the Appendix). A summary of the results from the spreadsheet is shown below.

Table 14: ROI Analysis for the Third Year of Operation

		Costs
Annual Sales		554,683
Annual Costs	$	(1,224,459)
Variable Costs	$	(381,470.59)
Fixed Costs	$	(881,135.95)
Depreciation	$	(283,206)
Income Tax	$	0
Net Earnings	$	(952,983)
Total Capital Investment	$	3,650,842
ROI	$	**-26.10%**

As shown by Table 14, the hydrogen system we designed is not profitable; the annual costs are more than twice the annual sales revenue. Since there is a negative net income, the income tax is zero.

Additionally, the system has an ROI in the third year of operation of -26.10%. This can be attributed to the low profit margin. The only revenue generated by this process is the electricity that it can produce, and since it is inherently less than 100% efficient, the profit margin (peak price minus off-peak price) is the only factor that could make the process profitable. This ROI value was calculated with off-peak energy prices at $0.06/kWh and peak energy prices at $0.20/kWh, a $0.14/kWh profit margin. Both of these prices are fairly reasonable based on data we found from the New York State Energy Research and Development Authority[12].

To see what the profit margin would need to be for the process to get a positive ROI in its third year of operation, a sensitivity analysis was conducted. The results are shown on the next page.

Table 15 ROI at Varying Profit Margins

Peak Cost ($/kWh)	Profit Margin ($/kW)	ROI
0.25	0.19	-22.47%
0.30	0.24	-18.86%
0.35	0.29	-15.28%
0.40	0.34	-11.71%
0.45	0.39	-8.17%
0.50	0.44	-4.65%
0.55	0.49	-1.15%
0.60	0.54	2.33%
0.65	0.59	5.78%
0.70	0.64	9.22%

To achieve an ROI of 0%, the peak electricity price would need to be $0.57/kWh, much higher than any reasonable electricity price in the United States. At this price, this system would not be competitive with any other form of electrical energy storage.

System Efficiency

While this system is not economically profitable, it achieves a relatively high electrical efficiency. During the operation of the reversible fuel cell itself, ignoring the rest of the system, the efficiency is less than 100% because of waste heat caused by overvoltage, as stated previously. For the currents and voltages of the hydrogen system, the fuel cell efficiency is 80.4%. To calculate the other efficiencies of the system, Table 16 below lists the electricity sources and sinks.

Table 16: Electricity Inputs and Outputs

Electricity Sinks		
Unit No.	**Electricity (kW)**	**Electricity (kWh/day)**
C-100	1.03E+01	444,234
C-101	1.11E+01	477,415
C-102	1.16E+01	502,220
P-100	4.55E-01	19,651
R-100	1.00E+03	43,200,000
C-103	3.74E+01	1,469,565
C-104	2.90E-01	11,392
P-101	7.46E-04	29
Total w/o additional energy		46,124,506
Additional Energy	1.99E+02	8,585,741
Total		**54,710,247**
Energy Sources		
Unit No.	**Electricity (kW)**	**Electricity (kWh/day)**
R-100	8.84E+02	34,721,495

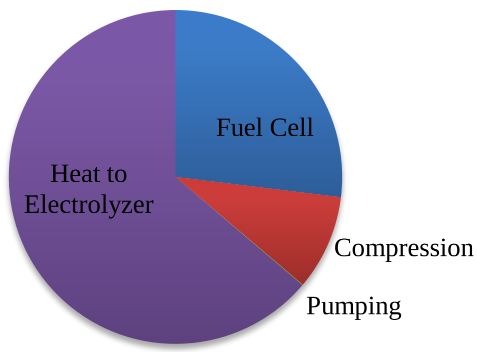
The overall electrical efficiency is defined as the electricity output divided by all the electricity inputs. For this system, counting the excess energy to the electrolyzer as a heat source, the overall electrical efficiency is 75.3%. If the excess energy to the electrolyzer is counted as electricity, the electrical efficiency falls to 63.5%. The additional energy to the electrolyzer accounts for 11.8% efficiency losses alone. If implemented, the electrical efficiency would be in between these two values because the additional energy would be supplied as a mixture of overvoltage and heat to the inlet stream.

In addition to electrical efficiency, the overall efficiency of the system can be calculated. This is defined as the useful energy out of the system divided by all energy inputs into the system. Based on all electrical inputs and utilities of this design, the overall efficiency of the system is 52.4%, meaning that 47.6% of the energy put into the system is lost. To determine the cause of these losses, we further explored the energy inputs of the system. Table 17 summarizes the efficiency losses.

Table 17: Efficiency Losses of the Hydrogen System

	Losses (kWh)	% of Total
Fuel Cell	2,355	26.93%
Compression	807	9.23%
Pumping	5	0.06%
Heat to Electrolyzer	5,577	63.78%
Total Losses	**8,744**	**100%**

Figure 7: Efficiency Losses in Hydrogen System



The two biggest efficiency losses in the system are caused by the heat needed to keep the electrolyzer running at operating temperature and the losses caused by running a reversible fuel cell. Both of these efficiency losses are unavoidable in a reversible fuel cell system. The reaction occurring in electrolysis mode is always going to be very endothermic and therefore require large amounts of heat to keep its temperature up. This required heat accounts for 63.78% of the losses incurred by this system. Additionally, the round-trip efficiency of a fuel cell can never be 100% because there will always be heat losses due to overvoltage at both the anode and cathode. These losses accounted for 26.93% of the total losses in the system.

The compression losses that occur are due to pressure drop of streams across heat exchangers and other units throughout the system and only account for 9.23% of total losses. Since the compression of the streams is equal the minimum pressure drop through the system based on results from ASPEN Heat Exchanger Design, these losses have been minimized. Therefore, in order to increase the overall efficiency of this system, the improvements must come from operating conditions closer to the open circuit voltage and other ways to heat the electrolyzer.

Methane Case

Concept Stage

Operating Pressure and Voltage Selection

The selection of the operating pressure and voltage of the fuel cell during electrolysis mode were coupled due to the relationship between the Nernst equation and pressure. The operating pressure of 10 atm was selected due to the increased cell efficiency at this elevated pressure. At 10 atm, difference between the operating voltage and the open cell voltage is much lower than at atmospheric pressure, and this translates to higher reversible cell efficiency. Bierschenk proposes an operating pressure of 10 atm due to the efficiency benefits that can be realized at higher operating pressures and the lower thermoneutral voltage. The thermoneutral voltage of the cell is the voltage at which the heat generated by the inefficiencies in the cell are equal to the amount of energy that is consumed by the endothermic reaction in electrolysis, so it is ideal to minimize the difference in voltage between V_{TN} and the operating voltage of the cell during electrolysis mode. Additionally, a lower V_{TN} values translates to a lower heat duty on the fuel cell during fuel cell mode, and this further increases the efficiency of fuel cell mode by reducing parasitic losses. Figure 10 – Potential as a Function of Temperature and Pressure from Bierschenk demonstrates how the thermoneutral voltage range decreases as the operating pressure increases. The dark gray shaded region in Figure 8 represents the range of Nernst potentials that can be achieved during electrolysis mode running at 10 atm with Beirschenk's experimental composition. The lighter gray region represents the Nernst potentials that can be achieved when operating the cell at atmospheric pressure. Figure 8 clearly demonstrates how the voltage range of operation can be optimized at higher pressures.

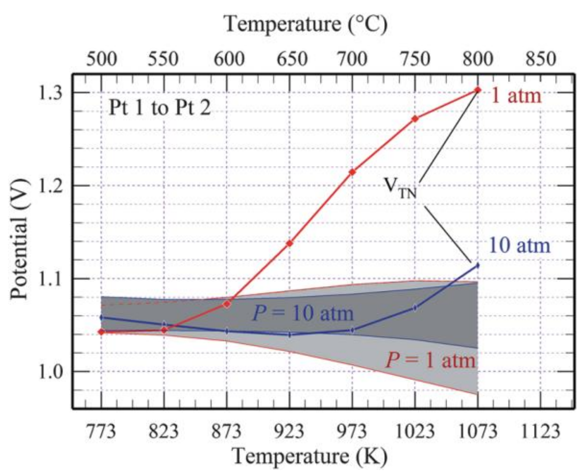


Figure 10 – Potential as a Function of Temperature and Pressure

Bierschenk supplied a full V-i curve for different operating conditions, so careful approximations were used to determine the operating cell voltages for electrolysis and fuel cell modes. The open cell voltage of 0.99 V was calculated based on the operating pressure of 10 atm and the composition of the electrolysis Stream 9. This value is 0.09 V higher than the open cell voltage at an operating pressure of 1 atm. The operating voltage for electrolysis was then determined to be 1.06 V using a linear approximation based on Beirschenk's data. The V-i curve, Figure 1, for methane operating demonstrated a linear relationship between operating voltage and current density at atmospheric conditions, and it was assumed that this linear behavior would exist at 10 atm as well. The difference between the upper and lower limits was divided by a current density of 0.5 A/cm^2, and this value was added to the open cell voltage to arrive at the operating pressure of the cell during electrolysis mode. The same V-i curve slope was used to determine the operating voltage during fuel cell mode.

A linear approximation The V-i curve that Bierschenk compiled at 1 atm revealed a difference in voltage between electrolysis and fuel cell mode of 0.12 V, and this translates to a cell efficiency of 88.1% when running at -0.5 A/cm^2 and +0.5 A/cm^2 in electrolysis and fuel cell modes, respectively. However, this does not take into account the additional efficiency of operating at a slightly higher current density during fuel cell mode. This must be done in order to allow for the difference in operation times.

Composition Selection

The composition and molar flowrate of the feed stream in electrolysis mode was chosen based on the amount of oxygen that needed to be produced to store 12 MWh of electricity. Both reactions for this case produce oxygen during electrolysis, so the sum of the extents of reaction for the reduction of water and carbon dioxide must be equal to the extent of reaction of the oxidation of O^{2-} ions at the cathode. The power input was divided by the current density and multiplied by the electrolysis operating voltage in order to determine the number of moles of electrons that had to be removed from the oxygen ions to produce the desired amount of oxygen. Please refer to the calculations on pages 185 to 186 for further details about this procedure.

An initial composition of roughly 90% reactant, a combination of water and carbon dioxide, and 10% product, hydrogen gas and carbon monoxide, was chosen for high conversion. It was assumed that the product stream in electrolysis mode would be in equilibrium, so the final composition of the product stream was determined by solving for the two extents of reaction for the reduction of water and carbon dioxide. These reactions could not be modeled in ASPEN due to the separation of the gases at the anode and the cathode. Therefore, all equilibrium calculations were performed in Microsoft Excel. The sum of the extents of these two reactions was set equal to the extent of reaction of the oxidation at the cathode to conserve mass.

The relative amounts of carbon dioxide and water were selected based on the desired composition of the storage gas. The methanation reaction results in a 4:1 reduction in the number of moles of gas that need to be stored, and 3 moles of hydrogen are consumed for each mole of methane consumed. Based on this stoichiometric ratio, it was decided that the fuel cell product stream should have an excess of hydrogen relative to carbon monoxide to achieve maximum reduction in the number of moles of gas to minimize the volume of the storage vessel.

The extents of the two reactions were then calculated based on the equilibrium constants of the two reactions. The change in Gibbs free energy was calculated for each reaction, and these values were then used to determine K_{eq} values for the two reactions. Expressions for the final molar composition of the product were then built in Microsoft Excel, using an initial estimate for the extent of each reaction to calculate the final molar amount of each species. Thefinal molar compositions were then set equal to the overall K_{eq} value, and the extents of the two reactions were then found iteratively. Since Keq is very large for these reactions, the two reactions proceed nearly to completion. These molar extent values were converted to conversion values and put into ASPEN to model the fuel cell as an RSTOICH block.

Methanation Reaction

The next process in the electrolysis process for the methane case is the methanation reaction. As previously discussed, this reaction was included to reduce the volume and cost of the storage vessel for electrolysis mode. The methanation reaction was also assumed to proceed to equilibrium conditions, and it was modeled with an RGIBBS block in ASPEN, process block R-101. The equilibrium of this reaction is favored at high pressures and low temperatures, and an isothermal condition of 400°F was used to calculate the equilibrium composition. While this temperature is on the lower end of the range of acceptable operating temperatures for the catalyst, it was selected since the exit stream would have to be cooled additionally before storage. The cost of cooling water is relatively insignificant for the amount of heat that needs to be transferred out of the reactor. A packed bed shell and tube reactor design was selected so that the highly exothermic reaction could be cooled to prevent catalyst sintering. The catalyst used in this process is Haldor Topsoe PK-7R, and the properties of this catalyst are summarized in the Appendix on pages 360-362. The equilibrium composition of the methanation product Stream 12 modeled by APSEN confirms the success of the operating pressure selection; the product stream is 70% methane. This reaction also forms a significant amount of water, and this is removed from the storage gas stream by a condenser, E-104, cooled with cooling water later on in the process. The dehumidified product gas is stored at 143.5 psi for future use in fuel cell mode.

The amount of catalyst needed for this reaction was calculated so that the cost of the reactor could be estimated. The methanation reaction has been studied carefully, and the kinetics are well known. A kinetic model for methanation over a nickel-alumina catalyst proposed by Xu and Froment[13] was selected for the basis of this calculation due to the similarities between the operating conditions used in the paper and the operating conditions of this project. The kinetics were based on the rate of change of the mole fraction of CO in the reactor, and this resulted in a catalyst mass requirement of 0.043 $g_{catalyst}$*hr/$mole_{CO}$. When multiplied of the flowrate of carbon monoxide through the reactor, the mass of catalyst required was calculated to be 1095 kg. The void fraction and catalyst density were then used to find the volume of catalyst needed, 13.7 ft^3, and the price, $10,970.00. The reactor was then sized by modeling it in ASPEN as a heat exchanger.

Feedstock Preparation

The stored gas from electrolysis and the water needed for steam reformation must be heated before being processed by the fuel cell. Both feed streams are heated using the product streams from the fuel cell, and the water is heated further by a fired heater for complete vaporization. Once the water is vaporized, the two streams are mixed and heated again.

Reformation

In order for the methane in the feed stream to be processed by the fuel cell, it must be reformed into hydrogen and carbon dioxide. This reaction can be performed within the fuel cell as previously discussed due to the high operating temperature capable with SOFCs. At the operating temperature of 800°C, full conversion of methane can be assumed[14]. This reaction is endothermic, and it assists in cooling the fuel cell. The heat absorbed by this reaction on an hourly basis was calculated to be 265 kW.

Storage Pressure Selection

A sensitivity analysis was performed in order to determine the optimal storage pressure. Storing the fuel gas in both modes at a higher pressure than 10 atm would reduce the storage vessel size and cost, but it would also increase the cost of compression. The cost of compressions is twofold; compression requires both additional equipment and energy to drive the compression. Using an aspect ratio (length/diameter) of 10,000 and a gas flowrate of 17.3 ft^3/minute, the purchase costs of the storage vessel and compressor were calculated based on purchase cost equations from *Product and Process Design Principles.* The cost of electricity was calculated based on the horsepower required by the compressor, and this value was added to the purchase cost of the compressor to yield a total cost of compression. As Figure 11: Storage Pressure Selection Sensitivity Analysis demonstrates, the total purchase cost increased with storage pressure. Even though the overall storage volume would decrease with an increase in storage pressure, the wall thickness of the storage vessel would have to be greatly increased in order to withstand the high pressures. Due to the high purchase cost of additional compressors, it was decided that the storage gases would not be compressed above the operating pressure.

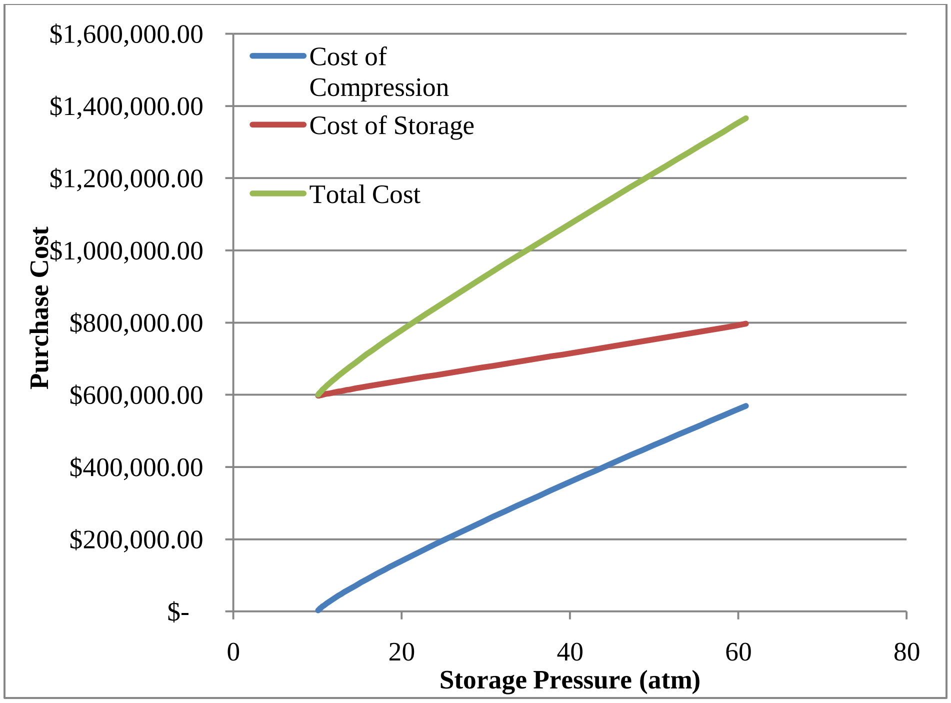
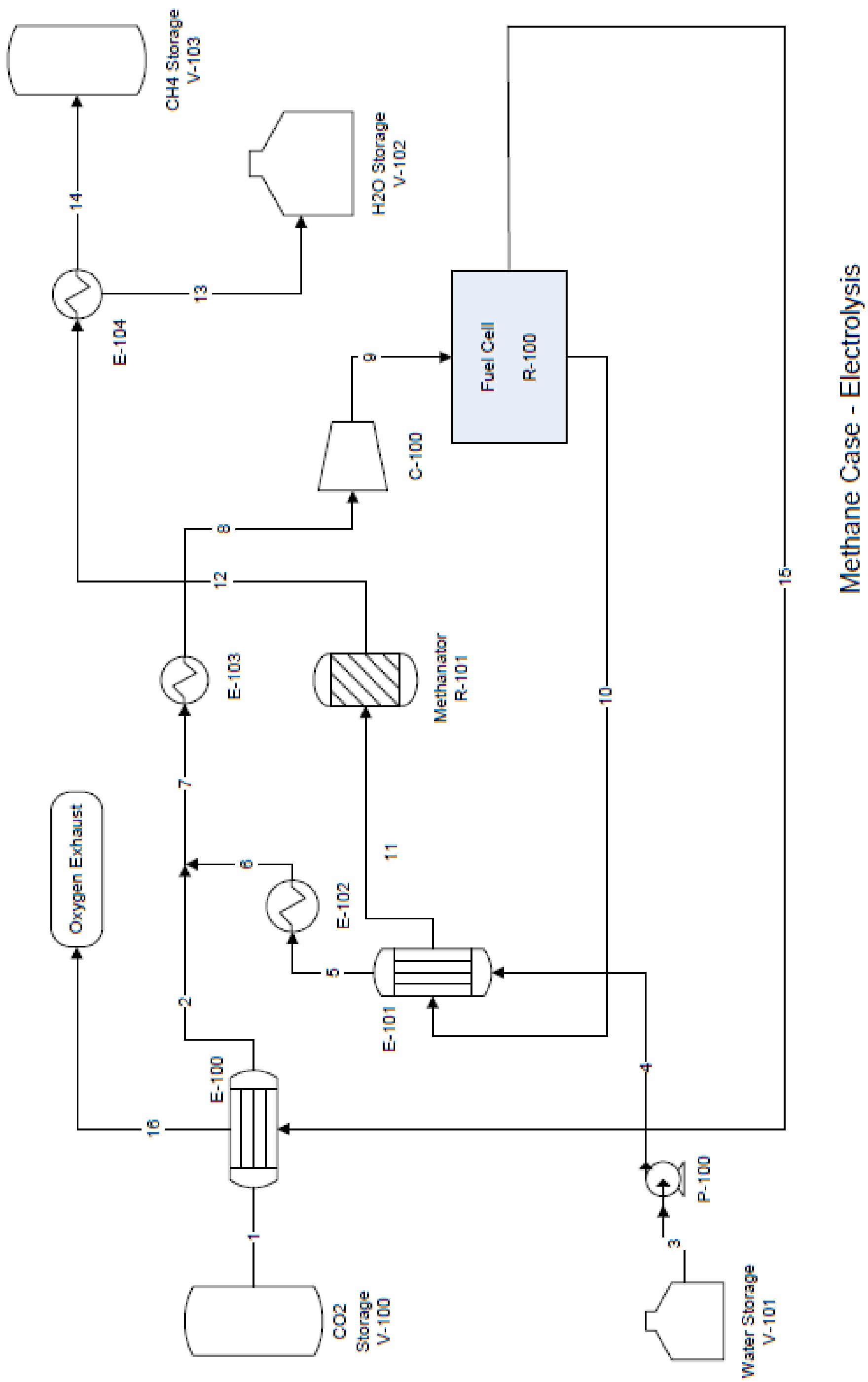


Figure 11: Storage Pressure Selection Sensitivity Analysis

This analysis was repeated for operating pressures of 1 atm and 5 atm to observe the effect of operating pressure on equipment purchase cost. Even though compressors would not be necessary at an operation pressure of 1 atm, the purchase cost of the storage vessel would be $4,000,000. Additionally, running the process at atmospheric pressure would negatively affect the equilibrium in the methanation reaction and would lead to slightly lower conversion.

Process Flow Diagrams and Material Balances - Electrolysis

Figure 12: Process Flow Diagram for Electrolysis Mode of the Methane Case



		1	2	3	4	5	6
From			E-100		P-100	E-101	E-102
To		E-100	M-100	P-100	E-101	E-102	M-100
Substream: MIXED							
Phase:		Vapor	Vapor	Liquid	Liquid	Mixed	Vapor
Component Mass Flow							
HYDROGEN	LBMOL/HR	3.527396	3.527396	0	0	0	0
CARBO-01	LBMOL/HR	8.818491	8.818491	0	0	0	0
CARBO-02	LBMOL/HR	2.204623	2.204623	0	0	0	0
WATER	LBMOL/HR	0	0	29.54194	29.54194	29.54194	29.54194
METHANE	LBMOL/HR	0	0	0	0	0	0
OXYGEN	LBMOL/HR	0	0	0	0	0	0
NITROGEN	LBMOL/HR	0	0	0	0	0	0
Mole Flow	LBMOL/HR	14.55051	14.55051	29.54194	2.95E+01	2.95E+01	2.95E+01
Mass Flow	LB/HR	456.9632	456.9632	532.2064	532.2064	532.2064	532.2064
Volume Flow	CUFT/HR	5.87E+02	1.03E+03	8.55E+00	8.55E+00	7.68E+02	1.75E+03
Temperature	F	77	440.33	76.73	76.84003	351.5895	351.5895
Pressure	PSIA	1.40E+02	1.37E+02	1.40E+02	1.55E+02	1.37E+02	1.37E+02
Vapor Fraction		1	1	0	0	0.435742	1
Liquid Fraction		0	0	1	1	0.564258	0
Solid Fraction		0	0	0	0	0	0
Molar Enthalpy	BTU/LBMOL	-1.10E+05	-1.07E+05	-1.23E+05	-1.23E+05	-1.11E+05	-1.02E+05
Mass Enthalpy	BTU/LB	-3496.594	-3393.68	-6820.894	-6820.743	-6164.282	-5673.855
Enthalpy Flow	BTU/HR	-1.60E+06	-1.55E+06	-3.63E+06	-3.63E+06	-3.28E+06	-3.02E+06
Molar Entropy	BTU/LBMOL-R	9.15E-01	5.54E+00	-3.90E+01	-3.90E+01	-2.30E+01	-1.21E+01
Mass Entropy	BTU/LB-R	0.0291437	0.1762911	-2.163532	-2.163336	-1.278971	-0.6742682
Molar Density	LBMOL/CUFT	2.48E-02	1.42E-02	3.46E+00	3.46E+00	3.85E-02	1.69E-02
Mass Density	LB/CUFT	0.778114	0.4453187	62.27774	62.27965	0.6931875	0.3041936
Average Molecular Weight		31.4053	31.4053	18.01528	18.01528	18.01528	18.01528

Stream ID:		7	8	9	10	11	12
From		M-100	E-103	C-100	SPLIT	E-101	R101
To		E-103	C-100	R-100	E-101	R101	E-104
Substream: MIXED							
Phase:		Vapor	Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow							
HYDROGEN	LBMOL/HR	3.527396	3.527396	3.527396	32.18308	32.18308	0.0715245
CARBO-01	LBMOL/HR	8.818491	8.818491	8.818491	0.8818491	0.8818491	0.4598979
CARBO-02	LBMOL/HR	2.204623	2.204623	2.204623	10.14126	10.14126	1.34E-05
WATER	LBMOL/HR	29.54194	29.54194	29.54194	0.8862583	0.8862583	11.87141
METHANE	LBMOL/HR	0	0	0	0	0	1.06E+01
OXYGEN	LBMOL/HR	0	0	0	0	0.00E+00	0
NITROGEN	LBMOL/HR	0	0	0	0	0	0
Mole Flow	LBMOL/HR	4.41E+01	4.41E+01	4.41E+01	4.41E+01	4.41E+01	2.30E+01
Mass Flow	LB/HR	989.1696	989.1696	989.1696	403.7143	403.7143	403.7143
Volume Flow	CUFT/HR	2.78E+03	7048.725	6614.166	5651.806	2656.369	1435.388
Temperature	F	377.9472	1805	1845.735	1292	200	4.00E+02
Pressure	PSIA	1.37E+02	1.37E+02	1.47E+02	1.47E+02	1.45E+02	1.44E+02
Vapor Fraction		1	1	1	1	1	1
Liquid Fraction		0	0	0	0	0	0
Solid Fraction		0	0.00E+00	0.00E+00	0.00E+00	0	0
Molar Enthalpy	BTU/LBMOL	-1.04E+05	-89479.66	-89038.29	-7617.826	-15541.47	-69224.14
Mass Enthalpy	BTU/LB	-4620.49	-3988.576	-3968.902	-831.9959	-1697.392	-3937.946
Enthalpy Flow	BTU/HR	-4.57E+06	-3.95E+06	-3.93E+06	-3.36E+05	-6.85E+05	-1.59E+06
Molar Entropy	BTU/LBMOL-R	-5.040384	4.729402	4.78314	10.06145	3.135608	-1.33E+01
Mass Entropy	BTU/LB-R	-0.2246762	0.2108142	0.2132096	1.098881	0.3424617	-0.757879
Molar Density	LBMOL/CUFT	1.59E-02	6.26E-03	6.67E-03	7.80E-03	1.66E-02	1.60E-02
Mass Density	LB/CUFT	0.3558399	0.1403331	0.1495532	0.071431	0.1519798	0.2812579
Average Molecular Weight		22.43399	22.43399	22.43399	9.156086	9.156086	17.57874

Stream ID:		13	14	15	16
From		E-104	E-104	SPLIT	E-100
To				E-100	
Substream: MIXED					
Phase:		Liquid	Vapor	Vapor	Vapor
Component Mole Flow					
HYDROGEN	LBMOL/HR	0	0.0715245	0	0.00E+00
CARBO-01	LBMOL/HR	0	0.4598979	0	0
CARBO-02	LBMOL/HR	0	1.34E-05	0	0
WATER	LBMOL/HR	11.79015	0.0812652	0	0
METHANE	LBMOL/HR	0	1.06E+01	0	0
OXYGEN	LBMOL/HR	0.00E+00	0	18.29616	18.29616
NITROGEN	LBMOL/HR	0	0	0	0
Mole Flow	LBMOL/HR	1.18E+01	1.12E+01	1.83E+01	1.83E+01
Mass Flow	LB/HR	212.4028	191.3115	585.4553	585.4553
Volume Flow	CUFT/HR	3.42E+00	970.5203	2346.535	2022.338
Temperature	F	1.00E+02	1.00E+02	1292	978.2161
Pressure	PSIA	1.44E+02	1.44E+02	1.47E+02	1.40E+02
Vapor Fraction		0	1	1	1
Liquid Fraction		1	0	0	0
Solid Fraction		0	0	0.00E+00	0.00E+00
Molar Enthalpy	BTU/LBMOL	-1.22E+05	-37869.41	9362.894	6792.514
Mass Enthalpy	BTU/LB	-6797.707	-2212.229	292.6014	212.274
Enthalpy Flow	BTU/HR	-1.44E+06	-4.23E+05	1.71E+05	1.24E+05
Molar Entropy	BTU/LBMOL-R	-38.21463	-21.92586	4.375205	2.855605
Mass Entropy	BTU/LB-R	-2.121235	-1.28085	0.1367303	0.089241
Molar Density	LBMOL/CUFT	3.44E+00	1.15E-02	7.80E-03	9.05E-03
Mass Density	LB/CUFT	62.02389	0.1971226	0.2494978	0.2894942
Average Molecular Weight		18.01528	17.11821	31.9988	31.9988

Process Description

In electrolysis mode, 12 MWh of electricity is used to convert water and carbon dioxide into syngas and ultimately methane.

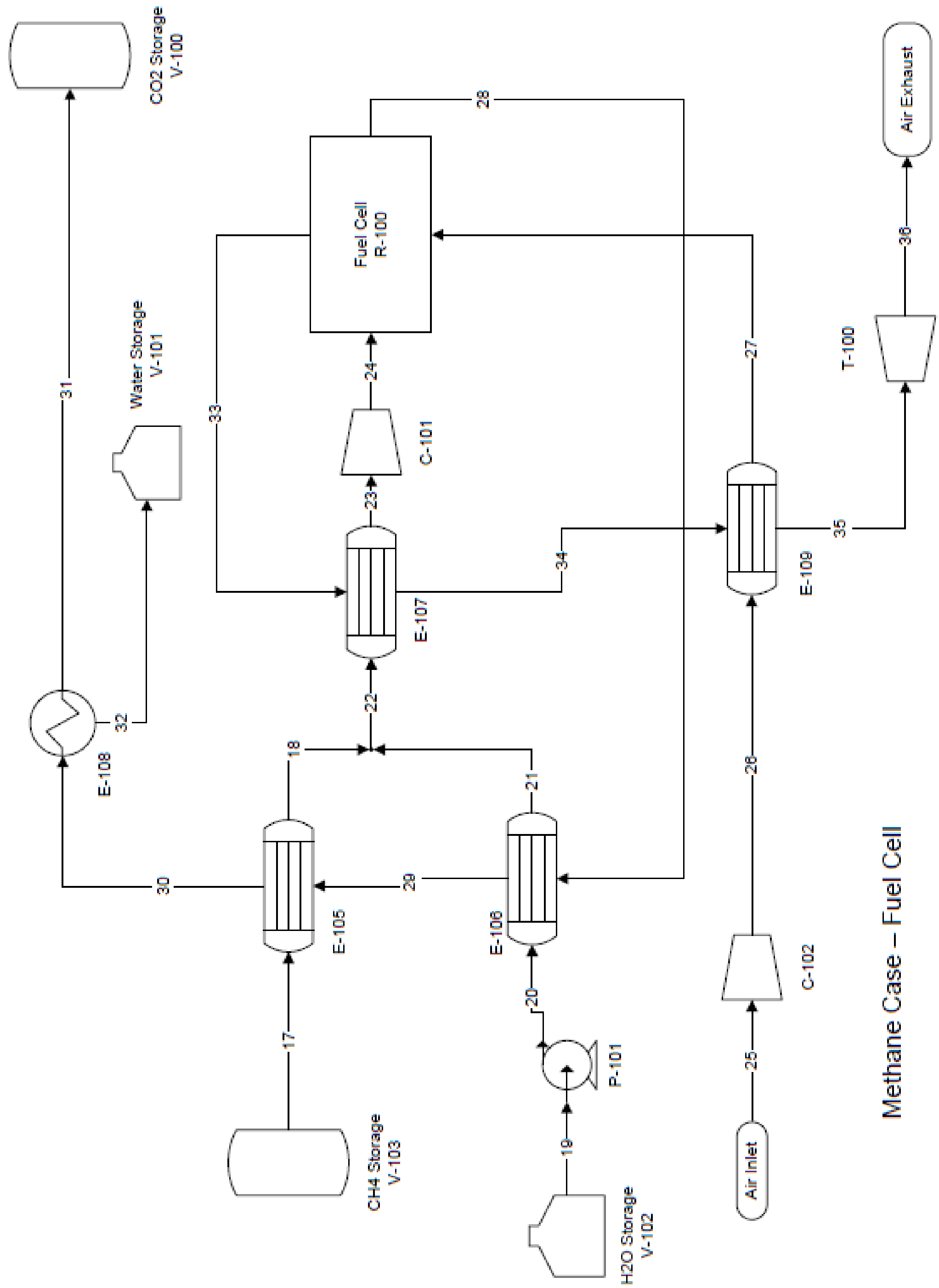
The two feed streams, Stream 1 and Stream 3, are initially at room temperature, and both streams are preheated in a heat exchanger network. Stream 1, which is comprised of 3.537 lb-moles of hydrogen, 8.812 lb-moles of carbon dioxide, and 2.205 lb-moles of carbon monoxide is heated from room temperature to 440.3°F by the oxygen product of the fuel cell in the Feedstock Preheater, E-100. The water feed, Stream 3, is stored at a pressure of 140 psi, and it is pumped in block P-100 to 144 psi. This pump is necessary to account for the pressure drop of water across the heat exchangers in fuel cell mode. The resulting stream, Stream 4, is then heated to 364.4°F by the electrolysis gas product in Water Preheater 1, block E-101. The resulting stream, Stream 5, is then completely vaporized by Fired Heater 1, block E-102, which uses 12.222 lbs/hr of natural gas for fuel. After the water is completely vaporized, Streams 2 and 6 mix to produce the electrolysis feed stream, Stream 7.

Stream 7 is then heated to 1805.0°F by Fired Heater 2, Block E-103, which uses 29.262 lbs/hr of natural gas for fuel. This stream is heated above the fuel cell operating temperature to counteract the endothermic reactions in the cell. Stream 8 is then compressed by the Electrolysis Feed Compressor, block C-100, to a pressure of 147.0 psi. This compressor uses 5.70 kW of power, and it was placed before the fuel cell due to the two-phase system that exists prior to complete vaporization of the water feed stream.

After being compressed, the electrolysis feed, Stream 9, then enters the fuel cell, block R-100. In electrolysis mode, the fuel cell operates at 147 psi and 1291.7°F, and a temperature gradient of 482°F is allowed across the cell. This temperature gradient is based on an example of an SOFC system presented in the DOE *Fuel Cell Handbook*. The two electrolysis reactions occur, and two product streams are produced at 1292°F and 147 psi. The oxygen product stream, Stream 15, is used in E-100 to heat the electrolysis feedstock as previously mentioned and leaves the heat exchanger at 978.2°F. The gas product stream, Stream 10, exchanges heat with the water feed in E-101, and it is cooled to 200°F. The gas product is then reacted in the Methanator, R-101, at 400°F and 143.5 psi to produce a methane-rich storage gas stream, Stream 12. This water in Stream 12 is then condensed out of the storage gas in Condenser 1, E-104. E-104 operates at 147 psi and 100°F. While this process does not completely eliminate all of the water from the storage gas stream, it removes all but 0.08 lb of water per hour. The water storage stream, Stream 13, is then stored at 143.5 psi and 100°F in the Water Storage Vessel 2, V-103. The dehydrated storage gas, Stream 14, is stored in the Methane Storage Vessel, V-102, at 143.5 psi and 100°F. It is assumed that the two storage vessels cool to 77°F over the 12 hour electrolysis period.

Process Flow Diagrams and Material Balances – Fuel Cell Mode

Figure 13: Process Flow Diagram for Fuel Cell Mode of the Methane Case



Stream ID:		17	18	19	20	21	22	23	24
From			E-105		P-101	E-106	M-101	E-107	C-101
To		E-105	M-101	P-101	E-106	M-101	E-107	C-101	REFORMER
Substream: MIXED									
Phase:		Mixed	Vapor	Liquid	Liquid	Vapor	Vapor	Vapor	Vapor
Component Mass Flow									
HYDROGEN	LBMOL/HR	0.0794972	0.079497	0	0	0	0.079497	0.079497	0.0794972
CARBO-01	LBMOL/HR	0.2634785	0.263479	0	0	0	0.263479	0.263479	0.2634785
CARBO-02	LBMOL/HR	8.82E-06	8.82E-06	0.00E+00	0	0	8.82E-06	8.82E-06	8.82E-06
WATER	LBMOL/HR	7.95E-02	7.95E-02	11.02311	11.02311	11.02311	1.11E+01	1.11E+01	1.11E+01
METHANE	LBMOL/HR	1.08E+01	1.08E+01	0	0	0	1.08E+01	1.08E+01	1.08E+01
OXYGEN	LBMOL/HR	0	0	0	0	0	0	0	0
NITROGEN	LBMOL/HR	0	0	0	0	0	0	0	0
Mole Flow	LBMOL/HR	1.12E+01	11.18214	11.02311	1.10E+01	11.02311	22.20526	22.20526	22.20526
Mass Flow	LB/HR	185.8031	185.8031	1.99E+02	1.99E+02	198.5845	384.3875	384.3875	384.3875
Volume Flow	CUFT/HR	8.06E+02	9.88E+02	3.19E+00	3.19E+00	1.12E+03	2.07E+03	3.29E+03	3.15E+03
Temperature	F	76.73	716.4141	77	77.00726	903.7819	791.8847	1472	1490.824
Pressure	PSIA	143.5	143.2	146.9595	147.9595	143.2	143.2	139.9	146.9595
Vapor Fraction		0.9954974	1	0	0	1	1	1.00E+00	1.00E+00
Liquid Fraction		4.50E-03	0	1	1	0	0	0.00E+00	0.00E+00
Solid Fraction		0	0	0	0	0	0	0.00E+00	0.00E+00
Molar Enthalpy	BTU/LBMOL	-35711.83	-28690.4	-1.23E+05	-1.23E+05	-97021.4	-62611.2	-53920.7	-53657.39
Mass Enthalpy	BTU/LB	-2149.237	-1726.67	-6820.61	-6820.6	-5385.51	-3616.92	-3114.89	-3099.674
Enthalpy Flow	BTU/HR	-3.99E+05	-3.21E+05	-1.35E+06	-1.35E+06	-1.07E+06	-1.39E+06	-1.20E+06	-1.19E+06
Molar Entropy	BTU/LBMOL-R	-22.94787	-14.5371	-38.9677	-38.9674	-7.31966	-9.58996	-4.03821	-4.000351
Mass Entropy	BTU/LB-R	-1.381067	-0.87488	-2.16303	-2.16302	-0.4063	-0.55399	-0.23328	-0.2310919
Molar Density	LBMOL/CUFT	0.0138659	0.011315	3.45688	3.456887	9.87E-03	0.010709	6.75E-03	7.05E-03
Mass Density	LB/CUFT	0.2303972	0.18801	62.27667	62.2768	0.177836	0.185374	0.116766	0.1220599
Average Molecular Weight		16.61605	16.61605	18.01528	18.01528	18.01528	17.31065	17.31065	17.31065

Stream ID:		25	26	27	28	29	30	31	32
From			C-102	E-109	SEP	E-106	E-105	E-108	E-108
To		C-102	E-109	R-100	E-106	E-105	E-108		
Substream: MIXED									
Phase:		Vapor	Vapor	Vapor	Vapor	Vapor	Vapor	Vapor	Liquid
Component Mole Flow									
HYDROGEN	LBMOL/HR	0	0	0	3.698293	3.698293	3.698293	3.698293	0
CARBO-01	LBMOL/HR	0	0	0	10.03878	10.03878	10.03878	10.03878	0
CARBO-02	LBMOL/HR	0	0	0	0.984342	0.984342	0.984342	0.984342	0
WATER	LBMOL/HR	0	0	0	29.00311	29.00311	29.00311	0.110715	28.89239
METHANE	LBMOL/HR	0	0	0	0	0	0	0	0
OXYGEN	LBMOL/HR	32.40795	32.40795	32.40795	0	0	0	0	0
NITROGEN	LBMOL/HR	121.9156	121.9156	121.9156	0	0	0	0	0
Mole Flow	LBMOL/HR	154.3236	154.3236	154.3236	43.72452	4.37E+01	4.37E+01	1.48E+01	2.89E+01
Mass Flow	LB/HR	4452.297	4452.297	4452.297	999.3307	9.99E+02	9.99E+02	4.79E+02	5.21E+02
Volume Flow	CUFT/HR	60468.83	1.35E+04	1.70E+04	6.26E+03	4.51E+03	3.97E+03	1.32E+03	8.39E+00
Temperature	F	77	7.58E+02	1.05E+03	1.56E+03	9.22E+02	7.34E+02	1.00E+02	1.00E+02
Pressure	PSIA	14.69595	1.50E+02	1.47E+02	1.47E+02	1.43E+02	1.40E+02	1.40E+02	1.40E+02
Vapor Fraction		1.00E+00	1	1.00E+00	1.00E+00	1	1	1	0
Liquid Fraction		0.00E+00	0	0.00E+00	0.00E+00	0.00E+00	0	0	1
Solid Fraction		0.00E+00	0	0.00E+00	0.00E+00	0.00E+00	0	0	0
Molar Enthalpy	BTU/LBMOL	-2.891061	4868.771	7043.198	-94916.3	-1.01E+05	-1.03E+05	-1.18E+05	-1.22E+05
Mass Enthalpy	BTU/LB	-0.1002087	168.7592	244.1283	-4152.95	-4438.13	-4516.69	-3665.22	-6797.716
Enthalpy Flow	BTU/HR	-446.1589	7.51E+05	1.09E+06	-4.15E+06	-4.44E+06	-4.51E+06	-1.76E+06	-3.54E+06
Molar Entropy	BTU/LBMOL-R	1.01556	2.231081	3.874103	2.943068	-0.86825	-2.22284	-0.71666	-38.21459
Mass Entropy	BTU/LB-R	0.0352008	0.077333	0.134283	0.12877	-0.03799	-0.09726	-0.0222	-2.121232
Molar Density	LBMOL/CUFT	2.55E-03	0.011435	9.07E-03	6.98E-03	9.69E-03	0.011017	0.011249	3.442813
Mass Density	LB/CUFT	0.0736296	0.329892	0.261676	0.159588	0.221445	0.251795	0.363153	62.02323
Average Molecular Weight		28.8504	28.8504	28.8504	22.85516	22.85516	22.85516	32.28305	18.01528

Stream ID:		33	34	35	36
From		SEP	E-107	E-109	T-100
To		E-107	E-109	T-100	
Substream: MIXED					
Phase:		Vapor	Vapor	Vapor	Vapor
Component Mole Flow					
HYDROGEN	LBMOL/HR	0	0	0	0
CARBO-01	LBMOL/HR	0	0	0	0
CARBO-02	LBMOL/HR	0	0	0	0
WATER	LBMOL/HR	0	0	0	0
METHANE	LBMOL/HR	0	0	0	0
OXYGEN	LBMOL/HR	13.19026	13.19026	13.19026	13.19026
NITROGEN	LBMOL/HR	121.9156	121.9156	121.9156	121.9156
Mole Flow	LBMOL/HR	135.1059	135.1059	135.1059	135.1059
Mass Flow	LB/HR	3837.354	3837.354	3837.354	3837.354
Volume Flow	CUFT/HR	2.00E+04	1.87E+04	1.58E+04	1.01E+05
Temperature	F	1.56E+03	1.38E+03	1.06E+03	5.66E+02
Pressure	PSIA	1.47E+02	1.44E+02	1.41E+02	1.47E+01
Vapor Fraction		1.00E+00	1.00E+00	1.00E+00	1.00E+00
Liquid Fraction		0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solid Fraction		0.00E+00	0.00E+00	0.00E+00	0.00E+00
Molar Enthalpy	BTU/LBMOL	11050.75	9622.434	7138.713	3444.689
Mass Enthalpy	BTU/LB	389.0759	338.7875	251.3404	121.2809
Enthalpy Flow	BTU/HR	1.49E+06	1.30E+06	9.64E+05	4.65E+05
Molar Entropy	BTU/LBMOL-R	5.760495	5.068185	3.630363	5.189795
Mass Entropy	BTU/LB-R	0.202816	0.178441	0.127818	0.182723
Molar Density	LBMOL/CUFT	6.75E-03	7.24E-03	8.57E-03	1.33E-03
Mass Density	LB/CUFT	0.1918465	0.205533	0.243341	0.037914
Average Molecular Weight		28.40256	28.40256	28.40256	28.40256

Process Description

In fuel cell mode, the storage gas is used as a feedstock for the fuel cell operating at a power output of 880 kW.

The two feed streams, Stream 17 and Stream 19, are initially at room temperature, and both streams are preheated in a heat exchanger network. Stream 17, is heated from room temperature to 716.4°F by the oxygen product of the fuel cell in the Methane Preheater, E-105. The water feed, Stream 19, is stored at a pressure of 143.5 psi, and it is pumped in block P-101 to 148 psi. This pump is necessary to account for the pressure drop of water across the heat exchangers in fuel cell mode. The resulting stream, Stream 20, is then heated to 903.8°F by the fuel cell gas product, Stream 26, in Water Preheater 2, block E-106. After the water is completely vaporized, Streams 21 and 18 mix to produce the fuel cell feed stream, Stream 22.

Stream 22 is then heated to 1472.0°F by the Fuel Cell Feed Preheater, Block E-107, which uses the hot air stream from the fuel cell, Stream 33, to heat the feed. Stream 23 is then compressed by the Fuel Cell Feed Compressor, block C-101, to a pressure of 147.0 psi. This compressor uses 1.71 kW of power, and it was placed before the fuel cell due to the two-phase system that exists prior to complete vaporization of the water feed stream.

The second feed stream for fuel cell mode is air. Ambient air, Stream 25, at 77°F and 14.7 is compressed to 147 psi in the Air Compressor, C-102 . This compression also heats the air stream to 758°F. The heated stream, Stream 26, is then heated further through exchange with the hot air product stream, Stream 34, in the Air Preheater, E-109. The resulting stream, Stream 27 exits the Air Preheater at 1045.1°F. This stream is not heated any further so that it can accept excess heat from the fuel cell and provide cooling.

After being compressed, the fuel cell feed, Stream 24, then enters the fuel cell, block R-100. In fuel cell mode, the fuel cell operates at 147 psi and 1560°F. The methane is internally reformed within the fuel cell as previously discussed. The two reactions occur, and two product streams are produced at 1560°F and 147 psi. The hot air product stream, Stream 33, is used in E-107 to heat the fuel cell feedstock as previously mentioned and leaves the heat exchanger at 1382.6°F, and then it is further cooled by exchanging heat with the incoming air stream in the Air Preheater, block E-109. Then, the air product stream is expanded in the Power Recovery Turbine, T-100, and 146 kW of power is recovered. The gas product stream, Stream 28, exchanges heat with the water feed in E-106, and it is cooled to 921.8°F. This water in Stream 30 is then condensed out of the storage gas in Condenser 2, E-108. E-108 operates at 147 psi and 100°F. The water condensed out of the gas product stream is stored for future use in electrolysis mode. The water storage stream, Stream 32, is then stored at 143.5 psi and 100°F in the Water Storage Vessel 2, V-103. The dehydrated storage gas, Stream 31, is stored in the Methane Storage Vessel, V-100, at 143.5 psi and 100°F. It is assumed that the two storage vessels cool to 77°F over the 11 hour fuel cell period.

Equipment Summary

Table 18 - Methane Sytem Equipment List

Unit No.	Unit Type	Function	Size	Material	Oper. T (°F)	Oper. P (psi)
R-100	Electrolyzer	Convert water and carbon dioxide to hydrogen and carbon monoxide	V=1.06 V I=0.5 A/cm^2 A=1.86E6 cm^2	YSZ, LaMnO3	1291.7	147
R-100	Fuel Cell	Convert hydrogen and carbon monoxide to carbon dioxide and water	V=0.933 V I=0.55 A/cm^2 A=1.86E6 cm^2	YSZ, LaMnO3	1291.7	147
R-101	Methanation Reactor	React hydrogen and carbon monoxide to methane	1065 kg catalyst	Steel, Ni-Al catalyst	400	147
E-100	Feedstock preheater	Heat feedstock	Q=47023 A=2.524	Carbon Steel	440.3	147
E-101	Water preheater	Heat water	Q=349373 A=15.01	Stainless Steel	364.4	147
E-102	Fired heater	Vaporize water	Q=265142.3	Stainless Steel	351.6	147
E-103	Fired heater	Preheat electrolysis feed	Q=625071	Stainless Steel	1805.0	147
E-104	Condenser	Condense water for storage	Q=624773.2	Stainless Steel	100.0	147
E-105	Methane preheater	Preheat methane	Q=78514.9 A=8.26	Stainless Steel	716.4	147
E-106	Water preheater	Preheat water	Q=78514.9 A=9.43	Stainless Steel	903.8	147
E-107	Fuel Cell Feed preheater	Preheat combined feedstock	Q=192974.4, A=34.06	Stainless Steel	1472.0	147
E-108	Air preheater	Heat airstream to fuel cell	Q=335565.29	Stainless Steel	1045	147
E-109	Condenser	Condense water for storage	Q=335565.29	Stainless Steel	100	147
C-100	Electrolysis Feed Compressor	Compress feed to overcome pressure drop	Net work=5.70 kW	Stainless Steel	1845.7	147
C-101	Fuel Cell Feed Compressor	Compress feed to overcome pressure drop	Net work=1.71	Stainless Steel	1490.8	147
C-102	Air Compressor	Compress air for fuel cell mode	Net work=220.33	Stainless Steel	757.5	147
T-100	Power Recovery Turbine	Recuperate energy used in compression	Net work=-146.27	Stainless Steel	565.7	147

V-100	CO2 Storage Vessel	Stores pressurized CO2 for electrolysis mode	V=9700 gallons	Stainless Steel	100	143.5
V-101	Water Storage Vessel	Stores water for electrolysis mode	V=50 gallons	Stainless Steel	100	143
V-102	Water Storage Vessel	Stores water for fuel cell mode	V=13200 gallons	Stainless Steel	100	140
V-103	Methane Storage Vessel	Stores compressed methane for fuel cell mode	V=85	Stainless Steel	100	140
P-100	Electrolysis Water Pump	Pumps water to overcome pressure losses	Pressure head=9.25 ft	Stainless Steel	76.8	144
P-101	Fuel Cell Water Pump	Pumps water to overcome pressure losses	Pressure head=2.31 ft	Stainless Steel	77.0	148

Feedstock Preheater, E-100

The double-pipe heat exchanger uses the oxygen product stream from the fuel cell to preheat the electrolysis feed (Stream 1). A double-pipe design was chosen due to the heat transfer area of the heat exchanger. The bare-module cost of E-100 is $7,947.15. Please refer to specification sheet on page 105 as well as the sample calculation on page 178 for further details.

Water Preheater, E-101

The double-pipe heat exchanger uses the electrolysis product stream from the fuel cell (Stream 10) to preheat the water feed for electrolysis (Stream 4). A double-pipe design was chosen due to the heat transfer area of the heat exchanger, and stainless steel was chosen for the material since water is involved. The bare module cost is $10,585.96. Please refer to specification sheet on page 106 as well as the sample calculation on page 178 for further details.

Water Vaporizer, E-102

This fired heater uses the heat from the combustion of natural gas to completely vaporize the water feed (Stream 5) before it mixes with the carbon dioxide stream for electrolysis. The bare module cost is $56,300.98. Please refer to specification sheet on page 107 as well as the sample calculation on page 179 for further details.

Final Preheater, E-103

This fired heater uses the heat from the combustion of natural gas to preheat the electrolysis feed (Stream 7) to 1805°F before the electrolysis reaction. This was done so that the fuel cell would have sufficient heat during electrolysis mode. The bare module cost is $109,891.80. Please refer to specification sheet on page 108 as well as the sample calculation on page 179 for further details.

Electrolysis Storage Condenser, E-104

E-104 is a condenser that removes water from the electrolysis product (Stream 12) so that it can be stored separately from the gas product. A cooling water utility is used to condense the water out of the product stream. The bare module cost of E-104 is $109,811.32. Please refer to specification sheet on page 109 as well as the sample calculation on page 177 for further details.

Fuel Cell Feed Preheater, E-105

The double-pipe heat exchanger uses the gas product stream from the fuel cell to preheat the fuel cell feed (Stream 17). A double-pipe design was chosen due to the small heat transfer area of the heat exchanger. The bare module cost is $9,606.67. Please refer to specification sheet on page 110 as well as the sample calculation on page 178 for further details.

Fuel Cell Water Preheater, E-106

The double-pipe heat exchanger uses the gas product stream from the fuel cell to preheat the water feed from storage (Stream 20). A double-pipe design was chosen due to the small heat transfer area of the heat exchanger. The bare module cost is $7,984.12. Please refer to specification sheet on page 111 as well as the sample calculation on page 178 for further details.

Fuel Preheater, E-107

The double-pipe heat exchanger uses the air stream from the fuel cell to preheat the fuel cell feed (Stream 22). A double-pipe design was chosen due to the small heat transfer area of the heat exchanger. The bare module cost is $12,050.98. Please refer to specification sheet on page 112 as well as the sample calculation on page 178 for further details.

Fuel Cell Storage Condenser, E-108

E-109 is a condenser that removes water from the fuel cell product (Stream 12) so that it can be stored separately from the gas product. A cooling water utility is used to condense the water out of the product stream. A cooling water flowrate of 26074 lb/hr is needed for this block, and the bare module cost is $12,130.46. Please refer to specification sheet on page 113 as well as the sample calculation on page 177 for further details.

Air Preheater, E-109

The double-pipe heat exchanger uses the air stream from the fuel cell to preheat the air feed (Stream 26). A double-pipe design was chosen due to the small heat transfer area of the heat exchanger. The bare module cost is $12,130.46. Please refer to specification sheet on page 114 as well as the sample calculation on page 178 for further details.

Electrolysis Feed Compressor, C-100

C-100 is a stainless steel compressor that increases the pressure of the electrolysis feed stream by 10 psi in order to account for the pressure drops across the system during electrolysis mode. ASPEN was used to calculate the net work used by this compressor, and that value is 5.70 kW. The bare module cost is $79,098.03. Please refer to specification sheet on page 115 as well as the sample calculation on page 179 for further details.

Fuel Cell Feed Compressor, C-101

C-101 is a stainless steel compressor that increases the pressure of the fuel cell feed stream by 7 psi in order to account for the pressure drops across the system during fuel cell mode. ASPEN was used to calculate the net work used by this compressor, and that value is 1.71 kW. The bare module cost of C-101 is $33,067.66. Please refer to specification sheet on page 116 as well as the sample calculation on page 179 for further details.

Air Compressor, C-102

C-102 is a stainless steel compressor that increases the pressure of the fuel cell air feed stream up to the operating pressure. The output pressure of this compressor is 150 psi, which is slightly about the operating pressure of the fuel cell to account for the pressure drop across the heat exchanger before the fuel cell. ASPEN was used to calculate the net work used by this compressor, and that value is 220.33 kW. A power recovery turbine recoups 66% of this work later in the process. The bare module cost of C-101 is $1,116,259.20. Please refer to specification sheet on page 117 as well as the sample calculation on page 179 for further details.

Recovery Turbine, T-100

T-100 is a turbine that recovers power from the compressed air stream in fuel cell mode. This turbine recovers 146.27 of the 220.33 kW used to compress the air in C-102. The bare module cost is also $38,130.11. Please refer to specification sheet on page 118.

Electrolysis Water Pump, P-100

The pump increases the pressure of the water feed stream in electrolysis mode by 4 psi to account for the pressure drops across the heat exchanges in electrolysis mode. The head of this pump is 9.25 ft, and the volumetric flow rate is 1.07 gallons/minute. The bare module cost is $37,791.19. Please refer to specification sheet on page 122.

Fuel Cell Feed Pump, P-101

The pump increases the pressure of the water feed stream in fuel cell mode by 1 psi to account for the pressure drops across the heat exchanges in electrolysis mode. The head of this pump is 2.31 ft, and the volumetric flow rate is 0.40 gallons/minute. The bare module cost is $45,539.31. Please refer to specification sheet on page 122.

Electrolysis Gas Storage, V-100

V-100 is the storage vessel for the gas product stream in electrolysis mode. It is a 9,700 gallon tank that is 5481 ft long and 0.55 ft in diameter. The gas is stored at 143.5 psi. The purchase cost of V-100 is $399,532.70, and the bare-module cost is $1,218,574.72. Please refer to specification sheet on page 123 as well as the sample calculation on page 180 for further details.

Electrolysis Water Storage, V-101

V-101 is the storage vessel for the liquid product stream in electrolysis mode. It is a 50 gallon pressurized tank, and it is to be purchased through mywaterneeds.com[15]. The bare module cost of this tank is $953.85. Please refer to specification sheet on page 124.

Electrolysis Gas Storage, V-102

V-102 is the storage vessel for the gas product stream in fuel cell mode. It is a 13200 gallon tank that is 6100 ft long and 0.61 ft in diameter. The gas is stored at 140 psi. The purchase cost of V-100 is $444,117.11 and the bare-module cost is $1,354,557.20. Please refer to specification sheet on page 125 as well as the sample calculation on page 180 for further details.

Electrolysis Water Storage, V-103

V-103 is the storage vessel for the liquid product stream in fuel cell mode. It is an 85 gallon pressurized tank, and it is to be purchased through mywaterneeds.com. The bare module cost of this tank is $1,455.00. Please refer to specification sheet on page 126.

Fuel Cell, R-100

R-100 is the reversible fuel cell on which this project is based. It has a power rating of 1 MW. During electrolysis mode, water and carbon dioxide are reduced to form hydrogen and carbon monoxide. During fuel cell mode, the hydrogen and carbon monoxide are oxidized to form water and carbon dioxide. This fuel cell was priced based on DOE cost targets for 2020. A bare module factor of 1 was assumed due to the unknown cost of installation and “plug-and-play” features of fuel cells. The bare module cost of R-100 is $450,000. Please refer to specification sheet on page 120 for further details.

Methanator, R-101

R-101 is a packed bed methanation reactor that features a Ni-Al catalyst. Hydrogen and carbon monoxide react to form methane in this reactor, and equilibrium is assumed. The catalyst was sized according to methods previously discussed, and the reactor was sized based on a double-pipe heat exchanger design. The bare module cost of R-101 is $71,700. Please refer to specification sheet on page 121 as well as the sample calculations on pages 177 and 186 for further details.

Specification Sheets

The following lists the page number of the specification sheets detailing the different units within electrolysis operation, followed by the specification sheets.

E-100

Identification	Item	Heat Exchanger	Date	4/5/2011
	Item No.	E-100	By	EH/MP/DS
	No. Required	1		

Function:

Preheat fuel cell feed

Operation: 12 hours, daily

Materials Handled		**Hot Side**		**Cold Side**	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		16	17	1	2
Quantity (lb/hr)		598.15	598.15	457.00	457.00
Composition:					
	Hyrogen	0.00	0.00	7.11	1.11
	CO2	0.00	0.00	388.10	388.1
	CO	0.00	0.00	61.75	61.75
	Water	0.00	0.00	0.00	0.00
	CH4	0.00	0.00	0.00	0.00
	Oxygen	585.46	598.15	0.00	0.00
	Nitrogen	0.00	0.00	0.00	0.00
Temperature (°F)		1292.0	978.2	77.0	440.3
Pressure (psi)		147.0	140	140.0	137.00
Vapor Fraction		1.0	1.0	1.0	1.0
Liquid Fraction		0.0	0.0	0.0	0.0

Design Data

Type	Double Pipe
Material	Carbon Steel
Heat Transfer (Btu/hr)	47028.099
Heat Transfer Coefficient (Btu/hr*ft2*F)	21.26
Heat Transfer Area (ft2)	2.524

C_P	$	4,451.08
$\mathbf{C_{BM}}$	**$**	**7,947.15**

E-101

Identification

Item	Heat Exchanger	Date	4/5/2011
Item No.	E-101	By	EH/MP/DS
No. Required	1		

Function:

Operation: 12 hours, daily

Materials Handled

	Hot Side		Cold Side	
	Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID	10	11	4	5
Quantity (lb/hr)	403.71	403.71	532.21	532.21
Composition:				
Hyrogen	64.88	64.88	0.00	0
CO2	38.81	38.81	0.00	0
CO	284.06	284.06	0.00	0.00
Water	15.97	15.97	532.21	532.21
CH4	0.00	0.00	0.00	0.00
Oxygen	0.00	0.00	0.00	0.00
Nitrogen	0.00	0.00	0.00	0.00
Temperature (°F)	1292.0	200.0	76.9	364.4
Pressure (psi)	147.0	143	144.0	137.00
Vapor Fraction	1.0	1.0	0.0	0.424
Liquid Fraction	0.0	0.0	1.0	0.576

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	349372.92
Heat Transfer Coefficient (Btu/hr*ft2*F)	57.89
Heat Transfer Area (ft2)	15.008421

C_P	**$ 5,881.09**
C_{BM}	**$ 10,585.96**

E-102

Identification

Item	Heater	Date	4/5/2011
Item No.	E-102	By	EH/MP/DS
No. Required	1		

Function:

Fired heater

Operation: 12 hours, daily

Materials Handled

Stream ID		**Inlet**	**Outlet**
Quantity (lb/hr)		532.21	532.21
Composition:			
	Hydrogen	0.00	0.00
	CO2	0.00	0.00
	CO	0.00	0.00
	Water	532.21	532.21
	CH4	0.00	0.00
	Oxygen	0.00	0.00
	Nitrogen	0.00	0.00
Temperature (°F)		351.6	351.6
Pressure (psi)		137.0	137
Vapor Fraction		0.4	1.0
Liquid Fraction		0.6	0.0

Design Data

Type	Fired Heater
Material	Stainless Steel
Heat Transfer (Btu/hr)	265142.3

C_P	$ 19,481.31
C_{BM}	$ 56,300.98

E-103

Identification

Item	Heater	Date	4/5/2011
Item No.	E-103	By	EH/MP/DS
No. Required	1		

Function:

Vaporize water in the feed stream

Operation: 12 hours, daily

Materials Handled

		Inlet	Outlet
Stream ID		7	8
Quantity (lb/hr)		989.17	989.17
Composition:			
	Hyrogen	7.11	7.11
	CO2	388.10	388.10
	CO	61.75	61.75
	Water	532.21	532.21
	CH4	0.00	0.00
	Oxygen	0.00	0.00
	Nitrogen	0.00	0.00
Temperature (°F)		377.9	1805.0
Pressure (psi)		137.0	137
Vapor Fraction		1.0	1.0
Liquid Fraction		0.0	0.0

Design Data

Type	Fired Heater
Material	Stainless Steel
Heat Transfer (Btu/hr)	625070.76

C_P	**$ 38,024.84**
C_{BM}	**$ 109,891.80**

E-104

Identification

Item	Condenser	Date	4/5/2011
Item No.	E-104	By	EH/MP/DS
No. Required	1		

Function:

Condenses water out of storage stream during electrolysis mode

Operation: 12 hours, daily

Materials Handled

		Inlet	Water	Outlet
Stream ID		12	13	14
Quantity (lb/hr)		989.17	989.17	
Composition:				
	Hyrogen	0.08	0.00	0.08
	CO2	0.26	0.00	0.26
	CO	0.00	0.00	0.00
	Water	11.47	11.39	0.08
	CH4	10.76	0.00	10.76
	Oxygen	0.00	0.00	0.00
	Nitrogen	0.00	0.00	0.00
Temperature (°F)		400.0	100.0	100
Pressure (psi)		147.0	146.95949	146.9595
Vapor Fraction		1.0	0.0	1
Liquid Fraction		0.0	1.0	0

Design Data

Type	Condenser
Material	Stainless Steel
Heat Transfer (Btu/hr)	624473.18

C_P $18067.00

C_{BM} $ 84192.05

E-105

Identification

Item	Heat Exchanger	Date	4/5/2011
Item No.	E-105	By	EH/MP/DS
No. Required	1		

Function:

Preheat fuel cell feed

Operation: 11 hours, daily

Materials Handled

	Hot Side		Cold Side	
	Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID	29	30	17	18
Quantity (lb/hr)	999.33	999.33	185.8031	185.80
Composition:				
Hyrogen	7.46	7.46	0.160257	0.16
CO2	441.80	441.80	11.59564	11.60
CO	27.57	27.57	2.47E-04	0.00
Water	522.50	522.50	1.432755	1.43
CH4	0.00	0.00	172.6142	172.61
Oxygen	0.00	0.00	0	0.00
Nitrogen	0.00	0.00	0	0.00
Temperature (°F)	921.8	734.4	76.7	716.4
Pressure (psi)	143.0	140	143.5	143.20
Vapor Fraction	1.0	1.0	1.0	1.0
Liquid Fraction	0.0	0.0	0.0	0.0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	78514.87
Heat Transfer Coefficient (Btu/hr*ft2*F)	24.46
Heat Transfer Area (ft2)	8.26

C_P	**$**	**5,337.04**
$\mathbf{C_{BM}}$	**$**	**9,606.67**

E-106

Identification

Item	Heat Exchanger	Date	4/5/2011
Item No.	E-106	By	EH/MP/DS
No. Required	1		

Function:

Preheat fuel cell feed

Operation: 11 hours, daily

Materials Handled	**Hot Side**		**Cold Side**	
	Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID	28	29	20	21
Quantity (lb/hr)	999.33	999.33	198.5845	198.58
Composition:				
Hyrogen	7.46	7.46	0	0.00
CO2	441.80	441.80	0	0.00
CO	27.57	27.57	0.00E+00	0.00
Water	522.50	522.50	198.5845	198.58
CH4	0.00	0.00	0	0.00
Oxygen	0.00	0.00	0	0.00
Nitrogen	0.00	0.00	0	0.00
Temperature (°F)	1562.0	921.8	77.0	903.8
Pressure (psi)	143.0	140	143.5	143.20
Vapor Fraction	1.0	1.0	1.0	1.0
Liquid Fraction	0.0	0.0	0.0	0.0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	78514.87
Heat Transfer Coefficient (Btu/hr*ft2*F)	40.41
Heat Transfer Area (ft2)	9.43

C_P	**$**	**4,435.62**
C_{BM}	**$**	**7,984.12**

E-107

Identification

Item	Heat Exchanger	Date	4/5/2011
Item No.	E-107	By	EH/MP/DS
No. Required	1		

Function:

Preheat fuel cell feed

Operation: 11 hours, daily

Materials Handled		Hot Side		Cold Side	
		Inlet	Outlet	Inlet	Outlet
Stream ID		33	34	22	23
Quantity (lb/hr)		3837.35	3837.35	384.3875	384.39
Composition:					
	Hydrogen	0	0	0.160257	0.16
	CO2	0	0	11.59564	11.60
	CO	0	0	2.47E-04	0.00
	Water	0	0	200.0172	200.02
	CH4	0	0	172.6142	172.61
	Oxygen	422.0724	422.0724	0	0.00
	Nitrogen	3415.281	3415.281	0	0.00
Temperature (°F)		1562.0	1382.6	791.9	1472.0
Pressure (psi)		143.2	139.9	147.0	143.50
Vapor Fraction		1.0	1.0	1.0	1.0
Liquid Fraction		0.0	0.0	0.0	0.0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	192974.41
Heat Transfer Coefficient (Btu/hr*ft2*F)	21.29
Heat Transfer Area (ft2)	34.06

C_P	**$**	**6,694.99**
$\mathbf{C_{BM}}$	**$**	**12,050.98**

E-108

Identification

Item	Heat Exchanger	Date	4/5/2011
Item No.	E-108	By	EH/MP/DS
No. Required	1		

Function:

Condenser

Operation: 11 hours, daily

Materials Handled		**Hot Side**		**Cold Side**	
		Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID		34	35	26	27
Quantity (lb/hr)		3837.35	3837.35	4452.297	4452.30
Composition:					
	Hydrogen	0	0	0	0.00
	CO2	0	0	0	0.00
	CO	0	0	0.00E+00	0.00
	Water	0	0	0	0.00
	CH4	0	0	0	0.00
	Oxygen	422.0724	422.0724	1037.016	1037.02
	Nitrogen	3415.281	3415.281	3415.281	3415.28
Temperature (°F)		1382.6	1063.1	757.5	1045.1
Pressure (psi)		143.5	140.5	150.0	147.00
Vapor Fraction		1.0	1.0	1.0	1.0
Liquid Fraction		0.0	0.0	0.0	0.0

Design Data

Type	Shell and Tube
Material	Stainless Steel
Heat Transfer (Btu/hr)	335565.29
Heat Transfer Coefficient (Btu/hr*ft2*F)	29.43
Heat Transfer Area (ft2)	35.49

C_P **$18,091.97**

C_{BM} **$83,719.11**

E-109

Identification

Item	Heat Exchanger	Date	4/5/2011
Item No.	E-109	By	EH/MP/DS
No. Required	1		

Function:

Preheat fuel cell feed

Operation: 11 hours, daily

Materials Handled	**Hot Side**		**Cold Side**	
	Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID	34	35	26	27
Quantity (lb/hr)	3837.35	3837.35	4452.297	4452.30
Composition:				
Hyrogen	0	0	0	0.00
CO2	0	0	0	0.00
CO	0	0	0.00E+00	0.00
Water	0	0	0	0.00
CH4	0	0	0	0.00
Oxygen	422.0724	422.0724	1037.016	1037.02
Nitrogen	3415.281	3415.281	3415.281	3415.28
Temperature (°F)	1382.6	1063.1	757.5	1045.1
Pressure (psi)	143.5	140.5	150.0	147.00
Vapor Fraction	1.0	1.0	1.0	1.0
Liquid Fraction	0.0	0.0	0.0	0.0

Design Data

Type	Double Pipe
Material	Stainless Steel
Heat Transfer (Btu/hr)	335565.29
Heat Transfer Coefficient (Btu/hr*ft2*F)	29.43
Heat Transfer Area (ft2)	35.49

C_P	**$**	**6,738.14**
$\mathbf{C_{BM}}$	**$**	**12,130.46**

C-100

Identification

Item	Compressor	Date	4/5/2011
Item No.	C-100	By	EH/MP/DS
No. Required	1		

Function:

Compress feed to overcome pressure drop

Operation: 12 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	8	9
Quantity (lb/hr)	989.17	989.17
Composition:		
Hydrogen	7.11	7.11
CO2	388.10	388.10
CO	61.75	61.75
Water	532.21	532.21
Methane	0	0
Oxygen	0	0
Nitrogen	0	0
Temperature (°F)	1805.0	1845.7
Pressure (psi)	137.0	146.9595
Vapor Fraction	1.0	1.0
Liquid Fraction	0.0	0.0

Design Data

Type	
Material	Stainless Steel
New Work (kW)	5.70
Efficiency	0.72

C_P	**$ 36,789.78**
C_{BM}	**$ 79,098.03**

C-101

Identification

Item	Compressor	Date	4/5/2011
Item No.	C-101	By	EH/MP/DS
No. Required	1		

Function:

Operation: 11 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	23	24
Quantity (lb/hr)	384.39	384.39
Composition:		
Hydrogen	0.16	0.16
CO2	11.60	11.60
CO	0.00	0.00
Water	200.02	200.02
Methane	172.6142	172.6142
Oxygen	0	0
Nitrogen	0	0
Temperature (°F)	1472.0	1490.8
Pressure (psi)	139.9	146.9595
Vapor Fraction	1.0	1.0
Liquid Fraction	0.0	0.0

Design Data

Type	
Material	Stainless Steel
Net Work (kW)	1.71
Efficiency	0.72

C_P	**$**	**15,380.31**
C_{BM}	**$**	**33,067.66**

C-102

Identification				
	Item	Compressor	Date	4/5/2011
	Item No.	C-102	By	EH/MP/DS
	No. Required	1		
Function:				
Operation:	11 hours, daily			

Materials Handled			**Inlet**	**Outlet**
Stream ID			25	26
	Quantity (lb/hr)		4452.30	4452.30
	Composition:			
		Hydrogen	0.00	0.00
		CO2	0.00	0.00
		CO	0.00	0.00
		Water	0.00	0.00
		Methane	0	0
		Oxygen	1037.016	1037.016
		Nitrogen	3415.281	3415.281
	Temperature (°F)		77.0	757.5
	Pressure (psi)		14.7	150
	Vapor Fraction		1.0	1.0
	Liquid Fraction		0.0	0.0

Design Data		
	Type	
	Material	Stainless Steel
	Net Work (kW)	220.33
	Efficiency	0.72

C_P	**$**	**519,190.33**
C_{BM}	**$**	**1,116,259.20**

T-100

Identification

Item	Power Recovery Turbine	Date	4/5/2011
Item No.	T-100	By	EH/MP/DS
No. Required	1		

Function:

Operation: 11 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	35.00	36.00
Quantity (lb/hr)	3837.35	3837.35
Composition:		
Hydrogen	0.00	0.00
CO2	0.00	0.00
CO	0.00	0.00
Water	0.00	0.00
Methane	0.00	0.00
Oxygen	422.07	422.07
Nitrogen	3415.28	3415.28
Temperature (°F)	1063.1	565.7
Pressure (psi)	140.5	14.70
Vapor Fraction	1.0	1.0
Liquid Fraction	0.0	0.0

Design Data

Type	
Material	Stainless Steel
Net Work (kW)	-146.27
Efficiency	0.72

C_P	**$**	**38,130.11**
C_{BM}	**$**	**38,130.11**

R-100 (Electrolysis)

Identification

Item	Fuel Cell	Date	4/5/2011
Item No.	R-100	By	EH/MP/DS
No. Required	1		

Function: Convert steam and carbon dioxide to hydrogen gas and carbon monoxide with the application of electrical current

Operation: 12 hours, daily

Materials Handled		Inlet(s)		Outlet
Stream ID		9	10	16
	Quantity (lb/hr)	391.00	391.00	598.15
	Composition:			
	Hydrogen	7.11	64.88	0
	CO2	388.10	3.88	0
	CO	61.75	306.30	0.00
	Water	532.20	15.97	0.00
	Methane	0.00	0.00	0.00
	Oxygen	0.00	0.00	598.15
	Nitrogen	0.00	0.00	0.00
	Temperature (°F)	1833.0	1292.0	1292.0
	Pressure (psi)	154.3	147.0	147.00
	Vapor Fraction	1.0	1.0	1.0
	Liquid Fraction	0.0	0.0	0.0

Design Data

Type	Reversible Fuel Cell
Material	YSZ, porous Ni, LaMNO3
Electricity Produced (kW)	952.67
Heat Duty (Btu/hr)	----
Operating Temperature (F)	1291.7
Operating Pressure (psia)	15
Voltage (V)	0.662
Current Density (A/cm2)	-0.5
Electrode Area (cm2)	1834862

R-100 (Fuel Cell)

Identification

Item	Fuel Cell	Date	4/5/2011
Item No.	R-100	By	EH/MP/DS
No. Required	1		

Function: Reforms methane feedstock and converts hydrogen and carbon monoxide into steam and carbon dioxide, generating electricity

Operation: 11 hours, daily

Materials Handled

	Inlet(s)		Outlet	
Stream ID	24	27	28	33
Quantity (lb/hr)	397.20	4452.30	1013.00	3836.44
Composition:				
Hydrogen	3.29	0.00	6.10	0.00
CO2	27.67	0.00	411.89	0
CO	0.22	0.00	46.61	0.00
Water	199.40	0.00	548.44	0.00
Methane	166.60	0.00	0.00	0.00
Oxygen	0.00	1037.00	0.00	421.16
Nitrogen	0.00	3415.30	0.00	3415.30
Temperature (°F)	1491.0	1020.0	1562.0	1562.0
Pressure (psi)	154.3	134	14.7	16.20
Vapor Fraction	1.0	1.0	0.0	1.0
Liquid Fraction	0.0	0.0	1.0	0.0

Design Data

Type	Reversible Fuel Cell
Material	YSZ, porous Ni, LaMNO3
Electricity Produced (kW)	
Operating Temperature (F)	1292
Operating Pressure (psia)	147
Voltage (V)	0.9238
Current Density (A/cm2)	0.56
Electrode Area (cm2)	1.835E+06

C_P	$	450,000.00
C_{BM}	$	450,000.00

R-101 (Methanator)

Identification

Item	Reactor	Date	4/5/2011
Item No.	R-101	By	EH/MP/DS
No. Required	1		

Function:

Operation: 12 hours, daily

Materials Handled	**Inlet(s)**	**Outlet**
Stream ID	11	12
Quantity (lb/hr)	391.00	391.00
Composition:		
Hydrogen	64.88	0.16
CO2	3.88	11.60
CO	306.30	2.47E-04
Water	15.97	206.65
Methane	0	172.6
Oxygen	0	0.00
Nitrogen	0	0
Temperature (°F)	200.0	400.0
Pressure (psi)	143.5	143.5
Vapor Fraction	1.0	1.0
Liquid Fraction	0.0	0.0

Design Data

Type	Methanator
Material	NI-Al catalyst packed bed reactor
Heat Duty (Btu/hr)	90203
Operating Temperature (F)	400
Operating Pressure (psia)	143.5

C_P	$	38,949.16
C_{BM}	$	134,368.84

P-101

Identification

	Item	Pump	Date	4/5/2011
	Item No.	P-101	By	EH/MP/DS
	No. Required	2		

Function:

Gas storage between electrolysis and fuel cell modes

Operation: 11 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		19	20
	Quantity (lb/hr)	198.58	198.58
	Composition:		
	Hydrogen	0.00	0.00
	CO2	0.00	0.00
	CO	0.00	0.00
	Water	198.58	198.58
	Methane	0	0
	Oxygen	0	0
	Nitrogen	0	0
	Temperature (°F)	77.0	77.0
	Pressure (psi)	147.0	147.96
	Vapor Fraction	0.0	0.0
	Liquid Fraction	1.0	1.0

Design Data

	Type	
	Material	Stainless Steel
	Flow Rate (gal/min)	0.40
	Head (ft)	2.31

C_P	**$ 22,769.65**
C_{BM}	**$ 45,539.31**

V-100

Identification

Item	Storage Vessel	Date	4/5/2011
Item No.	V-100	By	EH/MP/DS
No. Required	1		

Function:

Stores gas in between electrolysis mode and fuel cell mode

Operation: 12 hours, daily

Materials Handled

Stream ID		14
Quantity (lb/hr)		191.31
Composition:		
	Hydrogen	0.14
	CO2	20.24
	CO	0.00
	Water	1.46
	Methane	169.4629
	Oxygen	0
	Nitrogen	0
Temperature (°F)		100.0
Pressure (psi)		143.5
Vapor Fraction		1.0
Liquid Fraction		0.0

Design Data

Type	Gas Storage
Material	Stainless Steel
Storage Volume (gal)	9700.00
Length (ft)	5481.23
Diameter (ft)	0.55

C_P	**$ 399,532.70**
C_{BM}	**$ 1,218,574.72**

V-101

Identification

Item	Storage Vessel	Date	4/5/2011
Item No.	V-101	By	EH/MP/DS
No. Required	1		

Function:

Pressurized Water Storage for Electrolysis Mode

Operation: 12 hours, daily

Materials Handled

Stream ID	13
Quantity (lb/hr)	212.40
Composition:	
Hydrogen	0.00
CO2	0.00
CO	0.00
Water	212.40
Methane	0
Oxygen	0
Nitrogen	0
Temperature (°F)	100.0
Pressure (psi)	143.5
Vapor Fraction	0.0
Liquid Fraction	1.0

Design Data

Type	Liquid Storage	
Material	Stainless Steel	
Storage Volume (gal)	50.00	from Lowes

C_P **$ 317.95**

C_{BM} **$ 953.85**

V-102

Identification

	Item	Storage Vessel	Date	4/5/2011
	Item No.	V-101	By	EH/MP/DS
	No. Required	1		

Function:

Store water product from fuel cell operation

Operation: 11 hours, daily

Materials Handled

Stream ID		31
Quantity (lb/hr)		478.83
Composition:		
	Hydrogen	7.46
	CO2	441.80
	CO	27.57
	Water	1.99
	Methane	0
	Oxygen	0
	Nitrogen	0
Temperature (°F)		100.0
Pressure (psi)		140.0
Vapor Fraction		1.0
Liquid Fraction		0.0

Design Data

Type	Gas Storage
Material	Stainless Steel
Storage Volume (gal)	13200.00
Length (ft)	26.00
Diameter (ft)	0.61

C_P	**$ 444,117.11**
C_{BM}	**$ 1,354,557.20**

V-103

Identification

Item	Storage Vessel	Date	4/5/2011
Item No.	V-103	By	EH/MP/DS
No. Required	1		

Function:

Pressurized Water Storage for Electrolysis Mode

Operation: 11 hours, daily

Materials Handled

Stream ID	32
Quantity (lb/hr)	520.50
Composition:	
Hydrogen	0.00
CO2	0.00
CO	0.00
Water	520.50
Methane	0
Oxygen	0
Nitrogen	0
Temperature (°F)	100.0
Pressure (psi)	140.0
Vapor Fraction	0.0
Liquid Fraction	1.0

Design Data

Type	Liquid Storage	
Material	Steel, polymer bladder	
Storage Volume (gal)	85.00	from Lowes

C_P	**$**	**485.00**
C_{BM}	**$**	**1,455.00**

Energy Balance and Utility Requirements

The energy balance and utility requirements can be subdivided into three categories: electricity, natural gas, and cooling water. Additionally, the fuel cell generates heat in both modes due to the difference between the operating voltage and the open cell voltage. The heat duty calculated by ASPEN includes the electrical work on the system as well as any additional heating or cooling, depending on the mode.

The energy balance for the fuel cell is summarized in Table 19. The additional 72.0 kW of heating required for electrolysis mode could be provided by either increasing the temperature of the feed stream or increasing either the current density or operating voltage of the cell. This amount of heat could also be provided with a mixture of these two methods. A voltage increase of 0.08 V, which would result in the thermoneutral voltage of 1.16 V, could provide sufficient heating for the fuel cell in electrolysis mode, but as this change in operating voltage would significantly impact the material balances, this option was not pursued. For future work with reversible fuel cell systems, the operating voltage should be optimized to reduce the heating load during electrolysis mode without sacrificing efficiency.

Table 19 – Summary of Fuel Cell/Electrolyzer Energy Balances

	ASPEN Heat Duty (kW)	Electrical Energy (kW)	Overpotential Heating (kW)	Total (kW)
Electrolysis Mode	1178.0	1000.0	64.2	113.8
Fuel Cell Mode	-1040.9	-867.0	58.8	-232.7

The energy balance is more complicated in fuel cell mode due to the endothermic, internal reformation of the methane. The amount of cooling from the endothermic reaction in this case is 295 kW. Furthermore, the electricity output is dependent on the cell efficiency, hours of operation in fuel cell mode, and the current density. In order to recover the maximum amount of energy in fuel cell mode, the current density must be increased due to the operating time ratio of 11:12 between fuel cell mode and electrolysis mode. An operating current density of 0.55 A is needed to recover the maximum amount of energy from the system in the 11 hours of fuel cell mode operation.

Electrical utilities are also needed for running the compressor in fuel cell mode, but some of this energy is recuperated in the turbine block, T-100. The electrical energy utility needs of fuel cell mode are summarized in Table 20.

Table 20 – Electrical Utilities in Fuel Cell Mode

Block	Power (kW)
C-100	5.70
C-101	1.70
C-102	220.00
T-100	-146.60
P-100	0.01
P-101	5E-4
Total	74.0

Cooling water is needed in electrolysis mode and fuel cell mode. In electrolysis mode, cooling water is needed for the methanation reactor, and for each of the outlet streams. The heat duties, flow rates of cooling water needed, and cost of cooling water utilities are shown in Table 21.

Table 21 – Cooling Water Flowrates

	Heat Duty (kW)	Flowrate of Cooling Water (kg/hr)	Cost ($/hr)	Annual Cost ($)
E-104	-33.92	1756.03	0.04	139.08
E-105	-9.21	476.79	0.01	34.62
R-101	-291.63	15096.33	0.30	1195.63
Total	-334.76	17329.14		1369.32

Additionally, the two fired heaters in electrolysis mode require natural gas as a fuel source. The natural gas utilities are summarized below in Table 22.

Table 22 – Natural Gas Utilities

Equipment	Unit	Heat Duty	Flowrate (lb/hr)	Annual Consumption	Price ($/lb)	Annual Cost($)
Fired Heater 1	E-102	265142.30	12.22	48397.25	$ 0.08	$ 3,629.79
Fired Heater 2	E-103	625070.76	29.26	115876.85	$ 0.08	$ 8,690.76
Total		890213.05	41.48	164274.10		$ 12,320.56

Equipment Cost Economic Analysis

Gas Storage

The efficacy of this system depends on successful storage of electrolysis product gas. Since the system is converting electrical energy into stored chemical energy, it was expected that the storage vessel costs would be a major component of the total cost of the process. For the methane base case, these costs were minimized by operating and storing at an elevated pressure.

A sensitivity analysis on the gas vessel cost as a function of the aspect ratio was performed for the electrolysis storage gas with the expectation that the cost of the fuel cell product gas storage vessel would follow a similar trend. The purchase cost of the storage vessel decreased as the aspect ratio increased, and a clear plateau in price reduction was evident at aspect ratios about 50. Increasing the aspect ratio results in longer, more slender pipes, and this decreases the price for horizontal storage vessels because the wall thickness decreases. At low aspect ratios, the walls of the vessel must be thick enough to support the weight of the upper portion of the vessel. At higher aspect ratios, the weight that must be supported decreases and results in thinner walls and lower cost. Even though the price continues to decrease as the aspect ratio of the vessel increases, the minimum wall thickness for any storage vessel in this situation must be at least 0.325 inches because of the need for a corrosion allowance of 1/8 inch. Therefore, increasing the aspect ratio above 1000 resulted in no further reductions in cost due to the minimum wall thickness requirements, and this aspect ratio was selected.

Despite these efforts to minimize storage costs, the purchase costs of the two gas storage vessels still comprised a large percentage of the total fixed costs. If the selling price of electricity were to increase enough to make this process more economically feasible, then further investigations into reducing these storage costs should be made. The two storage tanks could be combined with the proper control mechanism, and this would reduce the storage costs by nearly 50%. Another design option could be to discard the fuel cell exhaust gas in fuel cell mode and replenish the carbon dioxide gas at the anode of the fuel cell during electrolysis mode. This option was not pursued for this project since the process would not have been completely reversible if the feedstock needed to be continually replenished.

Compression Costs

Due to the high cost of C-102, the air stream compressor in fuel cell mode, this block was investigated in an attempt to determine if the price could be reduced. The compressor is expensive because of the flowrate of air that it must process and the large difference between the inlet and outlet pressures, and these two factors were examined in sensitivity analyses. The outlet pressure could be decreased to reduce the cost of the compressor. The *Fuel Cell Handbook* uses a pressure gradient of 1.4 atm in an example of an SOFC system, so the outlet pressure could be reduced to 8.6 atm in the methane base case. At an outlet pressure of 8.6 atm, the purchase cost of the compressor fell to $480,000, 8% lower than the original purchase cost.

The second option for reducing the cost of C-102 would be to lower the amount of excess air fed to the fuel cell. The original air stream was being fed at a 75% molar excess for cooling purposes, but the excess could be reduced. At 50% molar excess, the air flowrate would be 60 kmol/hr rather than 70 kmol/hr, and this reduction would result in a compressor purchase cost of $454,000, a 9.2% decrease in purchase price, if the original outlet pressure were maintained. If both factors were altered, then the purchase cost of C-102 would be $427,700, which is 14.6% lower than the original purchase cost. However, this change would greatly affect the cooling load on the fuel cell.

While these factors ought to be investigated in further detail, the changes that they would incur on the heat exchanger network and the fuel cell performance were too significant to be included in the scope of this project. The reduction in the compressor outlet pressure would affect the equilibrium in the fuel cell and change the composition of the product stream as a result. Furthermore, the reduction in the excess air molar ratio would change the amount of usable heat for the heat exchanger network.

Fixed-Capital Investment Summary

Table 23 - Methane System Equipment Cost Summary

Unit No. Name	Unit Name	Purchase Cost	Bare Module Factor	Bare Module Cost
R-100	Fuel Cell	$450,000	1.00	$450,000
R-101	Methanator	$50,000	3.25	$123,468.84
E-100	Feedstock Preheater	$3,107	1.80	$5,592
E-101	Water Preheater 1	$3,262	1.80	$5,872
E-102	Fired Heater 1	$18,767	3.00	$56,301
E-103	Fired Heater 2	$50,179	2.19	$109,892
E-104	Condenser 1	$50,142	2.19	$109,811
E-105	Methane Preheater	$2,965	1.80	$5,337
E-106	Water Preheater 2	$3,029	1.80	$5,452
E-107	Fuel Cell Feed Preheater	$3,719	1.80	$6,695
E-108	Condenser 2	$3,744	1.80	$6,739
E-109	Air Preheater	$3,744	1.80	$6,739
C-100	Electrolysis Feed Compressor	$25,000	2.15	$53,751
C-101	Fuel Cell Feed Compressor	$6,470	2.15	$13,911
C-102	Air Compressor	$241,557	2.15	$519,347
T-100	Power Recovery Turbine	$38,130	1.00	$38,130
V-100	CO_2 Storage Vessel	$399,533	3.05	$1,218,575
V-101	Water Storage Vessel 1	$313	3.05	$954
V-102	Methane Storage Vessel	$444,117	3.05	$1,354,557
V-103	Water Storage Vessel 2	$477	3.05	$1,455
P-100	Electrolysis Water Pump	$37,791	1.00	$37,791
P-101	Fuel Cell Water Pump	$45,539	1.00	$45,539
Total				***$4,277,378***

Additional Considerations

Environmental and Safety Concerns

While there are no toxic chemicals in this process, the operating conditions could lead to potential risks. The storage gas streams are stored at 147 psi, and care must be taken to keep flames and sparks away from these vessels due to the flammability of hydrogen and methane. Furthermore, the high operating temperature of the fuel cell could lead to injury in the event of a burst pipe or cell malfunction. Care must be exercised when operating the fuel cell and the methanator to ensure that these two reactors stay below critical temperatures. The methanator temperature must also be carefully monitored to prevent catalyst sintering.

Operating Costs

This process requires an initial purchase of carbon dioxide, hydrogen, carbon monoxide, and water, but these materials are conserved and regenerated since the process is reversible. Therefore, raw material costs were omitted from the operating costs.

Table 24 - Variable Cost Summary for Methan System

Variable Costs				Annual Cost
General Expenses				
	Selling / Transfer Expenses:		$	18,513
	Direct Research:		$	12,342
	Allocated Research:		$	3,086
	Administrative Expense:		$	12,342
	Management Incentive compensation:		$	7,714
Total General Expenses			$	53,996
Utilities	$0.059203	per kWh of Electricity	$	182,669
Total Variable Costs			**$**	**236,666**

Overall Economic Analysis

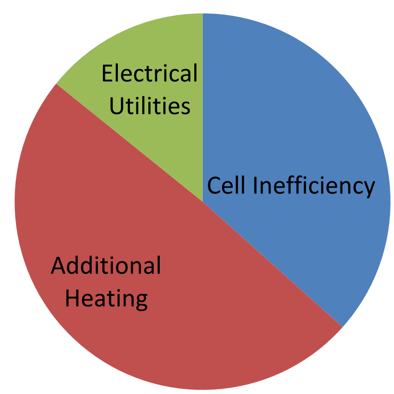
The profitability of this energy storage system was analyzed using the Profitability Analysis Spreadsheet (see page 200 of the Appendix), but the current low cost of electricity prevents this system from being profitable. The economic driving force of this process is the difference in cost between electricity during times of low demand and peak demand. At current electricity pricing, this difference is only $0.12/kWh, so the system makes $1,161.00 per day. Annual electricity sales are $575,000, and the equipment costs far outweigh the sales. However, this is not a typical chemical process; the goal is to even out peak demand loads in an efficient manner. This technology is still in the development phase, and additional advancements are needed before the systems are market-ready. Additionally, the price of electricity is likely to increase in the future as fossil fuel sources are depleted and carbon dioxide emissions become regulated. The Return on Investment (ROI) of this process is -19.42%, as demonstrated in Table 25.

Table 25 – ROI Analysis for Methane System

ROI Analysis (Third Production Year)	
Annual Sales	**574,992**
Annual Costs	**(1,348,470)**
Depreciation	**(524,829)**
Income Tax	**-**
Net Earnings	**(1,298,307)**
Total Capital Investment	**6,685,105**
ROI	**-19.42%**

System Efficiency

The overall system efficiency for the methane case was calculated to be 58.8%, and the electrical efficiency of the system was found to be 64.6%. Efficiency loses occur in this system in three main ways: cell efficiency, compression loses, and heat requirements for electrolysis mode.



Cell Efficiency

The operating conditions of this system were selected to maximize the electrical efficiency of the cell, but some of the losses were unavoidable. The difference in voltage significantly impacts the cell efficiency and thus the overall efficiency of the system. The equation used to calculate the cell efficiency is Equation 5. As previously discussed, the cell efficiency for the methane case is 88%.

$$\eta_{cell} = \frac{V_{fuel\ cell\ mode} Q_{fuel\ cell}}{V_{electrolsis} Q_{electrolysis}}$$

Equation 5

Compression Losses

Although the cell efficiency is higher at elevated pressures, this design parameter led to significant efficiency loses for compression. However, these energy penalties are mitigated by the power recovery turbine, which recuperates 66% of the electricity supplied to the compressor. The compression of the air stream in fuel cell mode is by far the largest consumer of electricity in the system.

Electrolysis Heat Requirements

Additional heat must be supplied to the feed stream during electrolysis since the operating voltage is lower than the thermoneutral voltage. The efficiency losses associated with this need for additional energy input are inevitable. Raising the voltage to

V_{TN} in order to avoid the need for heat input would also decrease efficiency since the difference between $V_{electrolysis}$ and $V_{fuel\ cell}$ would increase. The energy balance on the fuel cell in electrolysis mode reveals a ΔH value of 4.51×10^6 kJ, which converts to a required energy input of 253 kW. The heat generated by the voltage difference in electrolysis mode provides 64 kW of heating, so 189 kW of additional energy must be provided to the system in order for the fuel cell to maintain operation temperature. A temperature gradient of 250°C was allowed for the fuel cell to mitigate the heating requirement. This value was selected based on data from a sample SOFC system highlighted in the Fuel Cell Handbook**Error! Bookmark not defined.**. The electrolysis feed was overheated to 000°C, and it was allowed to cool to 750°C during electrolysis. This temperature gradient resulted in a reduction in the heating duty of the fuel cell to 113 kW, 75 kW lower than if the fuel cell were isothermal, but it also introduced a heating duty of 183 kW to the fired heater that preheats the electrolysis feed. This design choice was kept even though it produced efficiency losses because the alternative was to run at V_{TN}, which would have resulted in an efficiency loss of 4.5%. This efficiency loss is relatively small when compared to efficiency losses at V_{TN} for fuel cells operating at lower pressures. Optimization of operating conditions to reduce efficiency losses by running at V_{TN} should be performed if reversible fuel cells for energy storage are pursued in the future.

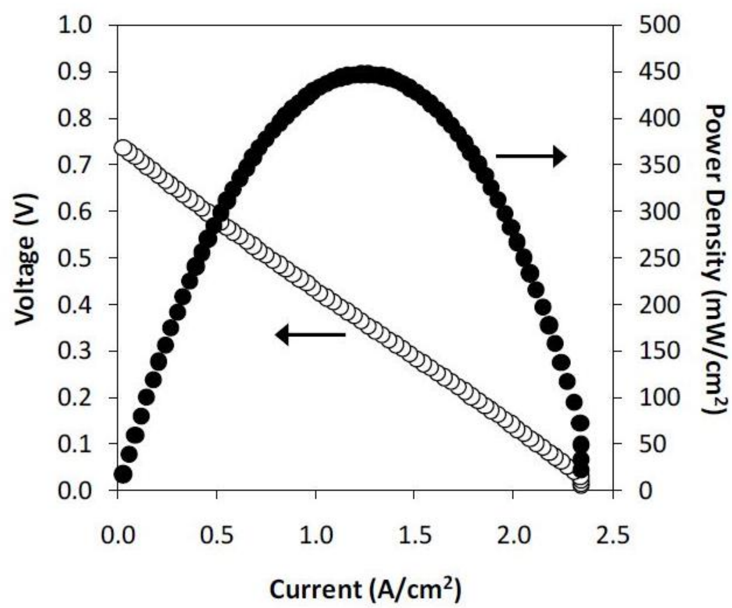
Antimony Case

Concept Stage

Operating Conditions Choices

For the antimony-based energy storage system, the current density for electrolysis operation was chosen to be 0.20 A/cm^2. The low current density allows for high overall efficiencies for the charge/discharge cycle. The corresponding operating voltage was determined using the the V-i curve from *Gorte and Gross*, shown in Figure 14. The open cell voltage for the antimony/antimony trioxide fuel cell is 0.75 V. The curve has a slope of 0.4 Ω·cm^2. For the selected electrical operating conditions, the maximum theoretical round-trip efficiency is 79.8%.

Figure 14 - V-i Curve for Antimony Fuel Cell



In fuel cell mode, the system oxidizes pure antimony. In electrolysis operation, however, the system cannot run on pure molten antimony oxide. There needs to be a significant portion of antimony in the feed stream because the molten metal acts as both the feed stream and the electrode. If the concentration of antimony is too low in electrolysis mode, the electrical conductivity of the mixture decreases. For the purpose of this report, it was assumed that converting between pure antimony and an equimolar mixture of antimony and its oxide would maintain a high enough conductivity for effective operation while not appreciably affecting the V-i curve for the system.

Electrolysis Heating

During electrolysis, the antimony trioxide in the feed is reduced to form molten antimony. This reaction is carried out under isothermal conditions at 1292°F. The reaction is highly endothermic. In order to maintain constant temperature, a significant amount out of heat must be supplied to the electrolyzer. The heat supplied to the electrolyzer has a detrimental effect on the overall processes efficiency. Minimizing the necessary heat load is critical to designing a system with high efficiency.

Compression

During fuel cell mode, the oxidation reaction is highly exothermic. In order to maintain the fuel cell at 1292°F, excess air is used to cool the cell. Air is fed to the cell at a temperature 200°C below the operating temperature of the cell[5]. Air enters the fuel cell at 932°F. The amount of excess air needed was determined thorough energy balance calculations. Increasing the air flow through the cell increases the necessary heat removal from the cell. The air flow rate was manipulated such that the excess heat not removed by the air stream in one fuel cell operating period is equal to the heat lost from the antimony storage vessel in one day. Under this operating constraint, the small amount of heat produced in the stack that is not removed via the air helps to overcome the heat losses through the tank.

Antimony Storage

The melting point of antimony is 1167°F and the melting point of antimony trioxide is 1213°F. Both substances must be kept above their melting point at all times throughout the system. Molten antimony is a very difficult substance to handle. If it is in the presence of oxygen, it will oxidize very easily. It is critical that the molten antimony does not come into contact with oxygen. Furthermore, molten antimony will also dissolve most metals. For that reason, metals were not considered for construction of the storage vessel and process piping. Ceramic material, specifically alumina, is used for the piping needed to transfer the molten metal to the fuel cell. The storage vessel was constructed out of concrete.

The volume required for storing the molten metal is 240 ft^3. To determine the optimal dimensions for the storage vessel, a sensitivity analysis was conducted. The purchase cost of the vessel was computed for a range of aspect ratios. Equation 22.52 from ***Product and Process Design Principles*** was used to calculate the purchase cost of the vessel. For all calculations, a material factor of 0.50 was used. The material factor was calculated by comparing the cost of high pressure (10 ksi) concrete with that of carbon steel, the benchmark material for costs in ***Product and Process Design Principles.*** The aspect ratio for these calculations was defined as the height of the vessel divided by the diameter. In addition to the purchase cost of the vessel, the additional cost of sufficient mineral wool insulation was also added into the purchase costs. Table 26 shows the total purchase cost of the vessel for several different aspect ratios. For these calculations, the thickness of insulation required was calculated to maintain a temperature of 122°F at the outside of the insulation layer. Please refer to the sample calculations on page 188 for the calculation of the necessary insulation thickness. The minimum purchase cost is minimized at an aspect ratio of 1.0, which results in a vessel with a length/height of 6.74 ft.

Table 26 – Aspect Ratio Sensitivity Analysis

Aspect Ratio (L/D)	Purchase Cost
0.25	$31,410
0.50	$29,820
0.75	$29,060
1.00	$28,900
2.00	$29,110

Process Flow Diagram and Material Balances - Electrolysis

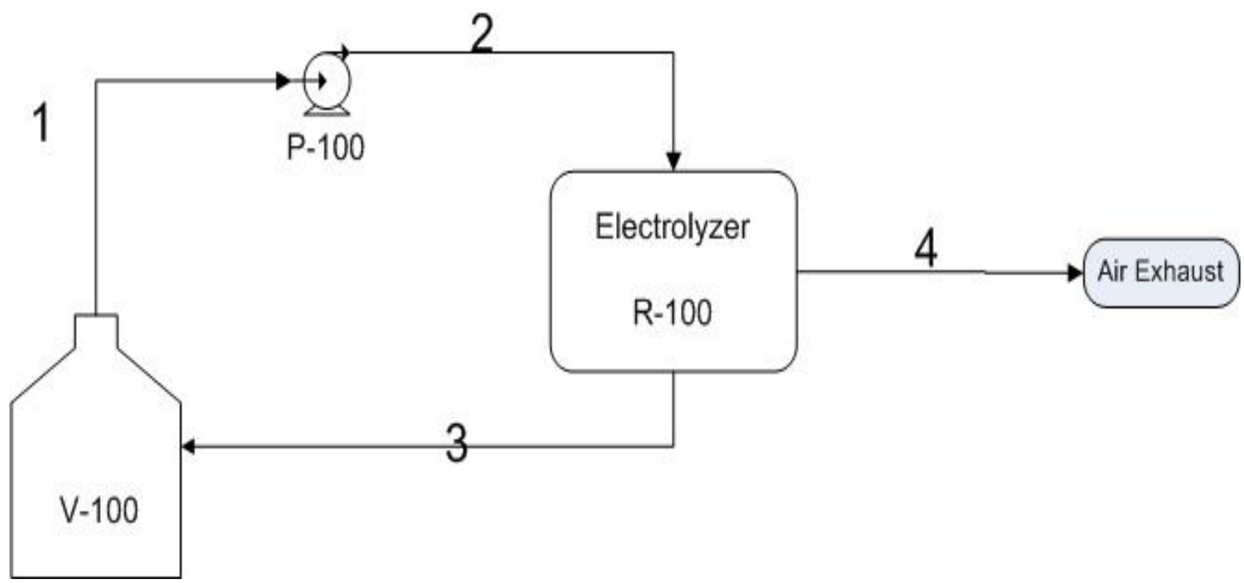


Figure 15 – Process Flow Diagram for Antimony Electrolysis

Table 27-Antimony Electrolysis Stream Summary

Stream ID:		1	2	3	4
From		V-100	P-100	R-100	R-100
To		P-100	R-100	V-100	
Substream: MIXED					
Phase:		Liquid	Liquid	Liquid	Vapor
Component Mass Flow					
Sb	Lb/hr	2006.969059	2006.969059	6020.907176	0
Sb2O3	Lb/hr	4805.121715	4805.121715	0	0
O2	Lb/hr	0	0	0	791.1835974
N2	Lb/hr	0	0	0	0
Mole Flow	Lbmol/hr	33.03542369	33.03542369	49.55313553	24.77656776
Mass Flow	lb/hr	6812.090774	6812.090774	6020.907176	791.1835974
Volume Flow	ft3/hr				3.16E+04
Temperature	F	1291.73	1291.73	1291.73	1291.73
Pressure	psia	14.7	14.7	14.7	14.7
Vapor Fraction		0	0	0	1
Liquid Fraction		1	1	1	0
Molar Enthalpy	Btu/lbmol	-126558.5905	-126558.5905	8060.310549	9354.5302
Mass Enthalpy	Btu/lb	-613.7494048	-613.7494048	66.33778753	292.34
Enthalpy Flow	Btu/hr	-4180916.658	-4180916.658	399413.661	2.31E+05
Avg. Molecular Weight		206.64	206.64	121.76	31.9988

Process Description

An equimolar mixture of molten antimony and antimony trioxide is stored in a concrete storage vessel (V-100) at 1292°F and 14.7 psia. A transfer pump (P-100) is used to transport the molten mixture from the storage vessel to the electrolyzer at a flow rate of 6812 lb/hr (Stream 2). In the electrolyzer, the mixture is reduced to pure antimony. The reduction is facilitated by an electric current, which is delivered at 0.83 V and 0.20 A/cm^2. To accept 1.0 MW of electric power, the electrolyzer has a total area of 6.024x10^6 cm^2. The electrolyzer operates isothermally at a temperature of 1292°F. There are two effluent streams from the electroltyzer. The molten antimony stream flows from the electrolyzer to the concrete storage vessel (V-100) at a total flow rate of 6021 lb/hr (Stream 3). The oxygen produced is released to the atmosphere at a rate of 791.2 lb/hr at a pressure of 14.7 psia (Stream 4).

To maintain isothermal conditions within the electrolyzer 1402464.45 Btu/hr of heat must be supplied. This heat must be provided at 1292°F. Heating at such a high temperature is very challenging because traditional heat sources such as high pressure steam cannot be used. The best source of heat for the electrolyzer is direct electric heating. Assuming a 100% conversion of electrical energy to heat, the required heat can be supplied via electricity at 411 kW. This electrical heat requirement has a significant effect on the overall efficiency of the system. One way to mitigate the heat requirement needed during electrolysis operation is to allow the molten feed to enter the electrolyzer at a temperature above 1292°F. The principal source of heat to allow for this high inlet temperature would be the excess heat in fuel cell mode. Allowing this temperature rise, however, does not have a significant effect on the amount of heat input required. A 50 kW decrease in heating load requires a 245°F rise in inlet temperature.

Both the molten antimony and antimony trioxide used in this process are stored in a cylindrical concrete storage vessel (V-100). The vessel maintains the molten metal at 1292°F. It is insulated with mineral wool to reduce heat losses to the surroundings. The heat losses from the vessel were calculated to be 11049 Btu/hr. The heat loss was calculated from the temperature profile of the insulation layer, which was derived from first principles. Please refer to the sample calculations on page 188, for the derivation of the temperature profile.

Energy Balance and Utilities

Table 28 – Utilities Summary

Equipment	Unit No.	Power (kW)	Annual Consumption (kWh)	Price	Annual Cost
Transfer Pump	P-100	1.119	4431.24	$.06/kWh	$265.87
Electrolyzer Power	R-100	1000	3,960,000	$.06/kWh	$237,600.00
Electrolyzer Heat	R-100	411	1,627,560	$.06/kWh	$97,653.60
Total Electricity Cost:					$335,519.47

Electricity is the only utility used in electrolysis. The transfer pump (P-100) requires a net power of 1.119 kW. The electrolyzer (R-100) is the biggest consumer of electric power in the system. The 1000 kW of electric energy which drives the reaction is the biggest utility requirement for electrolysis mode. The 411 kW of electric of heat consumed by the electrolyzer is the second largest energy input to the system. The electricity used in electrolysis mode costs $335,519.47 annually.

Process Flow Diagram and Material Balances – Fuel Cell Mode

Figure 16 – Flow Diagram for Fuel Cell Mode

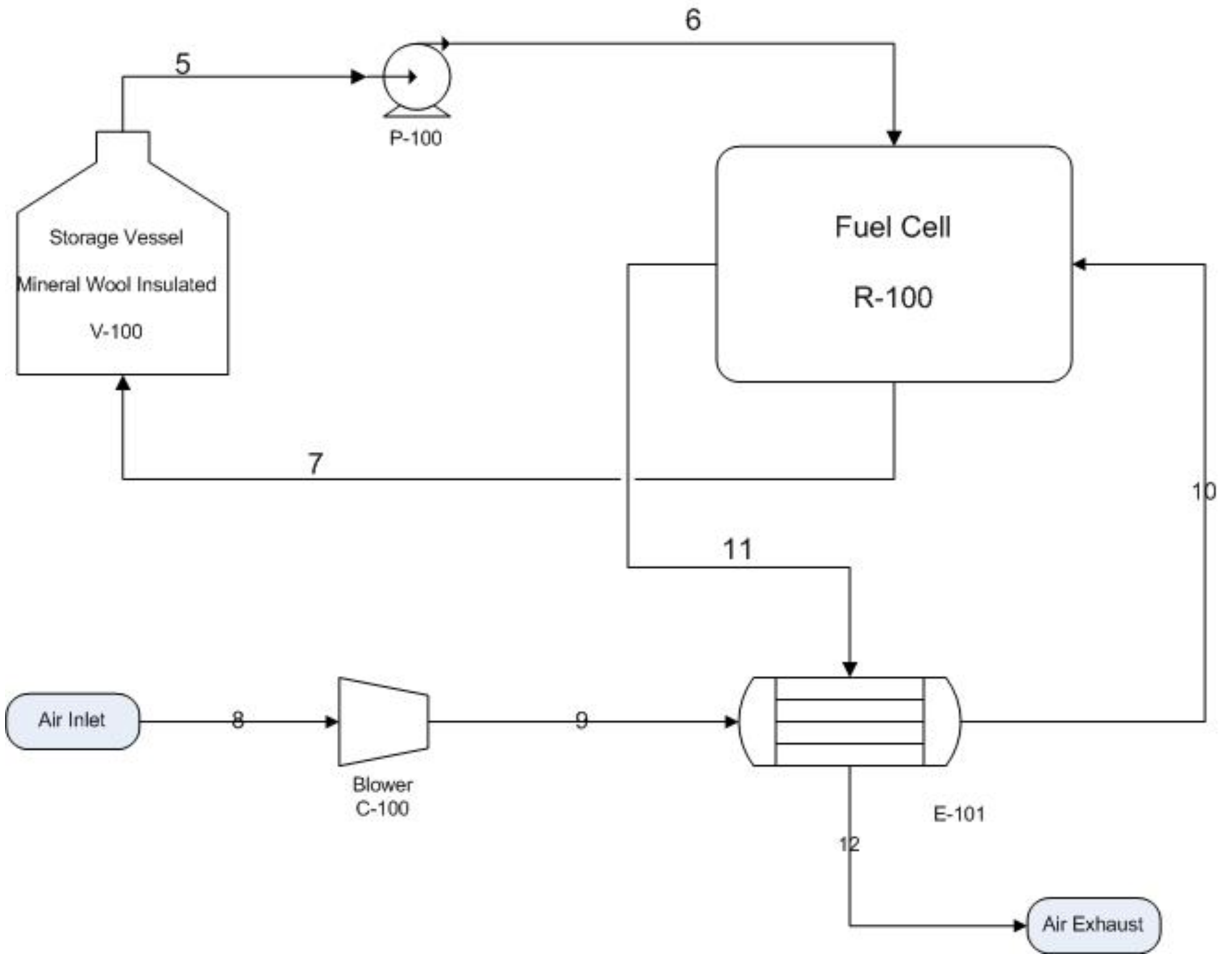


Table 29 - Antimony Fuel Cell Stream Summary

Stream ID:		5	6	7	8	9
From		V-100	P-100	R-100		C-100
To		P-100	R-100	V-100	C-100	E-100
Substream: MIXED						
Phase:		Liquid	Liquid	Liquid	Vapor	Vapor
Component Mass Flow						
Sb	Lb/hr	6622.997894	6622.997894	2207.665965	0	0
Sb2O3	Lb/hr	0	0	5285.633887	0	0
O2	Lb/hr	0	0	0	6618.34	6618.34
N2	Lb/hr	0	0	0	21796.7	21796.7
Mole Flow	Lbmol/hr	54.50844908	54.50844908	36.33896606	984.9094	984.9094
Mass Flow	lb/hr	6622.997894	6622.9979	7493.299851	28415	2.84E+04
Volume Flow	ft3/hr				385920	3.45E+05
Temperature	F	1291.73	1291.73	1291.73	77	117.5
Pressure	psia	14.7	14.7	14.7	14.7	17.6959
Vapor Fraction		0	0	0	1	1
Liquid Fraction		1	1	1	0	0
Molar Enthalpy	Btu/lbmol	8060.310549	8060.310549	-126558.5905	-2.8911	279.4625
Mass Enthalpy	Btu/lb	66.33778753	66.33778753	-613.7494048	-0.1002	9.6866
Enthalpy Flow	Btu/hr	439355.0271	439355.0271	-4599008.324	-2847.4332	2.75E+05
Avg. Molecular Weight		121.76	121.76	206.64	2.89E+01	2.89E+01

Stream ID:		10	11	12
From		E-100	R-100	E-100
To		R-100	E-100	
Substream: MIXED				
Phase:		Vapor	Vapor	Vapor
Component Mass Flow				
Sb	Lb/hr	0	0	0
Sb2O3	Lb/hr	0	0	0
O2	Lb/hr	6618.34	5748	5748
N2	Lb/hr	21796.7	21796.7	21796.7
Mole Flow	Lbmol/hr	984.9094	957.7107	957.7107
Mass Flow	lb/hr	2.84E+04	27544.7	2.75E+04
Volume Flow	ft3/hr	8.66E+05	1.11E+06	6.59E+05
Temperature	F	931.73	1292	337.7574
Pressure	psia	16.9859	16.1959	14.7659
Vapor Fraction		1	1	1
Liquid Fraction		0	0	0
Molar Enthalpy	Btu/lbmol	6170.8071	8946.328	1826.1951
Mass Enthalpy	Btu/lb	213.8898	311.0606	63.4961
Enthalpy Flow	Btu/hr	6.08E+06	7.29E+06	1.49E+06
Molar Entropy	Btu/lbmol-R	7.5636	9.3661	3.7204
Mass Entropy	Btu/lb-R	0.2622	0.3257	0.1294
Molar Density	lbmol/ft3	1.14E-03	8.61E-04	1.72E-03
Mass Density	lb/ft3	3.28E-02	2.48E-02	4.96E-02
Avg. Molecular Weight		2.89E+01	2.88E+01	2.88E+01

Process Description

The pure molten antimony produced during electrolysis is held in the storage vessel (V-100) for use during fuel cell mode. The antimony is pumped from the vessel by the antimony transfer pump (P-100) at a flow rate of 6623 lb/hr (Stream 6).

The operating conditions for fuel cell mode are different than for electrolysis. The fuel cell produces an electric current at 0.622 V and 0.22 A/cm^2. Under these operating conditions, the fuel cell produces 877.35 kW of useful electric power. The current density for fuel cell mode was selected to provide a total downtime of 1.1 hour in a 24 hour period, or 0.55 hour (33 minutes) for switching between operating modes. The total operating time for fuel cell mode is 10.9 hours.

In addition to the antimony feed stream (Stream 6), the fuel cell also has an inlet stream of air (Stream 10), which enters the fuel cell at a flow rate of 28,415 lb/hr. For all calculations, the inlet air molar composition was assumed to be 79% nitrogen and 21% oxygen. The pressure of the air stream is first increased from 14.7 psia to 17.7 psia by the air blower (C-100) to overcome the pressure drop through the system and maintain a steady flow. The pressure drops through the air heater were calculated using ASPEN's Heat Exchange Design program. For the fuel cell, the pressure drop was calculated by hand and found to be negligible. For this calculation, please refer to the sample calculations on page 181. After passing though the blower, the air stream is preheated in a shell and tube heat exchanger (E-100). The heat source for the temperature increase is the effluent air stream from the fuel cell (Stream 11). The cold air enters the exchanger at 117.5°F and exits at 932°F before entering the fuel cell.

The air stream exits the fuel cell with a flow rate of 27545 lb/hr (Stream 11) with an oxygen mole fraction of 0.188. The air outlet then enters the air preheater before being released to the environment. The fuel stream exits the fuel cell as an equimolar mixture of antimony and antimony trioxide at a flow rate of 7493.3 lb/hr (Stream 7). The molten outlet stream is returned to the antimony storage vessel (V-100).

Energy Balance and Utilities

Table 30 – Utilities Summary

Equipment	Unit No.	Power (kW)	Annual Consumption (kWh)	Price	Annual Cost
Transfer Pump	P-100	1.119	4028.4	$.06/kWh	$241.70
Air Blower	C-100	81.5	293,400	$.06/kWh	$17,604.00
Total Electricity Cost:					$17,845.70

Electricity is the only utility used during fuel cell operation. The transfer pump (P-100) requires 1.119 kW or electric power. The air blower (C-100) requires 81.5 kW of electric power, which costs $17,604.00 annually. The blower consumes the vast majority of the overall electricity input for fuel cell mode. Annual fuel cell mode electricity costs total $17,845.70,

Equipment List and Unit Descriptions

Table 31 – Electrolysis Process Units

Unit No.	Unit Type	Function	Size	Material	Oper. T (˚F)	Oper. P (psia)
P-100	Pump	Maintain flow of molten metal through the system.	P=1.11 hp	Ceramic	1292	14.7
R-100	Fuel Cell	Reduce antimony trioxide via an electric current.	V=0.83 V I=0.2 A/cm^2 A=6.024×10^6 cm^2	Sb, YSZ	1292	14.7
V-100	Storage Vessel	Store a mixture of molten antimony and antimony trioxide.	L= 6.8 ft D= 6.8 ft	Concrete	1292	14.7

Antimony Transfer Pump

The antimony transfer pump is used to facilitate flow of the molten mixture of antimony and antimony trioxide from the storage vessel to the electrolyzer. The pump is made of alumina, with some graphite. The pump requires a power of 1.11 hp to produce a flow rate of 6812 lb/hr. Please refer to the specification sheet on page 154.

Electrolyzer

The electrolyzer reduces antimony trioxide to antimony at the anode. The molten antimony in the feed stream acts as the anode. The electrolyzer operates under isothermally at 1292°F and a pressure of 14.7 psia. To maintain isothermal conditions a heat duty of 1402464 Btu/hr is needed. A direct electric current is supplied to the electrolyzer at a voltage of 0.83 V and a current density of 0.2 A/cm^2. The total electrode area for the electrolyzer totals 6.024×10^6 cm^2. The purchase cost of the electrolyzer is $450,000, which is based on USDOE price estimates for residential SOFC systems for 2020. Please refer to the specification sheet on page 156 and the sample calculation on page 187.

Storage Vessel

During electrolysis mode, the storage vessel holds the mixture of molten antimony and antimony trioxide which is fed to the electrolyzer. The mixture is kept at 1292°F. After the mixture passes through the electrolyzer and converted to pure antimony, it is returned to the vessel. The storage vessel is built of concrete. It is insulated with a 2.2 ft thick layer of mineral wool insulation. The total bare module cost for the storage vessel, including the mineral wool insulation, is $89,400. Please refer to the specification sheet on page 159 and the sample calculation on page 181.

Table 32 – Fuel Cell Process Units

Unit No.	Unit Type	Function	Size	Material	Oper. T (˚F)	Oper. P (psia)
C-100	Blower	Increase the pressure of the air inlet stream.	P=109.3 hp	Cast Iron	117.5	17.7
E-100	Shell and Tube Heat Exchanger	Preheat the air inlet to the fuel cell.	Q=5802441 Btu/hr A=2164 ft^2	Carbon Steel	932	14.7
P-100	Pump	Maintain flow of molten metal through the system.	P=1.11 hp	Ceramic	1292	14.7
R-100	Fuel Cell	Produce an electric current via the oxidation of antimony.	V=0.662 V I=0.22 A/cm^2 A=$6.024x10^6$ cm^2	Sb,YSZ	1292	14.7
V-100	Storage Vessel	Store molten antimony and molten antimony trioxide.	L=6.8 ft D=6.8 ft	Concrete	1292	14.7

Air Blower

The blower is used to increase the pressure of the air inlet from 14.7 psia to 17.7 psia. This unit is a cast iron rotary s straight lobe blower with cast aluminum blades. It produces a net work of 109.3 hp, which is supplied via an electric motor. The total bare module cost for the blower is $112,000. Please refer to the Specification sheet on page 152 and the sample calculations on page 179.

Air Preheater

The air preheater increases the temperature of the inlet air stream from 117.5°F to 12952°F. The hot stream is the air outlet form the fuel cell, which enters the exchanger at a temperature of 1272°F and exits at 338°F. The cold air stream (9) flows through the tube side of the exchanger at a flow rate of 28415 lb/hr, while the hot stream (10) flows through the shell side with an overall flow rate of 27545 lb/hr. The unit is made of carbon steel with 2164 ft^2 of heat transfer area and an overall heat transfer coefficient of 7.35 $Btu/hr \cdot ft^2 \cdot °F$. The total bare module cost of the heat exchanger is $118,380. Please refer to the specification sheet on page 153 and the sample calculation on page 177.

Fuel Cell

The fuel cell oxidizes the molten antimony fuel stored in the storage vessel to antimony trioxide. Pure molten antimony is fed at the anode at a flow rate of 6623 lb/hr. Air is fed to the cathode at a flow rate of 28415 lb/hr. The fuel cell produces an electric power at 0.662 V and a current density of 0.22 A/cm^2. The cell has a total area of 6.024×10^6 cm^2. The total power output for the fuel cell is 877.35 kW. The purchase cost of the fuel cell is $450,000, which is based on USDOE price estimates for residential SOFC systems for 2020. Please refer to the specification sheet on page 157 and the sample calculation on page 187.

Storage Vessel

The storage vessel holds the molten antimony which acts as the fuel for fuel cell operation. The metal is kept at 1292°F. After the metal is oxidized in the fuel cell, the mixture of antimony and antimony trioxe is returned to the storage vessel. The vessel is built out of concrete and insulated with mineral wool. The total bare module cost for the storage vessel is $89,400. Please refer to the specification sheet on page 159 and the sample calculation on page 180.

Specification Sheets

The following lists the page number of the specification sheets detailing the different units within the antimony system, followed by the specification sheets.

Air Blower(C-100)

Identification

Item	Blower	Date	4/5/2011
Item No.	C-100	By	EH/MP/DS
No. Required	1		

Function:

Increase the air inlet pressure from 14.7 psia to 17.7 psia.

Operation: 10.9 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		8	9
Quantity (lb/hr)		28415.00	28415.00
Composition:			
	Antimony	0.00	0.00
	Antimony Trioxide	0.00	0.00
	Oxygen	6618.00	6618.00
	Nitrogen	21797.00	21797.00
Temperature (°F)		77.0	117.5
Pressure (psia)		14.7	17.7
Vapor Fraction		1.0	1.0

Design Data

Type	Rotary Straight Lobe Blower, Cast Aluminum Blades
Material	Cast Iron
Net Work (HP)	109.2915
Efficiency	0.72

C_P	$	37,049
C_{BM}	$	79,655

Air Preheater (E-100)				
Identification				
Item	Heat Exchanger		Date	4/5/2011
Item No.	E-101		By	EH/MP/DS
No. Required	1			
Function:	Preheat air inlet from 117.5°F to 1292°F.			
Operation:	10.9 hours, daily			
Materials Handled	**Hot**		**Cold**	
	Inlet	**Outlet**	**Inlet**	**Outlet**
Stream ID	11	12	9	10
Quantity (lb/hr)	27545	27545.00	28415.00	28415.00
Composition:				
Antimony	0	0.00	0.00	0
Antimony Trioxide	0	0.00	0.00	0
Oxygen	5748	5748.00	6618.00	6618.00
Nitrogen	21797	21797.00	21797.00	21797.00
Temperature (°F)	1292	338.0	117.5	932.0
Pressure (psi)	16. 2	14.8	17.7	16.99
Vapor Fraction	1.0	1.0	1.0	1.0
Liquid Fraction	0.0	0.0	0.0	0.0
Design Data				
Type	Shell and Tube, Floating Head			
Material	Carbon Steel			
Heat Transfer Area	2164 ft2			
Heat Transfer Coefficient	7.35 Btu/(hr*ft2*F)			
Heat Duty	5802440.82 Btu/hr			
C_P	$ 37,340.00			
C_{BM}	$ 118,380.00			

Transfer Pump (Electrolysis)				
Identification				
	Item	Compressor	Date	4/5/2011
	Item No.	P-100	By	EH/MP/DS
	No. Required	1		
Function:	Increase the velocity of the molten metal stream.			
Operation:	12 hours, daily			
Materials Handled			**Inlet**	**Outlet**
Stream ID			1	2
	Quantity (lb/hr)		6812.00	6812.00
	Composition:			
		Antimony	2007.00	2007.00
		Antimony Trioxide	4805.00	4805.00
		Oxygen		
		Nitrogen		
	Temperature (°F)		1292.0	1292.0
	Pressure (psi)			
	Vapor Fraction		0.0	0.0
	Liquid Fraction		1.0	1.0
Design Data				
	Type	Transfer Pump		
	Material	Ceramic, Graphite		
	Net Work	1.11 HP		
	C_P	$	N/A	
	C_{BM}	$	N/A	

Transfer Pump (Fuel Cell)			
Identification			
Item	Compressor	Date	4/5/2011
Item No.	P-100	By	EH/MP/DS
No. Required	1		
Function:	Increase the velocity of the molten metal stream.		
Operation:	10.9 hrs, daily		
Materials Handled		**Inlet**	**Outlet**
Stream ID		5	6
Quantity (lb/hr)		6623.00	6623.00
Composition:			
	Antimony	6623.00	6623.00
	Antimony Trioxide	0.00	0.00
	Oxygen	0.00	0.00
	Nitrogen	0.00	0.00
Temperature (°F)		1292	1292
Pressure (psi)		14.7	14.7
Vapor Fraction		0.0	0.0
Design Data			
Type	Transfer Pump		
Material	Ceramic, Graphite		
Net Work	1.11 HP		
C_P	$ N/A		
C_{BM}	$ N/A		

Fuel Cell/Electrolyzer (Electrolyzer)

Identification

Item	Electrolyzer	Date	4/5/2011
Item No.	R-100	By	EH/MP/DS
No. Required	1		

Function:

Reduce antimony trioxide to antimony via electric current.

Operation: 12 hrs, daily

Materials Handled		**Inlet(s)**	**Outlet**	
Stream ID		2	3	4
Quantity (lb/hr)		6812.10	6020.90	791.20
Composition:				
	Antimony	2007.00	6020.90	0
	Antimony Trioxide	4805.00	0.00	0
	Oxygen	0.00	0.00	791.20
	Nitrogen	0.00	0.00	0.00
Temperature (°F)		1291.7	1291.7	1291.7
Pressure (psi)		14.7	14.7	14.70
Vapor Fraction		0.0	0.0	1.0
Liquid Fraction		1.0	1.0	0.0

Design Data

Type	Reversible Fuel Cell
Material	Sb, YSZ
Electricity Supplied (kW)	1000.00
Heat Duty (Btu/hr)	1402464.45
Operating Temperature (F)	1291.70
Operating Pressure (psia)	14.7
Voltage (V)	0.83
Current Density (A/cm2)	0.2
Electrode Area (cm2)	6.024E+06

C_P	$ 450,000.00
C_{BM}	$ 450,000.00

Fuel Cell/Electrolyzer (Fuel Cell)					
Identification					
	Item	Fuel Cell		Date	4/5/2011
	Item No.	R-100		By	EH/MP/DS
	No. Required	1			
Function:	Oxidize antimony to produce an electric current.				
Operation:	10.9 hrs, daily				
Materials Handled		**Inlet(s)**		**Outlet**	
Stream ID		6	10	7	11
	Quantity (lb/hr)	6623.00	28415.00	7493.30	27545.00
	Composition:				
	Antimony	6623.00	0.00	2207.70	
	Antimony Trioxide	0.00	0.00	5285.60	0
	Oxygen	0.00	6618.00	0.00	5748.00
	Nitrogen	0.00	21797.00	0.00	21797.00
	Temperature (°F)	1291.7	932.0	1291.7	1292.0
	Pressure (psi)	14.7	16.99	14.7	16.20
	Vapor Fraction	0.0	1.0	0.0	1.0
	Liquid Fraction	1.0	0.0	1.0	0.0
Design Data					
	Type	Reversible Fuel Cell			
	Material	Sb, YSZ			
	Electricity Produced (kW)	877.35			
	Operating Temperature (F)	1291.7			
	Operating Pressure (psia)	14.7			
	Voltage (V)	0.662			
	Current Density (A/cm2)	0.22			
	Electrode Area (cm2)	6.024E+06			
	C_P	$ 450,000.00			
	C_{BM}	$ 450,000.00			

Storage Vessel (Electrolysis)				
Identification				
	Item	Vessel	Date	4/5/2011
	Item No.	V-100	By	EH/MP/DS
	No. Required	1		
Function:	Store molten mixture of antimony and antimony trioxide.			
Operation:	Continuous			
Materials Handled			**Inlet**	**Outlet**
Stream ID			3	1
	Quantity (lb/hr)		6021.00	6812.00
	Composition:			
		Antimony	6021.00	2007.00
		Antimony Trioxide	0.00	4805.00
		Oxygen	0.00	0.00
		Nitrogen	0.00	0.00
	Temperature (°F)		1291.7	1291.7
	Pressure (psi)		14.7	14.7
	Vapor Fraction		0.0	0.0
	Liquid Fraction		1.0	1.0
Design Data				
	Type			
	Material		Concrete	
	Storage Volume		247 ft3	
	Dimensions			
		Diameter	6.8 ft	
		Length	6.8 ft	
	Weight		9450 lbs	
	Insulation		Mineral Wool	
	Insulation Thickness		2.2 ft	
	Operating Temperature (F)		1291.7	
	Operating Pressure (psia)		14.7	
	C_P	$ 29,307.00		
	C_{BM}	$ 89,400.00		

Storage Vessel (Fuel Cell)				
Identification				
	Item	Vessel	Date	4/5/2011
	Item No.	V-100	By	EH/MP/DS
	No. Required	1		
Function:	Store molten antimony.			
Operation:	Continuous			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		5	6	
	Quantity (lb/hr)	7493.30	6623.00	
	Composition:			
	Antimony	2207.70	6623.00	
	Antimony Trioxide	5285.60	0.00	
	Oxygen	0.00	0.00	
	Nitrogen	0.00	0.00	
	Temperature (°F)	1291.7	1291.7	
	Pressure (psi)	14.7	14.7	
	Vapor Fraction	0.0	0.0	
	Liquid Fraction	1.0	1.0	
Design Data				
	Type			
	Material	Concrete		
	Storage Volume	247 ft3		
	Dimensions			
	Diameter	6.8 ft		
	Length	6.8 ft		
	Weight	9450 lbs		
	Insulation	Mineral Wool		
	Insulation Thickness	2.2 ft		
	Operating Temperature (F)	1291.7		
	Operating Pressure (psia)	14.7		
	C_P	$ 29,307.00		
	C_{BM}	$ 89,400.00		

Fixed Capital Investment Summary

Table 33-Equipment Cost Summary

Unit No.	Equipment	Purchase Cost	Bare Module Factor	Bare Module Cost
---	Antimony	$170,512	1.00	$170,512
C-100	Air Blower	$37,049	2.15	$79,654
E-100	Air Preheater	$29,427	3.17	$93,284
P-100	Transfer Pump	N/A	3.30	N/A
R-100	Reversible Fuel Cell	$450,000	1.00	$450,000
V-100	Storage Vessel	$29,307	3.05	$89,386
Total:		$716,295		$882,838

Table 33 shows the equipment cost summary for the antimony system. The purchase cost is the cost of the physical equipment. The bare module cost is the total cost of the equipment as well as the cost of installation. The bare module factor varies for different types of process equipment. The bare module factors used in this report were taken from Table 22.11 of *Product and Process Design Principles*. The purchase cost for the antimony transfer pump was not included in this calculation. *Seider et al*. does not provide correlations for molten metal transfer pumps. The pump used in the design is based off of the model T(B)502 pump sold by High Temperature Systems, Inc[16]. The pump is designed to transfer molten aluminum for smelting applications. An aluminum pump was used because molten aluminum transfer pumps are rated to operate in the temperature range of this design. Unfortunately, at the time of this report, the vendor has yet to return a price quote for the pump model used in this design.

Table 34-Capital Investment Summary

C_{TBM}	Total Bare Module Cost		
$\mathbf{C_{PM}}$	Equipment Bare Module Cost	$	622,938
$\mathbf{C_{Sb}}$	Initial Charge for Antimony	$	170,512
$\mathbf{C_{storage}}$	Storage	$	---
	$\mathbf{C_{TBM}}$	$	882,838
C_{DPI}	**Direct Permanent Investment**		
$\mathbf{C_{TBM}}$	Equipment Bare Module Cost	$	882,838
$\mathbf{C_{site}}$	Site Preparation	$	44,142
$\mathbf{C_{serv}}$	Service Facilities	$	44,142
$\mathbf{C_{alloc}}$	Allocated Costs for Utility Plants	$	---
	$\mathbf{C_{DPI}}$	$	971,121
C_{TDC}	**Total Depreciable Capital**		
$\mathbf{C_{DPI}}$	Direct Permanent Investment	$	971,121
$\mathbf{C_{cont}}$	Contingencies and Contractor's Fees	$	174,802
	$\mathbf{C_{TDC}}$	$	1,145,923
C_{TPI}	**Total Permanent Investment**		
$\mathbf{C_{TDC}}$	Total Depreciable Capital	$	1,145,923
$\mathbf{C_{land}}$	Land	$	---
$\mathbf{C_{royalty}}$	Royalty	$	---
$\mathbf{C_{startup}}$	Plant Startup	$	114,592
	C_{TPI} (undadjusted)	$	1,260,515
	Site Factor		1.10
	$\mathbf{C_{TPI}}$ **(adjusted)**	$	1,386,567
C_{TCI}	**Total Capital Investment**		
$\mathbf{C_{TPI}}$	Total Permanent Investment	$	1,386,567
$\mathbf{C_{WC}}$	Working Capital	$	116,743
	$\mathbf{C_{TCI}}$	$	1,503,310

Table 34 lists the capital investment estimates for the antimony fuel cell system. The direct permanent investment, C_{DPI}, includes the total bare module cost of the equipment, the cost of site preparations, the cost of service facilities and the allocated costs for utility plants, which is zero for this system. The total bare-module cost for the equipment is $882,838. The cost of site preparations and the cost of service facilities are both $44,121. They are estimated as 5.0% of the total bare-module costs. Since the fuel cell system is located at a pre-existing power plant, with utility sources, an allocated cost for utility plants is not added. The total depreciable capital,

C_{TDC}, is calculated by adding the cost of contingencies and contractor's fees to the C_{DPI}. For these estimates, the contingencies and contractor fees were estimated to be 18.0% of C_{TDC}.

The total permanent investment, C_{TPI}, is calculated based on the total depreciable capital and other non-depreciable investments such as land and plant startup. The cost of land is not included in the calculation of C_{TPI} because the fuel cell system is located at a pre-existing power plant, land purchase is not necessary. There is no royalty cost for the fuel system, because the design does not include any proprietary technologies.

Working capital is the funds required to maintain operations until payments are received. As suggested in Section 23.3 of Product and Process Design., the working capital includes 30 days of cash reserves and 30 days of accounts receivable. There are no raw material inputs for this process, so there is no cost associated with storing the necessary inputs for production. Additionally, the electric power produced cannot be stored; it is delivered directly to the grid during fuel cell operation, so there is no inventory of product. After adding the working capital, C_{WC}, to the total permanent investment, C_{TPI}, the total capital investment, C_{TCI}, is $1,503,310.

Operating Costs

Table 35 – Variable Cost Summary

		Annual Cost
General Expenses		
	Selling/Transfer Expenses	$ 18,951
	Administrative Expenses	$ 12,634
	Management Incentive Compensation	$ 7,896
		$ 39,480
Utilities		
	Electricity	$ 353,366
		$ 353,366
Total Variable Costs		$ 392,846

The variable costs for the antimony fuel cell process include utility requirements, and other general expenses. Table 35 summarizes the variable costs for the antimony system. General expenses include selling/transfer expenses, administrative expenses and management incentive compensation. *Seider et al*. explain how to calculate these costs in Chapter 23 of *Product and Design Principles*. The total variable costs for the system total $392,846 annually. General expenses account for $39,480 of the total variable costs. The annual cost of utilities for running the process total $353,366. This cost is based on the assumption that electricity can be purchased for $0.06/kWh.

Table 36 – Fixed Cost Summary

			Annual Cost
Operations			
	Direct Wages and Benefits	$	327,600
	Direct Salaries and Benefits	$	49,140
	Operating Supplies and Services	$	19,656
		$	396,396
Maintenance			
	Wages and Benefits	$	51,567
	Salaries and Benefits	$	12,892
	Materials and Services	$	51,567
	Maintenance Overhead	$	2,578
		$	118,603
Operating Overhead			
	General Plant Overhead	$	31,325
	Mechanical Department Services	$	10,589
	Employee Relations Department	$	26,301
	Business Services	$	32,649
		$	100,593
Property Taxes and Insurance			
	Property Taxes and Insurance	$	22,918
		$	22,918
Total Fixed Costs		$	638,511

Fixed costs are incurred annually, regardless of overall power production. Table 36 summarizes the fixed costs for the antimony system. Fixed costs include operating costs, maintenance costs, operating overhead, property taxes and insurance. The values in Table 36 have been estimated as a percentage of total depreciable capital (C_{TDC}) as suggested in *Seider et al*. The operating costs are calculated on the assumption that the antimony system requires 1.5 operators per shift. One operator is required for the system, while the other half operator splits time between the fuel cell system and the power plant at which the system is located. Maintenance costs include costs of keeping equipment in working order, engineering and supervisory personnel salaries, materials and services, and maintenance overhead. Operating overhead includes the cost of providing services not directly related to system operation. These costs include safety and medical services, and purchasing and receiving. The total annual fixed costs total $638,511.

Overall Economic Analysis

The profitability of an energy storage system utilizing a molten antimony fuel cell was evaluated using the Profitability Analysis Spreadsheet (see page 208 of the Appendix). The profitability of the system is not promising. At a selling price of $0.20/kWh of energy produced, the, net present value (NPV) of the project is -$3,442,700. Additionally, the return on investment (ROI) for the system in its third production year is -35.51%. Table 37 shows the ROI summary for the third production year. For all of the profitability calculations, the income tax rate for the system was set to zero. Since the annual operating costs of the system are greater than annual sales, the net income for the system is negative, so there is no income to be taxed.

Table 37 – ROI Summary

ROI Analysis		
Annual Sales	$	568,517
Annual Costs	$	(991,374)
Annual Variable Costs	$	(392,846)
Annual Fixed Costs	$	(638,511)
Depreciation	$	(110,925)
Income Tax	$	---
Net Earnings	$	(533,782)
Total Capital Investment	$	1,503,310
ROI		-35.51%

When evaluating the overall economic performance of the system, it is important to note that the annual variable costs are dominated by the electrical utilities required to operate the system. Additionally annual sales income is very low because of the low price of electricity. The profit margin between peak and off-peak electricity prices is simply too small to produce a significant income stream for the system. If peak electricity prices were higher, the system would be more economically favorable. To obtain an ROI of 0.0%, the price of electricity needs to be $0.40/kWh. Another way of assessing the economic viability of the system is to evaluate the cost of the system per kilowatt of output capacity. The cost per kilowatt was calculated by dividing the total capital investment by the electrical power output. The antimony system costs $1,713.14 per kW of power.

Overall Efficiency

There are several sources of inefficiencies in the system. These include waste heat produced in the fuel cell and electrolyzer during both operating modes, the heat provided to the electrolyzer and energy required for pumping and compression. Figure 17 shows a comparison of the energy losses in the system. The largest energy loss for the system is the heat duty required to maintain isothermal conditions during electrolysis. The heat duty totals almost 60% of the total energy losses in the system. The waste heat produced as a result of cell inefficiencies in electrolysis and fuel cell modes represent 14% and 15% of the energy losses, respectively. The work done by the blower to move the air stream through the system during fuel cell operation makes up the remainder of the energy losses in the system.

Figure 17 – Efficiency Losses

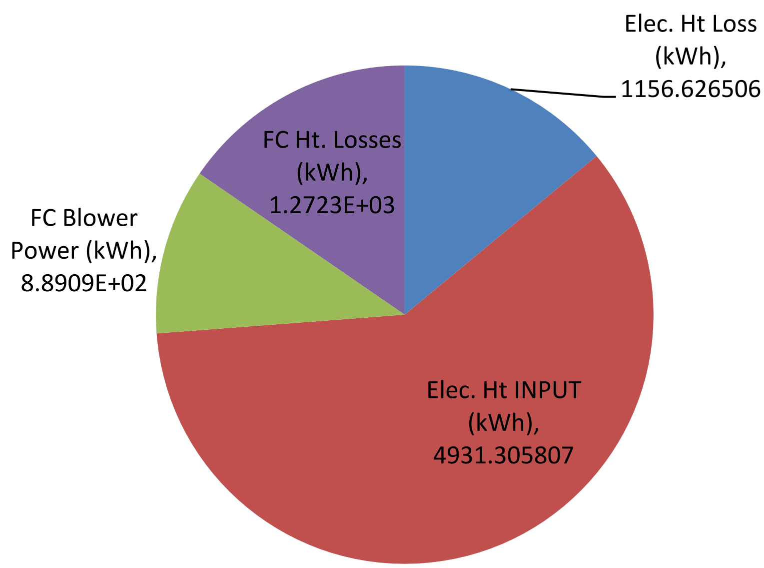


Table 38 – Summary of Energy Inputs and Outputs

Energy Output (kWh)	
Electricity Out (kWh)	9,571
Total:	**9,571**
Energy Inputs (kWh)	
Electrolyzer, electricity input	12,000
Electrolyzer, heating	4931.3
Compression	889.1
Total:	**17,820**

Improving efficiency will improve the economic viability of the system. The maximum theoretical round-trip efficiency for this system is 79.8%, which is based on thermodynamic limitations of the reversible fuel cell. The overall efficiency of the design presented here is 53.71%. Table 38 summarizes the overall energy inputs and outputs to the system. The most significant loss of energy in the system is the heat needed in electrolyzer mode. Compared to the other energy sinks in the system, the transfer pump, which operates at approximately 1.0 kW, is insignificant, which is why it is not included in Table 38. The required heat is almost half of what is added to the system to be stored. Lowering the electrical heat load could greatly improve the efficiency of the system while making it more economically favorable as well. As described above, this could be accomplished by relaxing the isothermal constraint on the system, by allowing for a temperature rise in the molten metal during fuel cell mode. The molten metal could then be fed to the electrolyzer at a higher temperature, reducing the heat load required to maintain the electrolysis reaction. Changing the operating conditions of the electrolyzer and/or fuel cell could also improve the overall efficiency of the system. Operating nearer to the open cell potential will reduce the energy lost to waste heat via ohmic losses.

Conclusions and Recommendations

These three process designs reveal some of the major benefits and challenges of fuel cells for reversible energy storage. The cost of the designs is high, but they will become more feasible as energy prices rise. Furthermore, energy storage systems are likely to receive government funding as energy efficiency agendas are pursued.

Efficiency

The overall efficiency of a system, as defined earlier in this report, is the useful energy generated divided by the total energy put into the system. For the three systems examined, the calculated efficiencies are very comparable.

Table 39: Comparison of System Efficiencies

System	Overall Efficiency
Hydrogen	52.4%
Methane	55.7%
Antimony	53.7%

In each system, the most significant efficiency loss occurred in the electrolyzer. In order to maintain operating temperature, a substantial amount of heat had to be added to the system in addition to the 1.0 MW of energy already being used to run the reaction. This heat, therefore, did not go towards generating useful energy, but rather was immediately wasted and lost. Additionally, since all of the systems are run at high temperatures, the streams exiting the fuel cell and electrolyzer are very hot. In order to prevent losses, all of this heat would need to be returned to the system through heat exchange with the inlet streams. However, because of the high temperatures, the amount of heat in these outlet streams was more than the inlet streams could absorb. This meant that a lot of heat was lost to cooling water and other non-recoverable sources, causing large efficiency losses.

Another loss for all three systems was compression. While the molten antimony system only needed one compressor, for air, the other two systems based on gases needed compressors on each gas stream. A lot of this energy was lost to pressure drops across heat exchangers and other units throughout the system that are unavoidable with moving streams.

Profitability

As shown throughout the report, none of the three systems designed generated a positive cash flow. This can be attributed to the small profit margin on the cost of electricity, the difference between peak and off peak energy prices. This margin becomes even smaller when the operating times and amount of electricity required by each mode are factored in. Since the operating time and electricity required for electrolysis are greater, the effective profit margin is even smaller than the already tiny normal profit margin.

To measure the profitability of each system, the ROI for the third year of operation was calculated. Additionally, the cost per kilowatt-hour was determined. This value takes both the efficiency and overall cost of the

Table 40: Return on Investment and Cost of Storage Capacity for the Three Systems

System	ROI	Cost/kWh
Hydrogen	-26.10%	$4,130
Methane	-19.21%	$7,597
Antimony	-35.51%	$1,714

As shown in Table 40, none of the systems were profitable; they all have a negative ROI. Based on these numbers, the antimony is the most viable option since the magnitude of its ROI is the greatest. Even though the ROI of the antimony case is the most negative value, the earnings from the system are the largest relative to the initial investment.

Comparing the methane system to the hydrogen system, the biggest difference in capital investment is in the storage of the products and feeds. The pressure vessels had the highest bare module costs of any units throughout the two systems. While the hydrogen case only needs one gas storage vessel to store hydrogen product from electrolysis operation, the methane system requires two vessels, one in each mode for storing the product gases. Other than the additional storage vessel, the capital investments of the two gas-based systems are very similar.

Overall Analysis and Recommendation

While none of the designs presented in this report are profitable, positive results can be deduced. Currently, there is a lot of research in the area of reversible SOFC's and SOFC's in general. Although the costs for fuel cells being used in this report are the 2020 Department of Energy targets, it can be assumed that the costs will eventually become even lower over time as technology improves. For this reason, the antinomy system is the most promising of the three developed systems.

As previously mentioned, the most expensive pieces of equipment in the methane and hydrogen systems are the storage vessels. Because the fuels are gases, a large volume is needed for storage, leading to the high prices of storage vessels. Even the minimum costs used in this report were too expensive to make the processes profitable. Since the cost of vessels is not going to decrease but rather stay constant over time, at the scale of this design, the systems will not become profitable. Even with decreasing costs and increasing efficiencies of fuel cells, these processed would need other help in becoming profitable.

In the antimony case, where the cost of the fuel cell is approximately 50% of the total capital investment of the process, a price decrease or efficiency increase will significantly help the process. Not only would the capital investment become less expensive, but also the efficiency losses would be less and therefore there would be more electricity to sell. This would bring the net income up and eventually lead to positive cash flows.

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References

1: Bierschenk, David M., James R. Wilson and Scott A. Barnett. "High efficiency electrical energy storage using a methane-oxygen solid oxide cell." Energy & Environmental Science (2011): 944-951.

2: U.S. Department of Energy. "The Smart Grid: An Introduction." 2008. Office of Electricity & Energy Reliability. 18 October 2010 <http://www.oe.energy.gov/DocumentsandMedia/DOE_SG_Book_Single_Pages(1).pdf>

3: Energy, U.S. Department of. "Office of Electrical Delivery & Energy Reliability." February 2011. Energy Storage Program Planning Document. 2 April 2011 <http://www.oe.energy.gov/DocumentsandMedia/OE_Energy_Storage_Program_Plan_Feburary_2011v3.pdf>.

4: Gross, M. D., and R. J. Gorte. "Solid Oxide Fuel Cells and Electrolyzers for Renewable Energy." *Renewable Resources and Renewable Energy: A Global Challenge*. 3rd ed. Boca Raton: CRC, 2007.

5: U.S. Department of Energy. Office of Fossil Energy. *Fuel Cell Handbook*. By EG&G Technical Services. 7th ed. 2004.

6: Energy, U.S. Department of Energy Office of Energy Efficiency & Renewable. Distributed/Stationary Fuel Cell Systems. 8 3 2011. 27 3 2011 <http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/systems.html>.

7: Seider, Warren D., et al. Product and Process Design Principles. Danvers: John Wiley & Sons, Inc., 2009.

8: Administration, U.S. Energy Information. Average Retail Price of Electricity to Ultimate Customers By End-Use, Sector. 11 March 2011. 1 April 2011 <http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html>.

9: AspenONE v.7.3 Exchanger Design and Rating User Interface.

10: "Wel-Bilt Cast Iron Clear Water Pump 720 GPH, 1/2 HP, 1in." *Northern Tool & Equipment*. Wed. 11 Apr. 2011. <http://www.northerntool.com/shop/tools/product_7738_7738>.

11: EVAL Europe. *EVAL for Hydrogen Fuel Cell Systems*. Belgium: Eval Europe, 2007.

12: NYSERDA. Monthly Average Retail Price Per Kilowatt-Hour of Electricity to Residential Consumers. 5 April 2011. 6 April 2011 <http://www.nyserda.org/energy_information/nyepo.asp>.

13: Xu, Jianguo and Gilbert F. Froment. "Methane Steam Reforming, Methanation and Water-Gas Shift: I. Intrinsic Kinetics." AIChE Journal (1989): 88-96.

14: Aguiar, P., D. Chadwick and L. Kershenbaum. "Modelling of an indirect reforming solid oxide fuel cell." Chemical Engineering Science (2002): 1665-1677.

15: Yourwaterneeds.com. Steel Pressurized Water System Tanks. 2011. 29 3 2011 <http://yourwaterneeds.com/WT_PressureTank.asp>.

16: "T-Series Transfer & Circulation Pumps." High Temperature Systems, Inc. Web. 28 Mar. 2011. <http://www.hitemp.com/images/hts/T-Series/T-Series_Table.pdf>

General References

Attributes of Power System Based on FFC's Stack Technology. Cambridge, MA: TIAX LLC, 2003. Print.

Felder, Richard M. and Ronald W. Rousseau. Elementary Principles of Chemical Processes. 3. Hoboken: Wiley, 2005.

Green, Don W. and Robert W. Perry. Perry's Chemical Engineers' Handbook. 8. McGraw-Hill, 2008.

Guan, Jie, et al. High Performance Flexible Reversible Solid Oxide Fuel Cell. Technical Report. Golden, CO: U.S. Department of Energy, 2006.

Incropera, Frank P., et al. Fundamentals of Heat and Mass Transfer. 6. Hoboken: Wiley, 2007.

Rawlings, James B. and John G. Ekerdt. Chemical Reactor Analysis and Design Fundamentals. Madison: Nob Hill, 2002.

Wilkes, James O. Fluid Mechanics for Chemical Engineers. Westford: Pearson Education, Inc., 2006.

FELDER & ROUSSEAU

Appendix

Problem Statement

. **Electrical Energy Storage Using Fuel-Cell Technology (recommended by Raymond J. Gorte, U. Penn)**

Reversible fuel cells are potentially useful to store electrical energy due to good storage-scalability. There have been concerns over *round-trip* efficiency. This project will consider two types of fuel cells that utilize two different feeds. The two concepts will be compared for economic viability. Your team is to design the two systems and detail the pros and cons of each.

Electrical energy storage has a number of well-known applications for improving the ability of the electrical-grid to respond to demand fluctuations. The need for storage has become more acute as increasing amounts of intermittent renewable electrical sources become available. Examples are solar and wind turbines that produce electrical energy for only parts of the day – and not always during the same time periods. Consequently, it is difficult to match fluctuations in supply and demand. Ability to store electrical power becomes key to maintaining continuously-available energy as needed. The challenge is to store energy over extended periods and on a large scale. Consider that a utility company generates power from conventional and renewable sources. Also, let all of its power generated from green sources be utilized during the peak period from 7 AM through 7 PM. Green power generated during the other 12 hours can be stored for use during the peak period, with conventional (expensive) power reduced or shutdown during the peak period.

The first type of reversible fuel cell will have cells comprised of dense zirconium tubes or other configurations coated with doped $LaMnO_3$ for the air electrode (cathode) and using a porous Ni electrode (anode) on the fuel side. During electrolysis, a mixture of H_2O and CO_2 will be fed to the anode which carries out the half-cell reactions:

$$CO_2 + 2e^- = CO + 2O^-$$
$$H_2O + 2e^- = H_2 + 2O^-$$

Electrons will be supplied to the anode at a potential sufficient to drive the oxygen ions into the electrolyte. After the ions pass through the electrolyte, O_2 will be produced on the cathode via the other half-cell reaction:

$$2O^- = \frac{1}{2} O_2 + 2e^-$$

Note that during electrolysis, the overall heats of reaction are:

$$H_2O = H_2 + \frac{1}{2} O_2 \qquad \Delta H(800^\circ C) = 248.3 \text{ KJ/mole}$$
$$CO_2 = CO + \frac{1}{2} O_2 \qquad \Delta H(800^\circ C) = 282.4 \text{ kJ/mole}$$

However, the overall Gibbs energies of reaction, ΔG, which are equivalent to the standard potentials, are more relevant than ΔH. This process produces O_2, H_2, and CO, and requires electrical energy. The H_2 and CO and unreacted H_2O and CO_2 are stored to be available for the reverse reaction – when power is required during the peak period.

Either stored O_2, or alternatively air, can be used to produce electrical energy and convert the CO, and H_2 back to H_2O and CO_2. Your team is to decide whether to store O_2 or utilize air – at some loss in efficiency.

Consider a typical periodic source of 1 MW electrical energy availability (from 7 PM – 7 AM). Design a system to convert and store the energy.

The second type of reversible fuel cell is comprised of similar materials, but involves liquid Sb and Sb_2O_3, with outside storage likely required. It operates at ~700ºC – to be adjusted as a design variable.

The anode reactions are replaced by:

$$Sb_2O_3 + 6e- = Sb + 3O_2-$$

No electrode material is required, since Sb is conductive.

The Sb_2O_3 floats above Sb. The vessel containing the mixture holds the total system, possibly comprised of multiple vessels. For the reverse reaction and production of electricity, Sb_2O_3 passes through the zirconium system and converts Sb to give up electrons.

References

Fuel Cell Handbook, DOE/METC-94/ 1006

Bierschenk, D., Wilson, J., and S. Barnett, "High Efficiency Electrical Energy Storage Using a Methane-Oxygen Solid Oxide Cell," submitted to the *J. Sci. Environ. Sci.*

Jayakumar, A., Vohs, J.M., and R.J. Gorte, "Molten-Metal Electrodes for Solid Oxide Fuel Cells," *Ind. Eng. Chem. Res.*, in press.

Gross, M.D., and R.J. Gorte, "Renewable Resources and Renewable Energy: A Global Challenge – Solid Oxide Fuel Cells and Electrolyzers for Renewable Energy," submitted as a book chapter.

Sample Calculations

Heat Exchanger (Shell & Tube, Floating Head)

$Q = UA\Delta T_{lm} \rightarrow A = \frac{Q}{U\Delta T_{lm}}$

$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$

$\Delta T_1 = T_{H,in} - T_{C,out}$

$\Delta T_2 = T_{H,out} - T_{C,in}$

Antimony Process – Block E-100

Variable	Value
$T_{H,in}$ (°F)	1292
$T_{H,out}$ (°F)	486.9
$T_{C,in}$ (°F)	117.5
$T_{C,out}$ (°F)	932
U (Btu/hr·ft²·°F)	7.35
Q (Btu/hr)	5802441

$\Delta T_1 = 1292 - 932 = 360°F$

$\Delta T_2 = 486.9 - 117.5 = 369.4°F$

$\Delta T_{lm} = \frac{364.82 - 360}{\ln\left(\frac{364.82}{360}\right)} = 364.82°F$

$A = \frac{5802441}{(7.35)(364.82)} = 2163.9\ ft^2$

Floating Head Base Cost Equation:

$C_B = exp\{11.667 - 0.8709[ln(A)] + 0.09005[ln(A)]^2\}$ (22.39)

$C_B = exp\{11.667 - 0.8709[ln(2164)] + 0.09005[ln(2164)]^2\} = \$29{,}516.551$

$C_P = F_P F_M F_L C_B$ (22.43)

F_M=1.00 (Carbon Steel/Carbon Steel)

F_P=1.00 (pressures below 100 psig)

F_L=1.12 (Tube length = 12 ft)

$C_p = (1.00)(1.00)(1.12)(\$29{,}428.13) = \$32{,}959.50$

$C_{BM} = F_{BM} C_P$

F_{BM}=3.17

$C_{BM} = (3.17)(\$32{,}959.60) = \$104{,}482$

Double Pipe Heat Exchangers

$Q = UA\Delta T_{lm} \rightarrow A = \frac{Q}{U\Delta T_{lm}}$

$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$

$\Delta T_1 = T_{H,in} - T_{C,out}$

$\Delta T_2 = T_{H,out} - T_{C,in}$

Hydrogen Process – E-100

Variable	Value
$T_{H,in}$ (°F)	672
$T_{H,out}$ (°F)	131
$T_{C,in}$ (°F)	76.21
$T_{C,out}$ (°F)	263.33
U (Btu/hr-ft²-°F)	52.16
Q (Btu/hr)	167,094

$\Delta T_1 = 672 - 263.33 = 408.67\,°F$

$\Delta T_2 = 131 - 76.21 = 54.79°F$

$\Delta T_{lm} = \frac{54.79 - 408.67}{\ln\left(\frac{54.79}{408.67}\right)} = 176.112°F$

$A = \frac{167094}{(52.16)(176.112)} = 18.19\,ft^2$

Double Pipe Base Cost Equation: $C_B = exp\{7.1460 + 0.16[ln(A)]\}$ (22.46)

$C_B = exp\{7.1460 + 0.16[ln(118.19)]\} = \$2,018.56$ (22.47)

$C_P = F_P F_M C_B$

F_M=3.0 (stainless steel)

F_P = 1.00 (Pressure below 600 psig)

$C_P = (1.00)(3.0)(\$2012.66) = \$6,037.97$

Fired Heater

E-103 (Hydrogen Process)
Q=153,569 Btu/hr
Fired Heater Bare Cost Equation: $C_B = exp\{0.32325 + 0.766[ln(Q)]\}$
$C_B = exp\{0.32325 + 0.766[ln(153{,}569)]\} = \$12{,}974.61$
$C_P = F_P F_M C_B$
F_P=1.00 (pressure below 500 psig)
F_M=1.7 (stainless steel)
$C_{BM} = (1.00)(1.7)(\$12{,}974.61) = \$22{,}056.83$

Screw Compressor
For Storage compressor 1 (C-100) [Hydrogen Process]
P_C = 13.79 hp
Screw Compressor Bare Cost Equation: $C_B = exp\{8.1238 + 0.7243[ln(P_C)]\}$ (22.38)
$C_B = exp\{8.1238 + 0.7243[ln(13.79)]\} = \$22{,}568.80$
$C_P = F_D F_M C_B$
F_D=1.0 (electric driver)
F_M=1.0 (carbon steel)
$C_{BM} = (1.0)(1.0)(\$22{,}568.80) = \$22{,}568.80$

Blower (Rotary Straight Lobe)

Air Blower (C-100) Antimony Process:
Rotary Straight Lobe Blower Bare Cost Equation
$C_B = exp\{7.59176 + .79320[ln(P_C)] - 0.0129[ln(P_C)]^2\}$
$C_B = exp\{7.59176 + .79320[ln(109.29)] - 0.0129[ln(109.29)]^2\} = \$61{,}747.60$
$C_P = F_M C_B$
F_M=0.6 (Cast Aluminum blades)
C_P=(.60)($61,747.60) = $37,048.60
$C_{BM} = F_{BM} C_P$
F_{BM}=2.15
C_{BM} = (2.15)($37,048.60) = $79,654.40

Horizontal Pressure Vessel ($F_{BM} = 3.05$)

Based on vessel for Hydrogen Storage

$C_P = F_M C_V + C_{PL}$
$C_V = \exp(8.09552 - 0.2330*\ln(W) + .04333*\ln(W)^2)$
$C_{PL} = 2005(D_i)^{0.20294}$
$W = \pi(D_i + t_s)(L + 0.8D_i)t_s\rho$
t_s (shell thickness)= $t_P + t_C$
t_C = 0.125 in (corrosion allowance)
t_P (wall thickness)= $P_d D_i / (2SE - 1.2 P_d)$

P_d (design pressure, psig) = $\exp\{0.60608 + 0.91615*\ln(P_o) + 0.0015655*\ln(P_o)\} - 14.7$ where P_o is the operating pressure, psi
S = Maximum Allowable Stress = 15,000 psi (for low alloy steel)
E = weld efficiency = 0.85

For the hydrogen storage tank, with an amplitude ratio of 20:1, P_o = 100 psi
D = 11.8 ft, L = 236 ft
$P_d = \exp\{0.60608 + 0.91615*\ln(100) + 0.0015655*\ln(100)\} - 14.7 = 114.11$ psi
t_P = (11.8 ft)(114.11 psi) / (2*15000*.85 – 1.2*114.11) = 0.053 ft
t_s = 0.053 ft + .125/12 = 0.064 ft
W = (3.14)(11.8 + 0.064)(236+.8*11.8)(.064)(490 lb/ft^3) = 284,164 lb
$C_V = \exp(8.09552 - 0.2330*\ln(284164) + .04333*\ln(284164)^2)$ = \$385,861
$C_{PL} = 2005(11.8)^{0.20294}$ = \$3,309
F_M = 1 (carbon steel)
C_P = (1)(385861) + (3309) = \$389,169
C_{BM} = 3.05*389169 = \$1,186,986

Pressure drop through the cell

The pressure drop through the cell was calculated to check the validity of the assumption that the pressure drop through the fuel cell is negligible. The calculations below are based on the assumption that each unit cell is 10cm x 10 cm, with a 1.0 mm opening for gases to flow through. The calculation was based on the Equation 3.53 in *Fluid Mechanics for Chemical Engineers*. For the purpose of these calculations, flow though the cell was assumed to be laminar and the volumetric flow rate of gases was calculated using the ideal gas law.

$$-\Delta p = 2 f_F \rho u_m^2 \frac{L}{D_e}$$

$$f_F = \frac{16}{Re} = \frac{16\mu}{\rho u_m D_e}$$

For the antimony fuel cell:

$$\dot{V}_{air} = \frac{\dot{n}_{air} RT}{P} = \frac{\left(124.02 \frac{mol}{s}\right)\left(8.206 \times 10^{-5} \frac{m^3 atm}{mol\ K}\right)(973\ K)}{1\ atm} = 9.902 \frac{m^3}{s}$$

Unit cell dimensions:
L=10 cm, W = 10 cm, H = 1 mm

$$A_{cell} = (10\ cm)(10\ cm) = 100\ cm^2$$

$$n_{cells} = \frac{A_{total}}{A_{cell}} = \frac{6.024 \times 10^6 cm^2}{100 cm^2} = 60241\ cells$$

$$\dot{V}_{air,cell} = \frac{\dot{V}_{air}}{n_{cells}} = \frac{9.902 \frac{m^3}{s}}{60241} = 1.64 \times 10^{-4} m^3$$

$$u_m = \frac{\dot{V}_{air,cell}}{A_c} = \frac{1.64 \times 10^{-4} m^3}{(.1\ m)(.001\ m)} = 1.64 \frac{m}{s}$$

$$D_e = \frac{4A_c}{P_w} = \frac{4(.1m)(.001m)}{(.1\ m + .1\ m + .001\ m + .001\ m)} = .00198\ m$$

For the pressure drop calculation, the density of air was assumed to be 0.37 kg/m^3, and the viscosity was assumed to be 3.63x10^{-5} kg/(m·s).

$$-\Delta p = 2 f_F \rho u_m{}^2 \frac{L}{D_e} = 2\left[\frac{16\left(3.63\times 10^{-5}\frac{kg}{m\cdot s}\right)}{\left(0.37\frac{kg}{m^3}\right)\left(1.64\frac{m}{s}\right)(.00198\,m)}\right]\left[\frac{\left(0.37\frac{kg}{m^3}\right)\left(1.64\frac{m}{s}\right)^2(.1\,m)}{(.00198\,m)}\right]$$

$$-\Delta p = 47.72\,Pa \times \frac{1\,psi}{6894.76\,Pa} = 6.921\times 10^{-3} psia \approx 0\,psia$$

Hydrogen System – Operating Conditions Calculations

Electrolysis

The following values are production rates during electrolysis mode, assuming an electrical input of 1.0 MW in electrolysis for 12 hours, at a current density of 0.5 A/cm^2 and a voltage of 1.07 V.

Cell area:

$$P = V \cdot i \cdot A$$

$$A = \frac{P}{V \cdot i} = \frac{10^6 W}{1.07 V \cdot 0.5 \frac{A}{cm^2}} = 1.896 \times 10^6 cm^2$$

Hydrogen Production Rate:

$$H_2\ production\ rate = \frac{1\ mol\ H_2}{2\ mol\ e^-} \cdot 0.5\ \frac{A}{cm} \cdot \frac{1\ mol\ e^-}{96{,}500\ C} \cdot 1.869 \times 10^6 cm = 4.842\ \frac{mol}{s}$$

$$H_2\ produced = 4.842 \frac{mol\ H_2}{s} \cdot 43200\ s = 2.092 \times 10^5\ mol\ H_2$$

Fuel Cell

The following values are based on the assumption that all of the hydrogen produced during electrolysis is consumed in fuel cell mode and the cell operates at 0.86 V with a current density of 0.55 A/cm^2.

Hydrogen Consumption Rate:

$$H_2\ consumption\ rate = 0.55 \frac{A}{cm^2} \cdot 1.869 \times 10^6 cm \cdot \frac{1\ mol\ e^-}{96500\ C} \cdot \frac{1\ mol\ H_2}{2\ mol\ e^-} = 5.327\ \frac{mol}{s}$$

Operating time:

$$Operating\ time = \frac{2.092 \times 10^5 mol\ H_2}{5.454 \frac{mol\ H_2}{s}} \cdot \frac{1\ hr}{3600\ s} = 10.9\ hr$$

Methane Case – Operating Conditions Calculations

Electrolysis

The following values are production rates during electrolysis mode, assuming an electrical input of 1.0 MW in electrolysis for 12 hours, at a current density of 0.5 A/cm^2 and a voltage of 1.06 V.

Cell area:

$$P = V \cdot i \cdot A$$

$$A = \frac{P}{V \cdot i} = \frac{10^6 W}{1.07 V \cdot 0.5 \frac{A}{cm^2}} = 1.896 \times 10^6 cm^2$$

Oxygen Production Rate:

$$O_2 \ production \ rate = \frac{1 \ mol \ O_2}{4 \ mol \ e^-} \cdot 0.5 \ \frac{A}{cm} \cdot \frac{1 \ mol \ e^-}{96{,}500 \ C} \cdot 1.869 \times 10^6 cm = 2.444 \ \frac{mol}{s}$$

Daily Total Amount of Oxygen Produced:

$$O_2 \ produced = 2.444 \frac{mol \ H_2}{s} \cdot 43200 \, s = 1.056 \times 10^5 \ mol \ O_2$$

Composition Calculations:

Reaction 1: $H_2O + 2e^- \leftrightarrow H_2 + \frac{1}{2}O_2$

Reaction 2: $CO_2 + 2e^- \leftrightarrow CO + \frac{1}{2}O_2$

Overall Reaction: $aH_2O + bCO_2 \leftrightarrow aH_2 + bCO + \frac{(a+b)}{2}O_2$

Where a and b represent the stoichiometric ratio of moles of H_2O and CO_2 consumed, respectively, to moles of O_2 produced. The Bierschenck paper showed that the concentration of methane formed at these operating conditions would be quite low, so the methane-forming reaction was omitted from these calculations due to the complex coupling of the reactions. A final methane concentration of 0.5 mol% was assumed based on Figure 6a in the Bierschenck paper.

$$\Delta G = -RT \ln K_{eq}$$

Ideal gas behavior was chosen to model the partial pressures of the gases due to the complexity of the iterations.

Therefore, the equation becomes:

$$\Delta G = -RT\ln\left(\frac{p_{H_2}^{a} p_{CO}^{b} p_{O_2}^{\frac{(a+b)}{2}}}{p_{H_2O}^{a} p_{CO_2}^{b}}\right)$$

Where the partial pressure of each species can be related:

$$p_x = y_x P + \xi_{rxn}$$

Ideal gas behavior was chosen to model the partial pressures of the gases due to the complexity of the iterations.

Therefore, the equation becomes:

$$\Delta G = -RT\ln\left(\frac{(y_{H_2}P + \xi_{rxn\ 1})^{a}(y_{CO}P + \xi_{rxn\ 2})^{b} p_{O_2}^{\frac{(a+b)}{2}}}{p_{H_2O}^{a} p_{CO_2}^{b}}\right)$$

The change in Gibbs free energy can then be set equal to the electricity input for electrolysis, where E is the operating voltage.

$$\Delta G = -nFE$$

The results of these calculations are summarized below in Table ##

Species	Initial Composition (mole fraction)	Final Composition (mole fraction)
H2	0.080	0.737
H20	0.670	0.010
CO	0.050	0.239
CO2	0.200	0.010
CH4	0.000	0.005

	Moles/hr
ξ_1	13100
ξ_2	3900

Fuel Cell Mode

The following values are based on the assumption that the amount of oxygen consumed in fuel cell mode is equivalent to the amount of oxygen produced in electrolysis mode. The fuel cell operates at 0.925 V with a current density of 0.55 A/cm^2.

Oxygen Consumption Rate:

$$O_2\ consumption\ rate = 0.55\frac{A}{cm^2}\cdot 1.869\times10^6 cm\cdot\frac{1\ mol\ e}{98500\ C}\cdot\frac{1\ mol\ O_2}{4\ mol\ e^-} = 2.615\frac{mol}{s}$$

Operating time:

$$Operating\ time = \frac{1.056\times10^5 mol\ O_2}{2.615\frac{mol\ O_2}{s}}\cdot\frac{1\ hr}{3600\ s} = 10.9\ hr$$

Catalyst Amount/Methanation Kinetics

$$W/F^0_{CO} = 0.04339\,\frac{g_{catalyst}\,hour}{mol_{CO}}$$

$$0.04339\frac{g_{catalyst}\,hour}{mol_{CO}} * 4800\frac{mol_{CO}}{hour} \div 1000\frac{g}{kg} = 1095.65\ kg\ catalyst$$

$$1095.65kg \div 5.19\frac{kg}{L} \div 0.55 * 0.0353\frac{L}{ft^2} * \$800/ft^2 = \$10968.67$$

Antimony Case – Operating Conditions Calculations

Electrolysis:

The following production rates during electrolysis mode are based on an electrical input of 1.0 MW for 12 hrs, at an electric voltage of 0.83 V and a current density of 0.20 A/cm^2.

Cell Area:

$$P = V \cdot i \cdot A$$

$$A = \frac{P}{V \cdot i} = \frac{10^6 W}{0.83 V \cdot 0.2 \frac{A}{cm^2}} = 6.024 \times 10^6 cm^2$$

Antimony Production Rate:

$$Sb\ production\ rate = 0.20 \frac{A}{cm^2} \cdot 6.024 \times 10^6 cm \cdot \frac{1\ mol\ e^-}{96500\ C} \cdot \frac{2\ mol\ Sb}{6\ mol\ e^-} = 4.162 \frac{mol}{s}$$

$$Sb_2\ producd = 4.162 \frac{mol\ Sb}{s} \cdot 43200 s = 1.80 \times 10^5\ mol\ Sb$$

Fuel Cell

The following values are based on the electrical operating conditions for fuel cell mode, 0.662 V and 0.22 A/cm^2.

Antimony Consumption Rate:

$$Sb\ Consumption\ rate = 0.22 \frac{A}{cm^2} \cdot 6.024 \times 10^6 cm \cdot \frac{1\ mol\ e^-}{96500\ C} \cdot \frac{2\ mol\ Sb}{6\ mol\ e^-} = 4.578 \frac{mol}{s}$$

Operating time:

$$Operating\ time = \frac{1.80 \times 10^5 mol\ Sb}{4.578 \frac{mol\ Sb}{s}} \cdot \frac{1\ hr}{3600\ s} = 10.9\ hr$$

Derivation of Temperature Profile in Insulation Layer of the Antimony Storage Vessel

1. Heat Equation in Cylindrical Coordinates

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \Phi}\left(k\frac{\partial T}{\partial \Phi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho C_p\frac{\partial T}{\partial t}$$

2. Simpifications/Assumptions
   a. Temperature varies in the radial direction only.
   b. Steady State
   c. Heat generation is zero
   d. Thermal conductivity is independent of temperature.

$$\frac{1}{r}\frac{d}{dr}\left(kr\frac{dT}{dr}\right)=0$$

$$kr\frac{dT}{dr}=c_1$$

$$\int kr\frac{dT}{dr}dr=\int c_1 dr$$

$$T(r)=C_1\ln(\mathrm{r})+\ \mathrm{C}_2$$

3. Boundary Conditions
   a. Let R_1 be the radius of the concrete tank

$$T(R_1)=700°C$$

   b. Let R_2 be the outside radius of the insulation

$$T(R_2)=50°C$$

   c. Let T_∞ be the ambient air temperature

$$-k\frac{dT}{dr}_{r=R_2}=h_{air}[T_\infty-T(R_2)]$$

Boundary Conditions (a) & (b)

$$T(R_1)-T(R_2)=700-50$$

$$650=C_1\ln\frac{R_1}{R_2}$$

Boundary Conditions (b) & (c)

$$-k\frac{dT}{dr}_{r=R_2} = h_{air}[T_\infty - T(R_2)]$$

$$-k\frac{dT}{dr}_{r=R_2} = \frac{C_1}{R_2}$$

$$\frac{-kC_1}{R_2} = h_{air}[T_\infty - T(R_2)] = h_{air}[T_\infty - C_1 \ln R_2 - C_2]$$

$$C_2 = T(R_1) - C_1 \ln R_1$$

$$\frac{-kC_1}{R_2} = h_{air}[T_\infty - C_1 \ln R_2 - T(R_1) + C_1 \ln R_1]$$

$$\frac{-kC_1}{h_{air}R_2} = T_\infty - T(R_1) + C_1 \ln\frac{R_1}{R_2}$$

$$C_1\left(\frac{-k}{h_{air}R_2} - \ln\frac{R_1}{R_2}\right) = T_\infty - T(R_1)$$

$$C_1 = \frac{T_\infty - T(R_1)}{\left[\frac{k}{h_{air}R_2} + \ln\frac{R_2}{R_1}\right]}$$

C_1 and R_2 must be solved for simultaneously and iteratively with the two equations below:

$$C_1 = \frac{T_\infty - T(R_1)}{\left[\frac{k}{h_{air}R_2} + \ln\frac{R_2}{R_1}\right]}$$

$$650 = C_1 \ln\frac{R_1}{R_2}$$

After solving for R_2 and C_1, C_2 can be solved for using the equation below.

$$50 = C_1 \ln R_2 + C_2$$

Results

Variable	Value	Units
k	0.029452	W ft^{-2} K^{-1}
h_{air}	0.2787	W ft^{-1} K^{-1}
R_1	3.617	ft
R_2	5.847	ft
C_1	-1354.854	°C
C_2	2442.012	°C
T_∞	50	°C

Temperature Profile:

$$T(r) = -1354.854 \ln r + 2442.012$$

Heat lost from the vessel:

$$q = -kA \frac{dT}{dr}_{r=R_2} = -k(2\pi R_2 L)\left(\frac{C_1}{R_2}\right)$$

$$q = 3155\ W = 3.155\ kW = 10766\ \frac{Btu}{hr}$$

Profitability Analysis Spreadsheets

Hydrogen System

General Information

Process Title:	**Hydrogen Reversible SOFC System**
Product:	**Electricity**
Plant Site Location:	**North East**
Site Factor:	**1.10**
Operating Hours per Year:	**7920**
Operating Days Per Year:	**330**
Operating Factor:	**0.9041**

Product Information

This Process will Yield

389	kWh of Electricity per hour
9,338	kWh of Electricity per day
3,081,540	kWh of Electricity per year

Price **$0.20 /kWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2012	Design		0.0%		
2013	Construction	100%	0.0%		
2014	Production	0%	81.0%	20.00%	$0.20
2015	Production	0%	90.0%	32.00%	$0.20
2016	Production	0%	90.0%	19.20%	$0.20
2017	Production		90.0%	11.52%	$0.20
2018	Production		90.0%	11.52%	$0.20
2019	Production		90.0%	5.76%	$0.20
2020	Production		90.0%		$0.20
2021	Production		90.0%		$0.20
2022	Production		90.0%		$0.20
2023	Production		90.0%		$0.20
2024	Production		90.0%		$0.20
2025	Production		90.0%		$0.20
2026	Production		90.0%		$0.20
2027	Production		90.0%		$0.20
2028	Production		90.0%		$0.20

Equipment Costs

Equipment Description		Bare Module Cost
Storage Compressor 1	Process Machinery	$48,523
Storage Compressor 2	Process Machinery	$51,122
Storage Compressor 3	Process Machinery	$53,032
Water Preheater 1	Fabricated Equipment	$10,900
Water Preheater 2	Fabricated Equipment	$11,489
Water Preheater 3	Fabricated Equipment	$15,865
Fired Heater	Fabricated Equipment	$48,304
Product Partial Condenser	Fabricated Equipment	$16,010
Intercooler for C-100	Fabricated Equipment	$13,229
Intercooler for C-101	Fabricated Equipment	$13,225
Intercooler for C-102	Fabricated Equipment	$13,231
Flash Vessel	Fabricated Equipment	$13,022
Water Feed Pump	Process Machinery	$396
Fuel Cell/Electrolyzer	Process Machinery	$450,000
Large Water Storage Tank	Storage	$10,265
Hydrogen Storage Tank	Storage	$1,383,041
Small Water Storage Tank	Storage	$3,172
Inlet Air Blower	Process Machinery	$46,840
Recycle Blower	Process Machinery	$1,198
Hydrogen Preheater	Fabricated Equipment	$9,821
Water Vaporizer & Preheater	Fabricated Equipment	$9,104
Product Stream Partial Condenser	Fabricated Equipment	$11,525
Recycle Heater	Fabricated Equipment	$7,433
Air Preheater	Fabricated Equipment	$12,846
FC-Water Feed Pump	Process Machinery	$396
Total		***$2,253,990***

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:
	Total Weighted Average:			$0.000E+00 per kWh of Electricity

Byproducts

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price
	Total Weighted Average:			$0.000E+00 per kWh of Electricity

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost
1	Natural Gas	SCF	1.122 SCF per kWh of Electricity	$3.200E-03 per SCF
2	Low Pressure Steam	lb	1.0647 lb per kWh of Electricity	$3.000E-03 per lb
3	Process Water	gal	0 gal per kWh of Electricity	$0.000E+00 per gal
4	Cooling Water	gal	7.82 gal per kWh of Electricity	$7.500E-05 per gal
5	Electricity	kWh	1.73 kWh per kWh of Electricity	$0.060 per kWh
	Total Weighted Average:			$0.111 per kWh of Electricity

Variable Costs

General Expenses:

Selling / Transfer Expenses:	**3.00% of Sales**
Direct Research:	**0.00% of Sales**
Allocated Research:	**0.00% 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**
Electricity Inventory	⇨	**0**	**Days**
Raw Materials	⇨	**0**	**Days**

Total Permanent Investment

Cost of Site Preparations:	5.00%	of Total Bare Module Costs
Cost of Service Facilities:	5.00%	of Total Bare Module Costs
Allocated Costs for utility plants and related facilities:	$0	
Cost of Contingencies and Contractor Fees:	18.00%	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:	1.5	(assuming 3 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:	4.50%	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 Benef
Mechanical Department Services:	2.40%	of Maintenance and Operations Wages and Benef
Employee Relations Department:	5.90%	of Maintenance and Operations Wages and Benef
Business Services:	7.40%	of Maintenance and Operations Wages and Benef

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:	$0

Depletion Allowance

Annual Depletion Allowance:	$0

Variable Cost Summary			
Variable Costs at 100% Capacity:			
General Expenses			
Selling / Transfer Expenses:		$	18,489
Direct Research:		$	-
Allocated Research:		$	-
Administrative Expense:		$	12,326
Management Incentive Compensation:		$	7,704
Total General Expenses		$	38,519
Raw Materials	$0.000000 per kWh of Electricity		$0
Byproducts	$0.000000 per kWh of Electricity		$0
Utilities	$0.111171 per kWh of Electricity		$342,578
Total Variable Costs		$	381,097
Fixed Cost Summary			
Operations			
Direct Wages and Benefits		$	327,600
Direct Salaries and Benefits		$	49,140
Operating Supplies and Services		$	19,656
Technical Assistance to Manufacturing		$	-
Control Laboratory		$	-
Total Operations		$	396,396
Maintenance			
Wages and Benefits		$	82,698
Salaries and Benefits		$	20,674
Materials and Services		$	82,698
Maintenance Overhead		$	4,135
Total Maintenance		$	190,204
Operating Overhead			
General Plant Overhead:		$	34,088
Mechanical Department Services:		$	11,523
Employee Relations Department:		$	28,327
Business Services:		$	35,528
Total Operating Overhead		$	109,466
Property Taxes and Insurance			
Property Taxes and Insurance:		$	36,754
Other Annual Expenses			
Rental Fees (Office and Laboratory Space):		$	-
Licensing Fees:		$	-
Miscellaneous:		$	-
Total Other Annual Expenses		$	-
Total Fixed Costs		$	732,820

Investment Summary

Bare Module Costs				
Fabricated Equipment	$	206,006		
Process Machinery	$	651,506		
Spares	$	-		
Storage	$	558,300		
Other Equipment	$	-		
Catalysts	$	-		
Computers, Software, Etc.	$	-		
Total Bare Module Costs:			$	1,415,812
Direct Permanent Investment				
Cost of Site Preparations:	$	70,791		
Cost of Service Facilities:	$	70,791		
Allocated Costs for utility plants and related facilities:	$	-		
Direct Permanent Investment			$	1,557,394
Total Depreciable Capital				
Cost of Contingencies & Contractor Fees	$	280,331		
Total Depreciable Capital			$	1,837,724
Total Permanent Investment				
Cost of Land:	$	-		
Cost of Royalties:	$	-		
Cost of Plant Start-Up:	$	183,772		
Total Permanent Investment - Unadjusted			$	2,021,497
Site Factor				1.10
Total Permanent Investment			$	2,223,646

Working Capital

		2013		2014		2015
Accounts Receivable	$	41,031	$	4,559	$	-
Cash Reserves	$	71,595	$	7,955	$	-
Accounts Payable	$	(22,807)	$	(2,534)	$	-
Electricity Inventory	$	-	$	-	$	-
Raw Materials	$	-	$	-	$	-
Total	$	89,819	$	9,980	$	-
Present Value at 15%	*$*	*78,103*	*$*	*7,546*	*$*	-
Total Capital Investment			$	2,309,296		

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%
2012	0%		-	-	-	-	-	-	-	-	-	-	-	-
2013	0%		-	(2,223,600)	(89,800)	-	-	-	-	-	-	-	(2,313,500)	(2,011,700)
2014	81%	$0.20	499,200	-	(10,000)	(308,700)	(732,800)	(367,500)	-	(909,800)	-	(909,800)	(552,300)	(2,429,300)
2015	90%	$0.20	554,700	-	-	(343,000)	(732,800)	(588,100)	-	(1,109,200)	-	(1,109,200)	(521,100)	(2,772,000)
2016	90%	$0.20	554,700	-	-	(343,000)	(732,800)	(362,800)	-	(874,000)	-	(874,000)	(521,100)	(3,069,900)
2017	90%	$0.20	554,700	-	-	(343,000)	(732,800)	(211,700)	-	(732,800)	-	(732,800)	(521,100)	(3,329,000)
2018	90%	$0.20	554,700	-	-	(343,000)	(732,800)	(211,700)	-	(732,800)	-	(732,800)	(521,100)	(3,554,300)
2019	90%	$0.20	554,700	-	-	(343,000)	(732,800)	(105,900)	-	(627,000)	-	(627,000)	(521,100)	(3,750,200)
2020	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(3,920,600)
2021	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(4,068,700)
2022	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(4,197,500)
2023	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(4,309,600)
2024	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(4,407,000)
2025	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(4,491,700)
2026	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(4,565,300)
2027	90%	$0.20	554,700	-	-	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(521,100)	(4,629,300)
2028	90%	$0.20	554,700	-	99,800	(343,000)	(732,800)	-	-	(521,100)	-	(521,100)	(421,300)	(4,674,400)

Profitability Measures

The Internal Rate of Return (IRR) for this project is Negative IRR

The Net Present Value (NPV) of this project in 2012 is $ (4,674,400)

ROI Analysis (Third Production Year)

Annual Sales	554,677
Annual Costs	(1,075,808)
Depreciation	(177,892)
Income Tax	-
Net Earnings	(699,022)
Total Capital Investment	2,323,445
ROI	-30.09%

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	50%
y-axis	50%

Product Price	Variable Costs										
	$190,549	$228,658	$266,768	$304,878	$342,987	***$381,097***	$419,207	$457,317	$495,426	$533,536	$571,646
$0.10	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.12	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.14	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.16	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.18	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.20	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.22	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.24	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.26	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.28	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.30	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR

Methane System

General Information

Process Title:	**Carbon Dioxide and Water Base Case for Energy Storage Using Reversible Fuel Cells**
Product:	**Electricity**
Plant Site Location:	**Northeast**
Site Factor:	**1.10**
Operating Hours per Year:	**3630**
Operating Days Per Year:	**151**
Operating Factor:	**0.4144**

Product Information

This Process will Yield

880	kWh of Electricity per hour
21,120	kWh of Electricity per day
3,194,400	kWh of Electricity per year

Price **$0.20 /kWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2012	Design		0.0%		
2013	Construction	100%	0.0%		
2014	Production	0%	81.0%	20.00%	$0.20
2015	Production	0%	90.0%	32.00%	$0.20
2016	Production	0%	90.0%	19.20%	$0.20
2017	Production		90.0%	11.52%	$0.20
2018	Production		90.0%	11.52%	$0.20
2019	Production		90.0%	5.76%	$0.20
2020	Production		90.0%		$0.20

Equipment Costs

Equipment Description		Bare Module Cost
R-100	Fabricated Equipment	$450,000
R-101	Fabricated Equipment	$134,369
E-100	Fabricated Equipment	$5,592
E-101	Fabricated Equipment	$5,872
E-102	Fabricated Equipment	$56,301
E-103	Fabricated Equipment	$109,892
E-104	Fabricated Equipment	$123,399
E-105	Fabricated Equipment	$5,337
E-106	Fabricated Equipment	$5,452
E-107	Fabricated Equipment	$6,695
E-108	Fabricated Equipment	$83,719
E-109	Fabricated Equipment	$6,739
C-100	Process Machinery	$53,751
C-101	Process Machinery	$13,911
C-102	Process Machinery	$519,347
T-100	Process Machinery	$38,130
V-100	Storage	$1,218,575
V-101	Storage	$954
V-102	Storage	$1,354,557
V-103	Storage	$1,455
P-100	Process Machinery	$37,791
P-101	Process Machinery	$45,539
Total		***$4,277,378***

Raw Materials

	Raw Material:	Unit:	Required Ratio:		Cost of Raw Material:
1	Hydrogen Gas		0	0	$0.000E+00
2	Carbon Dioxide		0	0	$0.00
3	Purified Water		0	0	$0.00
4	Methane		0	0	$0.00
5	Carbon Monoxide		0	0	$0.00

Total Weighted Average: $0.000E+00 per kWh of Electricity

Byproducts

Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price

Total Weighted Average: $0.000E+00 per kWh of Electricity

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost
1	High Pressure Steam	lb	0 lb per kWh of Electricity	$0.000E+00 per lb
2	Low Pressure Steam	lb	0 lb per kWh of Electricity	$0.000E+00 per lb
3	Process Water	gal	0 gal per kWh of Electricity	$0.000E+00 per gal
4	Cooling Water	lb	0 lb per kWh of Electricity	$0.000E+00 per lb
5	Electricity	kWh	1.4 kWh per kWh of Electricity	$0.060 per kWh
6	Methane	lb	0.04575 lb per kWh of Electricity	$0.070 per lb

Total Weighted Average: $0.087 per kWh of Electricity

Variable Costs

General Expenses:

Selling / Transfer Expenses:	**3.00% of Sales**
Direct Research:	**0.00% of Sales**
Allocated Research:	**0.00% 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**
Electricity Inventory	⇨	**0**	**Days**
Raw Materials	⇨	**0**	**Days**

Total Permanent Investment

Cost of Site Preparations:	**5.00% of Total Bare Module Costs**
Cost of Service Facilities:	**5.00% of Total Bare Module Costs**
Allocated Costs for utility plants and related facilities:	**$0**
Cost of Contingencies and Contractor Fees:	**18.00% of Direct Permanent Investment**
Cost of Land:	**2.00% 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:	**1 (assuming 3 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:	**4.50% 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:	**$0**
Depletion Allowance	
Annual Depletion Allowance:	**$0**

Variable Cost Summary			
Variable Costs at 100% Capacity:			
General Expenses			
Selling / Transfer Expenses:		$	19,166
Direct Research:		$	-
Allocated Research:		$	-
Administrative Expense:		$	12,778
Management Incentive Compensation:		$	7,986
Total General Expenses		$	39,930
Raw Materials	$0.000000 per kWh of Electricity		$0
Byproducts	$0.000000 per kWh of Electricity		$0
Utilities	$0.087203 per kWh of Electricity		$278,560
Total Variable Costs		**$**	**318,490**
Fixed Cost Summary			
Operations			
Direct Wages and Benefits		$	218,400
Direct Salaries and Benefits		$	32,760
Operating Supplies and Services		$	13,104
Technical Assistance to Manufacturing		$	-
Control Laboratory		$	-
Total Operations		**$**	**264,264**
Maintenance			
Wages and Benefits		$	249,842
Salaries and Benefits		$	62,460
Materials and Services		$	249,842
Maintenance Overhead		$	12,492
Total Maintenance		**$**	**574,636**
Operating Overhead			
General Plant Overhead:		$	40,006
Mechanical Department Services:		$	13,523
Employee Relations Department:		$	33,244
Business Services:		$	41,696
Total Operating Overhead		**$**	**128,469**
Property Taxes and Insurance			
Property Taxes and Insurance:		$	111,041
Other Annual Expenses			
Rental Fees (Office and Laboratory Space):		$	-
Licensing Fees:		$	-
Miscellaneous:		$	-
Total Other Annual Expenses		**$**	**-**
Total Fixed Costs		**$**	**1,078,410**

Investment Summary

Bare Module Costs				
Fabricated Equipment	$	993,367		
Process Machinery	$	708,470		
Spares	$	-		
Storage	$	2,575,541		
Other Equipment	$	-		
Catalysts	$	-		
Computers, Software, Etc.	$	-		
Total Bare Module Costs:			**$**	**4,277,378**
Direct Permanent Investment				
Cost of Site Preparations:	$	213,869		
Cost of Service Facilities:	$	213,869		
Allocated Costs for utility plants and related facilities:	$	-		
Direct Permanent Investment			**$**	**4,705,116**
Total Depreciable Capital				
Cost of Contingencies & Contractor Fees	$	846,921		
Total Depreciable Capital			**$**	**5,552,037**
Total Permanent Investment				
Cost of Land:	$	111,041		
Cost of Royalties:	$	-		
Cost of Plant Start-Up:	$	555,204		
Total Permanent Investment - Unadjusted			$	6,218,281
Site Factor				1.10
Total Permanent Investment			**$**	**6,840,109**

Working Capital

		2013		2014		2015
Accounts Receivable	$	42,534	$	4,726	$	-
Cash Reserves	$	90,341	$	10,038	$	-
Accounts Payable	$	(18,545)	$	(2,061)	$	-
Electricity Inventory	$	-	$	-	$	-
Raw Materials	$	-	$	-	$	-
Total	**$**	**114,329**	**$**	**12,703**	**$**	**-**
Present Value at 15%	*$*	*99,417*	*$*	*9,605*	*$*	-
Total Capital Investment			**$**	**6,949,131**		

Cash Flow Summary

Year	Percentage of Design Capacity	Product Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Depletion Allowance	Taxable Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 16%
2012	0%		-	-	-	-	-	-	-	-	-	-	-	-
2013	0%		-	(6,840,100)	(114,300)	-	-	-	-	-	-	-	(6,954,400)	(6,047,300)
2014	61%	$0.20	517,500	-	(12,700)	(258,000)	(1,078,400)	(1,110,400)	-	(1,929,300)	-	(1,929,300)	(831,600)	(6,676,100)
2015	90%	$0.20	575,000	-	-	(286,600)	(1,078,400)	(1,776,700)	-	(2,566,700)	-	(2,566,700)	(790,100)	(7,195,600)
2016	90%	$0.20	575,000	-	-	(286,600)	(1,078,400)	(1,066,000)	-	(1,856,000)	-	(1,856,000)	(790,100)	(7,647,300)
2017	90%	$0.20	575,000	-	-	(286,600)	(1,078,400)	(639,600)	-	(1,429,700)	-	(1,429,700)	(790,100)	(8,040,100)
2018	90%	$0.20	575,000	-	-	(286,600)	(1,078,400)	(639,600)	-	(1,429,700)	-	(1,429,700)	(790,100)	(8,381,700)
2019	90%	$0.20	575,000	-	-	(286,600)	(1,078,400)	(319,800)	-	(1,109,900)	-	(1,109,900)	(790,100)	(8,678,700)
2020	90%	$0.20	575,000	-	127,000	(286,600)	(1,078,400)	-	-	(790,100)	-	(790,100)	(663,000)	(8,895,500)

Profitability Measures

The Internal Rate of Return (IRR) for this project is Negative IRR

The Net Present Value (NPV) of this project in 2012 is $ (8,895,500)

ROI Analysis (Third Production Year)

Annual Sales	**574,992**
Annual Costs	**(1,365,051)**
Depreciation	**(547,209)**
Income Tax	**-**
Net Earnings	**(1,337,267)**
Total Capital Investment	**6,967,142**
ROI	**-19.19%**

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	50%
y-axis	50%

						Variable Costs					
Product Price	$159,245	$191,094	$222,943	$254,792	$286,641	***$318,490***	$350,339	$382,188	$414,037	$445,886	$477,734
$0.10	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.12	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.14	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.16	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.18	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.20	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.22	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.24	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.26	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.28	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.30	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR

Antimony System

General Information

Process Title:	**Antimony Fuel Cell System for Energy Storage**
Product:	**Electricity**
Plant Site Location:	**Northeast**
Site Factor:	**1.10**
Operating Hours per Year:	**7920**
Operating Days Per Year:	**330**
Operating Factor:	**0.9041**

Product Information

This Process will Yield

399	kWh of Electricity per hour
9,571	kWh of Electricity per day
3,158,430	kWh of Electricity per year

Price **$0.20 /kWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2008	Design		0.0%		
2009	Construction	100%	0.0%		
2010	Production	0%	81.0%	20.00%	$0.20
2011	Production	0%	90.0%	32.00%	$0.20
2012	Production	0%	90.0%	19.20%	$0.20
2013	Production		90.0%	11.52%	$0.20
2014	Production		90.0%	11.52%	$0.20
2015	Production		90.0%	5.76%	$0.20
2016	Production		90.0%		$0.20
2017	Production		90.0%		$0.20
2018	Production		90.0%		$0.20
2019	Production		90.0%		$0.20
2020	Production		90.0%		$0.20
2021	Production		90.0%		$0.20
2022	Production		90.0%		$0.20
2023	Production		90.0%		$0.20
2024	Production		90.0%		$0.20

Equipment Costs

Equipment Description		Bare Module Cost
Antimony	Other Equipment	$170,512
C-100	Process Machinery	$79,655
E-100	Fabricated Equipment	$93,284
P-100	Process Machinery	
R-100	Other Equipment	$450,000
V-100	Fabricated Equipment	$89,386
Total		***$882,837***

Raw Materials

Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:
Total Weighted Average:			$0.000E+00 per kWh of Electricity

Byproducts

Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price
Total Weighted Average:			$0.000E+00 per kWh of Electricity

Utilities

	Utility:	Unit:	Required Ratio		Utility Cost	
1	Electrolyzer	kWh	1.25	kWh per kWh of Electricity	$0.060	per kWh
2	Electrolyzer Heat	kWh	0.515	kWh per kWh of Electricity	$0.060	per kWh
3	Compressor Elec.	kWh	0.0929	kWh per kWh of Electricity	$0.060	per kWh
4	Pumping Elec.	kWh	0.002677	kWh per kWh of Electricity	$0.060	per kWh
	Total Weighted Average:				$0.112	per kWh of Electricity

Variable Costs

General Expenses:

Selling / Transfer Expenses:	**3.00%**	**of Sales**
Direct Research:	**0.00%**	**of Sales**
Allocated Research:	**0.00%**	**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 M	⇨	**30**	**Days**
Accounts Payable	⇨	**30**	**Days**
Electricity Inventory	⇨	**0**	**Days**
Raw Materials	⇨	**0**	**Days**

Total Permanent Investment

Cost of Site Preparations:	**5.00% of Total Bare Module Costs**
Cost of Service Facilities:	**5.00% of Total Bare Module Costs**
Allocated Costs for utility plants and related facilities:	**$0**
Cost of Contingencies and Contractor Fees:	**18.00% 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:	**1.5 (assuming 3 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:	**4.50% 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 & Operations Wages and Benefits**
Mechanical Department Services:	**2.40% of Maintenance & Operations Wages and Benefits**
Employee Relations Department:	**5.90% of Maintenance & Operations Wages and Benefits**
Business Services:	**7.40% of Maintenance & 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:	**$0**

Depletion Allowance

Annual Depletion Allowance:	**$0**

Variable Cost Summary				
Variable Costs at 100% Capacity:				
General Expenses				
	Selling / Transfer Expenses:		$	18,951
	Direct Research:		$	-
	Allocated Research:		$	-
	Administrative Expense:		$	12,634
	Management Incentive Compensation:		$	7,896
Total General Expenses			$	39,480
Raw Materials		$0.000000 per kWh of Electricity		$0
Byproducts		$0.000000 per kWh of Electricity		$0
Utilities		$0.111635 per kWh of Electricity		$352,590
Total Variable Costs			$	392,071
Fixed Cost Summary				
Operations				
	Direct Wages and Benefits		$	327,600
	Direct Salaries and Benefits		$	49,140
	Operating Supplies and Services		$	19,656
	Technical Assistance to Manufacturing		$	-
	Control Laboratory		$	-
	Total Operations		$	396,396
Maintenance				
	Wages and Benefits		$	51,567
	Salaries and Benefits		$	12,892
	Materials and Services		$	51,567
	Maintenance Overhead		$	2,578
	Total Maintenance		$	118,603
Operating Overhead				
	General Plant Overhead:		$	31,325
	Mechanical Department Services:		$	10,589
	Employee Relations Department:		$	26,031
	Business Services:		$	32,649
	Total Operating Overhead		$	100,593
Property Taxes and Insurance				
	Property Taxes and Insurance:		$	22,918
Other Annual Expenses				
	Rental Fees (Office and Laboratory Space):		$	-
	Licensing Fees:		$	-
	Miscellaneous:		$	-
	Total Other Annual Expenses		$	-
Total Fixed Costs			$	638,511

Investment Summary

Bare Module Costs				
Fabricated Equipment	$	182,670		
Process Machinery	$	79,655		
Spares	$	-		
Storage				
Other Equipment	$	620,512		
Catalysts	$	-		
Computers, Software, Etc.	$	-		
Total Bare Module Costs:			$	882,837
Direct Permanent Investment				
Cost of Site Preparations:	$	44,142		
Cost of Service Facilities:	$	44,142		
Allocated Costs for utility plants and related facilities:	$	-		
Direct Permanent Investment			$	971,121
Total Depreciable Capital				
Cost of Contingencies & Contractor Fees	$	174,802		
Total Depreciable Capital			$	1,145,923
Total Permanent Investment				
Cost of Land:	$	-		
Cost of Royalties:	$	-		
Cost of Plant Start-Up:	$	114,592		
Total Permanent Investment - Unadjusted			$	1,260,515
Site Factor				1.10
Total Permanent Investment			$	1,386,567

Working Capital

		2009		2010		2011
Accounts Receivable	$	42,055	$	4,673	$	-
Cash Reserves	$	65,983	$	7,331	$	-
Accounts Payable	$	(23,474)	$	(2,608)	$	-
Electricity Inventory	$	-	$	-	$	-
Raw Materials	$	-	$	-	$	-
Total	**$**	**84,564**	**$**	**9,396**	**$**	-
Present Value at 15%	$	*73,534*	$	*7,105*	$	-

Total Capital Investment	$	1,467,205

Cash Flow Summary

Year	Percentage of Design Capacity	Product Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Depletion Allowance	Taxable Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 15%
2008	0%		-	-	-	-	-	-	-	-	-	-	-	-
2009	0%		-	(1,356,600)	(86,600)	-	-	-	-	-	-	-	(1,471,100)	(1,279,200)
2010	61%	$0.20	$41,700	-	(6,400)	(317,600)	(638,500)	(229,200)	-	(673,600)	-	(673,600)	(453,800)	(1,622,400)
2011	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	(366,700)	-	(789,600)	-	(789,600)	(422,900)	(1,900,400)
2012	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	(220,000)	-	(642,900)	-	(642,900)	(422,900)	(2,142,200)
2013	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	(132,000)	-	(554,900)	-	(554,900)	(422,900)	(2,352,400)
2014	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	(132,000)	-	(554,900)	-	(554,900)	(422,900)	(2,535,200)
2015	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	(66,000)	-	(488,900)	-	(488,900)	(422,900)	(2,684,200)
2016	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(2,812,400)
2017	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(2,932,000)
2018	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(3,037,200)
2019	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(3,146,100)
2020	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(3,227,100)
2021	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(3,295,000)
2022	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(3,356,000)
2023	90%	$0.20	$98,500	-	-	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(422,900)	(3,407,000)
2024	90%	$0.20	$98,500	-	94,000	(352,900)	(638,500)	-	-	(422,900)	-	(422,900)	(328,900)	(3,442,700)

Profitability Measures

The Internal Rate of Return (IRR) for this project is Negative IRR

The Net Present Value (NPV) of this project in 2008 is $ (3,442,700)

ROI Analysis (Third Production Year)

Annual Sales	568,517
Annual Costs	(991,374)
Depreciation	(110,925)
Income Tax	-
Net Earnings	(533,782)
Total Capital Investment	1,480,526
ROI	-36.05%

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 recal the IRR values. (These two lines may be deleted before printing.)

	Vary Initial Value by +/-
x-axis	50%
y-axis	50%

Product Price / Variable Costs

	$196,035	$235,242	$274,449	$313,656	$352,863	**$392,071**	$431,278	$470,485	$509,692	$548,899	$588,106
$0.10	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.12	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.14	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.16	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.18	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.20	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.22	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.24	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.26	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.28	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$0.30	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR

ASPEN Results

Hydrogen System

Stream Results – Hydrogen Electrolysis

STREAM	ID	1	10	11	12	13
FROM	:	----	FC-SPLIT	S-100	S-100	E-101
TO	:	P-100	S-100	E-101	M-100	E-100
SUBSTREAM:	MIXED					
PHASE:	LIQUID	VAPOR	VAPOR	VAPOR	VAPOR	
COMPONENTS:	LBMOL/HR					
WATER		42.7071	4.8125	4.2778	0.5347	4.2778
HYDROGEN		0	43.2323	38.4292	4.8031	38.4292
OXYGEN		0	0	0	0	0
COMPONENTS:	LB/HR					
WATER		769.3798	86.6989	77.0667	9.6322	77.0667
HYDROGEN		0	87.1512	77.4687	9.6825	77.4687
OXYGEN		0	0	0	0	0
TOTAL	FLOW:					
LBMOL/HR		42.7071	48.0449	42.7071	5.3378	42.7071
LB/HR		769.3798	173.8501	154.5354	19.3147	154.5354
CUFT/HR		12.3859	5.1884+04	4.6120+04	5764.3015	2.7165+04
STATE	VARIABLES:					
TEMP	F	75	1472	1472	1472	672
PRES	PSIA	14.7	19.2	19.2	19.2	19.1
VFRAC		0	1	1	1	1
LFRAC		1	0	0	0	0
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		3.7569	-305.7493	-305.7493	-305.7493	-6179.4343
BTU/LB		-6900.1154	-84.4962	-84.4962	-84.4962	-1707.7356
BTU/HR		0.6912	2.531	2.6942	-1632.0232	2.3609
ENTROPY:						
BTU/LBMOL-R		-40.9705	8.2707	8.2707	8.2707	4.3644
BTU/LB-R		-2.2742	2.2857	2.2857	2.2857	1.2061
DENSITY:						
LBMOL/CUFT		3.448	9.2601-04	9.2601-04	9.2601-04	1.5721-03
LB/CUFT		62.1176	3.3508-03	3.3508-03	3.3508-03	5.6887-03
AVG	MW	18.0153	3.6185	3.6185	3.6185	3.6185

STREAM	ID	14	15	16	17	18
FROM	:	E-100	E-104	E-104	C-100	E-105
TO	:	E-104	C-100	----	E-105	C-101
SUBSTREAM:	MIXED					
PHASE:	MIXED	VAPOR	LIQUID	VAPOR	VAPOR	
COMPONENTS:	LBMOL/HR					
WATER		4.2778	2.9966-02	4.2479	2.9966-02	2.9966-02
HYDROGEN		38.4292	38.4292	0	38.4292	38.4292
OXYGEN		0	0	0	0	0
COMPONENTS:	LB/HR					
WATER		77.0667	0.5398	76.5268	0.5398	0.5398
HYDROGEN		77.4687	77.4687	0	77.4687	77.4687
OXYGEN		0	0	0	0	0
TOTAL	FLOW:					
LBMOL/HR		42.7071	38.4592	4.2479	38.4592	38.4592
LB/HR		154.5354	78.0085	76.5268	78.0085	78.0085
CUFT/HR		1.4327+04	1.2461+04	1.2343	8922.7671	7295.8853
STATE	VARIABLES:					
TEMP	F	131	100	100	231.4175	100
PRES	PSIA	18.85	18.55	18.55	32	31.7
VFRAC		0.9971	1	0	1	1
LFRAC		2.8890-03	0	1	0	0
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		2.9908	77.9663	3.7753	989.9785	78.4296
BTU/LB		-2789.0028	38.4384	-6798.0364	488.0718	38.6668
BTU/HR		0.69	2998.5208	-0.2023	3.8074+04	3016.3399
ENTROPY:						
BTU/LBMOL-R		-0.3346	-0.1696	-38.2124	0.2101	-1.2339
BTU/LB-R		-11.2476	-10.3609	-2.1211	0.1036	-0.6083
DENSITY:						
LBMOL/CUFT		2.9809-03	3.0863-03	3.4415	4.3102-03	5.2714-03
LB/CUFT		1.0786-02	6.2600-03	62.0003	8.7426-03	1.0692-02
AVG	MW	3.6185	2.0283	18.0153	2.0283	2.0283

STREAM	ID	19	2	20	21	22
FROM	:	C-101	P-100	E-106	C-102	E-107
TO	:	E-106	E-100	C-102	E-107	----
SUBSTREAM:	MIXED					
PHASE:	VAPOR	LIQUID	VAPOR	VAPOR	VAPOR	
COMPONENTS:	LBMOL/HR					
WATER		2.9966-02	42.7071	2.9966-02	2.9966-02	2.9966-02
HYDROGEN		38.4292	0	38.4292	38.4292	38.4292
OXYGEN		0	0	0	0	0
COMPONENTS:	LB/HR					
WATER		0.5398	769.3798	0.5398	0.5398	0.5398
HYDROGEN		77.4687	0	77.4687	77.4687	77.4687
OXYGEN		0	0	0	0	0
TOTAL	FLOW:					
LBMOL/HR		38.4592	42.7071	38.4592	38.4592	38.4592
LB/HR		78.0085	769.3798	78.0085	78.0085	78.0085
CUFT/HR		5176.7225	12.3939	4193.0106	2908.8729	2319.0877
STATE	VARIABLES:					
TEMP	F	235.3166	76.2077	100	244.9518	100
PRES	PSIA	55.51	214.6959	55.21	100.3	100
VFRAC		1	0	1	1	1
LFRAC		0	1	0	0	0
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		1018.1791	3.7573	79.2586	1087.3368	80.8399
BTU/LB		501.975	-6898.1003	39.0755	536.0707	39.8551
BTU/HR		3.9158+04	0.6927	3048.2201	4.1818+04	3109.0373
ENTROPY:						
BTU/LBMOL-R		-0.8446	-40.929	-2.3361	-1.9235	-3.5165
BTU/LB-R		-0.4164	-2.2719	-1.1517	-0.9483	-1.7337
DENSITY:						
LBMOL/CUFT		7.4293-03	3.4458	9.1722-03	1.3221-02	1.6584-02
LB/CUFT		1.5069-02	62.0772	1.8604-02	2.6817-02	3.3638-02
AVG	MW	2.0283	18.0153	2.0283	2.0283	2.0283

STREAM	ID	23	24	3	4	5
FROM	:	FC-SPLIT	E-102	E-100	F-100	F-100
TO	:	E-102	----	F-100	E-101	----
SUBSTREAM:	MIXED					
PHASE:	VAPOR	VAPOR	LIQUID	VAPOR	MISSING	
COMPONENTS:	LBMOL/HR					
WATER		0	0	42.7071	42.7071	0
HYDROGEN		0	0	0	0	0
OXYGEN		19.2146	19.2146	0	0	0
COMPONENTS:	LB/HR					
WATER		0	0	769.3798	769.3798	0
HYDROGEN		0	0	0	0	0
OXYGEN		614.8444	614.8444	0	0	0
TOTAL	FLOW:					
LBMOL/HR		19.2146	19.2146	42.7071	42.7071	0
LB/HR		614.8444	614.8444	769.3798	769.3798	0
CUFT/HR		2.0752+04	1.5077+04	13.8878	1.3238+04	0
STATE	VARIABLES:					
TEMP	F	1472	929	263.3308	242.1922	MISSING
PRES	PSIA	19.2	19	214.6959	24	24
VFRAC		1	1	0	1	MISSING
LFRAC		0	0	1	0	MISSING
SFRAC		0	0	0	0	MISSING
ENTHALPY:						
BTU/LBMOL		1.0860+04	6393.9113	3.7964	3.9733	MISSING
BTU/LB		339.4006	199.8172	-6680.9201	-5699.2659	MISSING
BTU/HR		2.0868+05	1.2286+05	0.8598	1.6151	MISSING
ENTROPY:						
BTU/LBMOL-R		9.235	6.5446	-34.6704	-9.4433	MISSING
BTU/LB-R		0.2886	0.2045	-1.9245	-0.5242	MISSING
DENSITY:						
LBMOL/CUFT		9.2592-04	1.2745-03	3.0752	3.2261-03	MISSING
LB/CUFT		2.9628-02	4.0781-02	55.3997	5.8119-02	MISSING
AVG	MW	31.9988	31.9988	18.0153	18.0153	MISSING

STREAM	ID	6	7	8	9	H20FEED
FROM	:	E-101	E-102	E-103	M-100	----
TO	:	E-102	E-103	M-100	R-100	----
SUBSTREAM:	MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	
COMPONENTS:	LBMOL/HR					
WATER		42.7071	42.7071	42.7071	43.2417	42.7071
HYDROGEN		0	0	0	4.8031	0
OXYGEN		0	0	0	0	0
COMPONENTS:	LB/HR					
WATER		769.3798	769.3798	769.3798	779.012	769.3798
HYDROGEN		0	0	0	9.6825	0
OXYGEN		0	0	0	0	0
TOTAL	FLOW:					
LBMOL/HR		42.7071	42.7071	42.7071	48.0449	42.7071
LB/HR		769.3798	769.3798	769.3798	788.6945	769.3798
CUFT/HR		3.0783+04	3.6136+04	4.6771+04	5.2556+04	12.3859
STATE	VARIABLES:					
TEMP	F	918.8573	1133.9903	1500	1497.5395	75
PRES	PSIA	20.5	20.2	19.2	19.2	14.7
VFRAC		1	1	1	1	0
LFRAC		0	0	0	0	1
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		-5.68	-5.4791	-5.1195	-4.1097	3.7569
BTU/LB		-5373.2268	-5261.6797	-5062.0779	-4940.1794	-6900.1154
BTU/HR		1.8659	1.9518	2.1053	2.1037	0.6912
ENTROPY:						
BTU/LBMOL-R		-3.3063	-1.923	0.2067	1.6762	-40.9705
BTU/LB-R		-0.1835	-0.1067	1.1476-02	0.1021	-2.2742
DENSITY:						
LBMOL/CUFT		1.3873-03	1.1818-03	9.1311-04	9.1416-04	3.448
LB/CUFT		2.4993-02	2.1291-02	1.6450-02	1.5007-02	62.1176
AVG	MW	18.0153	18.0153	18.0153	16.4158	18.0153

STREAM	ID	NOTREAL
FROM	:	R-100
TO	:	FC-SPLIT
SUBSTREAM:	MIXED	
PHASE:	VAPOR	
COMPONENTS:	LBMOL/HR	
WATER		4.8125
HYDROGEN		43.2323
OXYGEN		19.2146
COMPONENTS:	LB/HR	
WATER		86.6989
HYDROGEN		87.1512
OXYGEN		614.8444
TOTAL	FLOW:	
LBMOL/HR		67.2595
LB/HR		788.6945
CUFT/HR		7.2636+04
STATE	VARIABLES:	
TEMP	F	1472
PRES	PSIA	19.2
VFRAC		1
LFRAC		0
SFRAC		0
ENTHALPY:		
BTU/LBMOL		2884.2506
BTU/LB		245.9674
BTU/HR		1.9399+05
ENTROPY:		
BTU/LBMOL-R		9.7342
BTU/LB-R		0.8301
DENSITY:		
LBMOL/CUFT		9.2598-04
LB/CUFT		1.0858-02
AVG	MW	11.7262

Block Results – Hydrogen Electrolysis

```
BLOCK:  C-100    MODEL: COMPR
-----------------------------
 INLET STREAM:          15
 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)          38.4592        38.4592        0.00000
    MASS(LB/HR   )          78.0085        78.0085        0.00000
    ENTHALPY(BTU/HR  )      2998.52        38073.8        -0.921244

                   ***  INPUT DATA  ***

 ISENTROPIC CENTRIFUGAL COMPRESSOR
  OUTLET PRESSURE  PSIA                            32.0000
  ISENTROPIC EFFICIENCY                            0.72000
  MECHANICAL EFFICIENCY                            1.00000

                   ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  HP                13.7851
  BRAKE      HORSEPOWER REQUIREMENT  HP                13.7851
  NET WORK REQUIRED                  HP                13.7851
  POWER LOSSES                       HP                0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  HP                9.92526
  CALCULATED OUTLET TEMP  F                            231.418
  ISENTROPIC TEMPERATURE  F                            194.733
  EFFICIENCY (POLYTR/ISENTR) USED                      0.72000
  OUTLET VAPOR FRACTION                                1.00000
  HEAD DEVELOPED,       FT-LBF/LB                      251,921.
  MECHANICAL EFFICIENCY USED                           1.00000
  INLET HEAT CAPACITY RATIO                            1.40534
  INLET VOLUMETRIC FLOW RATE , CUFT/HR                 12,461.4
  OUTLET VOLUMETRIC FLOW RATE, CUFT/HR                 8,922.77
  INLET  COMPRESSIBILITY FACTOR                        1.00074
  OUTLET COMPRESSIBILITY FACTOR                        1.00106
  AV. ISENT. VOL. EXPONENT                             1.40346
  AV. ISENT. TEMP EXPONENT                             1.40211
  AV. ACTUAL VOL. EXPONENT                             1.63240
  AV. ACTUAL TEMP EXPONENT                             1.63084

BLOCK:  C-101    MODEL: COMPR
-----------------------------
 INLET STREAM:          18
 OUTLET STREAM:         19
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

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

MOLE(LBMOL/HR)	38.4592	38.4592	0.00000
MASS(LB/HR)	78.0085	78.0085	0.00000
ENTHALPY(BTU/HR)	3016.34	39158.3	-0.922971

*** INPUT DATA ***

ISENTROPIC CENTRIFUGAL COMPRESSOR

OUTLET PRESSURE PSIA	55.5100
ISENTROPIC EFFICIENCY	0.72000
MECHANICAL EFFICIENCY	1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP	14.2043
BRAKE HORSEPOWER REQUIREMENT HP	14.2043
NET WORK REQUIRED HP	14.2043
POWER LOSSES HP	0.0
ISENTROPIC HORSEPOWER REQUIREMENT HP	10.2271
CALCULATED OUTLET TEMP F	235.317
ISENTROPIC TEMPERATURE F	197.530
EFFICIENCY (POLYTR/ISENTR) USED	0.72000
OUTLET VAPOR FRACTION	1.00000
HEAD DEVELOPED, FT-LBF/LB	259,583.
MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.40536
INLET VOLUMETRIC FLOW RATE , CUFT/HR	7,295.89
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR	5,176.72
INLET COMPRESSIBILITY FACTOR	1.00126
OUTLET COMPRESSIBILITY FACTOR	1.00183
AV. ISENT. VOL. EXPONENT	1.40433
AV. ISENT. TEMP EXPONENT	1.40200
AV. ACTUAL VOL. EXPONENT	1.63271
AV. ACTUAL TEMP EXPONENT	1.63004

BLOCK: C-102 MODEL: COMPR

INLET STREAM: 20
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)	38.4592	38.4592	0.00000
MASS(LB/HR)	78.0085	78.0085	0.00000
ENTHALPY(BTU/HR)	3048.22	41818.1	-0.927108

*** INPUT DATA ***

ISENTROPIC CENTRIFUGAL COMPRESSOR

OUTLET PRESSURE PSIA	100.300
ISENTROPIC EFFICIENCY	0.72000
MECHANICAL EFFICIENCY	1.00000

*** RESULTS ***

```
 INDICATED  HORSEPOWER REQUIREMENT  HP                15.2371
 BRAKE      HORSEPOWER REQUIREMENT  HP                15.2371
 NET WORK REQUIRED                  HP                15.2371
 POWER LOSSES                       HP                0.0
 ISENTROPIC HORSEPOWER REQUIREMENT  HP                10.9707
 CALCULATED OUTLET TEMP  F                            244.952
 ISENTROPIC TEMPERATURE  F                            204.448
 EFFICIENCY (POLYTR/ISENTR) USED                      0.72000
 OUTLET VAPOR FRACTION                                1.00000
 HEAD DEVELOPED,       FT-LBF/LB                      278,457.
 MECHANICAL EFFICIENCY USED                           1.00000
 INLET HEAT CAPACITY RATIO                            1.40541
 INLET VOLUMETRIC FLOW RATE , CUFT/HR                 4,193.01
 OUTLET VOLUMETRIC FLOW RATE, CUFT/HR                 2,908.87
 INLET  COMPRESSIBILITY FACTOR                        1.00220
 OUTLET COMPRESSIBILITY FACTOR                        1.00326
 AV. ISENT. VOL. EXPONENT                             1.40586
 AV. ISENT. TEMP EXPONENT                             1.40176
 AV. ACTUAL VOL. EXPONENT                             1.63275
 AV. ACTUAL TEMP EXPONENT                             1.62806

BLOCK:  E-100    MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:          13
 OUTLET STREAM:         14
 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)           85.4141         85.4141       0.166376E-15
    MASS(LB/HR   )           923.915         923.915       0.00000
    ENTHALPY(BTU/HR  )      -0.557116E+07  -0.557116E+07  -0.167168E-15

                   ***  INPUT DATA  ***

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

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

 FLOW DIRECTION AND SPECIFICATION:
   COUNTERCURRENT   HEAT EXCHANGER
   SPECIFIED HOT OUTLET TEMP
```

```
  SPECIFIED VALUE              F                  131.0000
  LMTD CORRECTION FACTOR                                 1.00000

 PRESSURE SPECIFICATION:
  HOT  SIDE PRESSURE DROP       PSI                   0.2500
  COLD SIDE PRESSURE DROP       PSI                   0.0000

 HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R          52.1600

                 ***  OVERALL RESULTS  ***

 STREAMS:
            --------------------------------------
            |                            |
 13       ----->|              HOT              |-----> 14
 T=  6.7200D+02  |                            |      T=  1.3100D+02
 P=  1.9100D+01  |                            |      P=  1.8850D+01
 V=  1.0000D+00  |                            |      V=  9.9711D-01
            |                            |
 3        <-----|              COLD             |<----- 2
 T=  2.6333D+02  |                            |      T=  7.6208D+01
 P=  2.1470D+02  |                            |      P=  2.1470D+02
 V=  0.0000D+00  |                            |      V=  0.0000D+00
            --------------------------------------

 DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            167094.0100
  CALCULATED (REQUIRED) AREA     SQFT                  18.1898
  ACTUAL EXCHANGER AREA         SQFT                  18.1898
  PER CENT OVER-DESIGN                             0.0000

 HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R          52.1600
  UA (DIRTY)                  BTU/HR-R            948.7802

 LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                                 1.0000
  LMTD (CORRECTED)              F                 176.1146
  NUMBER OF SHELLS IN SERIES                             1

 PRESSURE DROP:
  HOTSIDE, TOTAL               PSI                  0.2500
  COLDSIDE, TOTAL              PSI                  0.0000

 PRESSURE DROP PARAMETER:
  HOT SIDE:                                 0.54248E+06
  COLD SIDE:                                  0.0000

BLOCK:  E-101    MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:         11
 OUTLET STREAM:        13
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
```

```
COLD SIDE:
----------
INLET STREAM:         4
OUTLET STREAM:        6
PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                        IN            OUT       RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)           85.4141        85.4141        0.00000
   MASS(LB/HR  )          923.915        923.915        0.00000
   ENTHALPY(BTU/HR  )      -0.439796E+07   -0.439796E+07    0.211763E-15

                 ***  INPUT DATA  ***

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

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

FLOW DIRECTION AND SPECIFICATION:
  COUNTERCURRENT   HEAT EXCHANGER
  SPECIFIED HOT TEMP CHANGE
  SPECIFIED VALUE               F                  800.0000
  LMTD CORRECTION FACTOR                               1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE PRESSURE DROP       PSI                   0.1000
  COLD SIDE PRESSURE DROP       PSI                   3.5000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT           BTU/HR-SQFT-R         20.3000

                ***  OVERALL RESULTS  ***

STREAMS:
            --------------------------------------
            |                            |
11       ----->|             HOT              |-----> 13
T=  1.4720D+03  |                            |      T=  6.7200D+02
P=  1.9200D+01  |                            |      P=  1.9100D+01
V=  1.0000D+00  |                            |      V=  1.0000D+00
            |                            |
6       <-----|             COLD             |<----- 4
T=  9.1886D+02  |                            |      T=  2.4219D+02
P=  2.0500D+01  |                            |      P=  2.4000D+01
V=  1.0000D+00  |                            |      V=  1.0000D+00
            --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            250847.8640
```

```
  CALCULATED (REQUIRED) AREA     SQFT                  25.2760
  ACTUAL EXCHANGER AREA          SQFT                  25.2760
  PER CENT OVER-DESIGN                                  0.0000

 HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R         20.3000
  UA (DIRTY)                     BTU/HR-R             513.1019

 LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                                1.0000
  LMTD (CORRECTED)               F                    488.8851
  NUMBER OF SHELLS IN SERIES                                 1

 PRESSURE DROP:
  HOTSIDE, TOTAL                 PSI                    0.1000
  COLDSIDE, TOTAL                PSI                    3.5000

 PRESSURE DROP PARAMETER:
  HOT SIDE:                                        0.12286E+06
  COLD SIDE:                                       0.14378E+07

BLOCK:  E-102    MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:          23
 OUTLET STREAM:         24
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
 COLD SIDE:
 ----------
 INLET STREAM:          6
 OUTLET 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)          61.9217       61.9217       0.00000
    MASS(LB/HR   )          1384.22       1384.22       0.00000
    ENTHALPY(BTU/HR  )   -0.392537E+07  -0.392537E+07  -0.237257E-15

                  ***  INPUT DATA  ***

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

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

 FLOW DIRECTION AND SPECIFICATION:
  COUNTERCURRENT   HEAT EXCHANGER
  SPECIFIED HOT OUTLET TEMP
```

SPECIFIED VALUE F 929.0000
LMTD CORRECTION FACTOR 1.00000

PRESSURE SPECIFICATION:
HOT SIDE PRESSURE DROP PSI 0.2000
COLD SIDE PRESSURE DROP PSI 0.3000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
OVERALL COEFFICIENT BTU/HR-SQFT-R 4.8400

*** OVERALL RESULTS ***

STREAMS:

```
           --------------------------------------
           |                           |
23    ----->|          HOT            |-----> 24
T= 1.4720D+03 |                        |    T= 9.2900D+02
P= 1.9200D+01 |                        |    P= 1.9000D+01
V= 1.0000D+00 |                        |    V= 1.0000D+00
           |                           |
7     <-----|          COLD           |<----- 6
T= 1.1340D+03 |                        |    T= 9.1886D+02
P= 2.0200D+01 |                        |    P= 2.0500D+01
V= 1.0000D+00 |                        |    V= 1.0000D+00
           --------------------------------------
```

DUTY AND AREA:
CALCULATED HEAT DUTY BTU/HR 85822.0672
CALCULATED (REQUIRED) AREA SQFT 189.6301
ACTUAL EXCHANGER AREA SQFT 189.6301
PER CENT OVER-DESIGN 0.0000

HEAT TRANSFER COEFFICIENT:
AVERAGE COEFFICIENT (DIRTY) BTU/HR-SQFT-R 4.8400
UA (DIRTY) BTU/HR-R 917.8099

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR 1.0000
LMTD (CORRECTED) F 93.5075
NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:
HOTSIDE, TOTAL PSI 0.2000
COLDSIDE, TOTAL PSI 0.3000

PRESSURE DROP PARAMETER:
HOT SIDE: 0.12632E+06
COLD SIDE: 81072.

BLOCK: E-103 MODEL: HEATER

INLET STREAM: 7
OUTLET STREAM: 8
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

```
                        IN          OUT       RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)         42.7071       42.7071       0.00000
   MASS(LB/HR   )        769.380       769.380       0.00000
   ENTHALPY(BTU/HR  )     -0.404823E+07   -0.389466E+07   -0.379350E-01

                 ***  INPUT DATA  ***
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE           F                1,500.00
 PRESSURE DROP                 PSI                1.00000
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                              0.000100000



                  ***  RESULTS  ***
 OUTLET TEMPERATURE    F                          1500.0
 OUTLET PRESSURE       PSIA                       19.200
 HEAT DUTY            BTU/HR                    0.15357E+06
 OUTLET VAPOR FRACTION                            1.0000
 PRESSURE-DROP CORRELATION PARAMETER                       0.21813E+06



 V-L PHASE EQUILIBRIUM :

   COMP          F(I)         X(I)          Y(I)          K(I)
   WATER          1.0000        1.0000        1.0000        MISSING

BLOCK:  E-104    MODEL: HEATER
------------------------------
 INLET STREAM:         14
 OUTLET STREAM:        15
 OUTLET WATER STREAM:   16
 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)         42.7071       42.7071      -0.166376E-15
   MASS(LB/HR   )        154.535       154.535      -0.183917E-15
   ENTHALPY(BTU/HR  )      -431000.       -517234.       0.166722

                 ***  INPUT DATA  ***
 TWO    PHASE  TP  FLASH
 FREE WATER CONSIDERED
 SPECIFIED TEMPERATURE           F                 100.000
 PRESSURE DROP                 PSI                0.30000
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                              0.000100000



                  ***  RESULTS  ***
```

OUTLET TEMPERATURE F 100.00
OUTLET PRESSURE PSIA 18.550
HEAT DUTY BTU/HR -86234.
OUTLET VAPOR FRACTION 0.90053
OUTLET: 1ST LIQUID/TOTAL LIQUID 0.0000
PRESSURE-DROP CORRELATION PARAMETER 0.10082E+07

V-L1-L2 PHASE EQUILIBRIUM :

COMP	F(I)	X1(I)	X2(I)	Y(I)	K1(I)	K2(I)
WATER	0.100	1.00	1.00	0.779E-03	0.388E-01	0.779E-03
HYDROGEN	0.900	0.943E-05	0.00	0.999	0.528E+07	

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER U-1
RATE OF CONSUMPTION 2884.2003 LB/HR
COST 2.5975-02 $/HR

BLOCK: E-105 MODEL: HEATER

INLET STREAM: 17
OUTLET STREAM: 18
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	38.4592	38.4592	0.00000
MASS(LB/HR)	78.0085	78.0085	0.00000
ENTHALPY(BTU/HR)	38073.8	3016.34	0.920776

*** INPUT DATA ***

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 100.000
PRESSURE DROP PSI 0.30000
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

OUTLET TEMPERATURE F 100.00
OUTLET PRESSURE PSIA 31.700
HEAT DUTY BTU/HR -35057.
OUTLET VAPOR FRACTION 1.0000
PRESSURE-DROP CORRELATION PARAMETER 0.32992E+07

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.77916E-03	0.99999	0.77916E-03	0.22720E-01

HYDROGEN 0.99922 0.94337E-05 0.99922 0.30886E+07

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER U-1
RATE OF CONSUMPTION 1172.5371 LB/HR
COST 1.0560-02 $/HR

BLOCK: E-106 MODEL: HEATER

INLET STREAM: 19
OUTLET STREAM: 20
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	38.4592	38.4592	0.00000
MASS(LB/HR)	78.0085	78.0085	0.00000
ENTHALPY(BTU/HR)	39158.3	3048.22	0.922157

*** INPUT DATA ***

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 100.000
PRESSURE DROP PSI 0.30000
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

OUTLET TEMPERATURE F 100.00
OUTLET PRESSURE PSIA 55.210
HEAT DUTY BTU/HR -36110.
OUTLET VAPOR FRACTION 1.0000
PRESSURE-DROP CORRELATION PARAMETER 0.57108E+07

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.77916E-03	0.99999	0.77916E-03	0.13067E-01
HYDROGEN	0.99922	0.94445E-05	0.99922	0.17743E+07

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER U-1
RATE OF CONSUMPTION 1207.7456 LB/HR
COST 1.0877-02 $/HR

BLOCK: E-107 MODEL: HEATER

INLET STREAM: 21
OUTLET STREAM: 22
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	38.4592	38.4592	0.00000
MASS(LB/HR)	78.0085	78.0085	0.00000
ENTHALPY(BTU/HR)	41818.1	3109.04	0.925653

*** INPUT DATA ***

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 100.000
PRESSURE DROP PSI 0.30000
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

OUTLET TEMPERATURE F 100.00
OUTLET PRESSURE PSIA 100.00
HEAT DUTY BTU/HR -38709.
OUTLET VAPOR FRACTION 1.0000
PRESSURE-DROP CORRELATION PARAMETER 0.10235E+08

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.77916E-03	0.99999	0.77916E-03	0.72373E-02
HYDROGEN	0.99922	0.94651E-05	0.99922	0.98060E+06

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER U-1
RATE OF CONSUMPTION 1294.6700 LB/HR
COST 1.1660-02 $/HR

BLOCK: F-100 MODEL: FLASH2

INLET STREAM: 3
OUTLET VAPOR STREAM: 4
OUTLET LIQUID STREAM: 5
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	42.7071	42.7071	0.00000
MASS(LB/HR)	769.380	769.380	0.00000
ENTHALPY(BTU/HR)	-0.514016E+07	-0.438490E+07	-0.146934

*** INPUT DATA ***

TWO PHASE PV FLASH
SPECIFIED PRESSURE PSIA 24.0000
VAPOR FRACTION 1.00000

```
 MAXIMUM NO. ITERATIONS                         30
 CONVERGENCE TOLERANCE                            0.000100000

                 ***  RESULTS  ***
 OUTLET TEMPERATURE    F                        242.19
 OUTLET PRESSURE       PSIA                   24.000
 HEAT DUTY             BTU/HR              0.75526E+06
 VAPOR FRACTION                           1.0000



 V-L PHASE EQUILIBRIUM :

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

               ***  ASSOCIATED  UTILITIES  ***

 UTILITY ID FOR STEAM                  U-2
 RATE OF CONSUMPTION                 828.5128  LB/HR
 COST                          2.4855  $/HR

BLOCK:  FC-SPLIT MODEL: SEP
---------------------------
 INLET STREAM:         NOTREAL
 OUTLET STREAMS:       23         10
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                         IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          67.2595        67.2595        0.00000
    MASS(LB/HR   )        788.695        788.695        0.00000
    ENTHALPY(BTU/HR  )       193993.        193989.       0.218613E-04


                 ***  INPUT DATA  ***

 FLASH SPECS FOR STREAM 23
 TWO    PHASE  TP  FLASH
 PRESSURE DROP         PSI                      0.0
 MAXIMUM NO. ITERATIONS                         30
 CONVERGENCE TOLERANCE                            0.000100000

 FLASH SPECS FOR STREAM 10
 TWO    PHASE  TP  FLASH
 PRESSURE DROP         PSI                      0.0
 MAXIMUM NO. ITERATIONS                         30
 CONVERGENCE TOLERANCE                            0.000100000

 FRACTION OF FEED
  SUBSTREAM= MIXED
    STREAM= 23       CPT= WATER     FRACTION=         0.0
                     HYDROGEN                0.0
                     OXYGEN                1.00000
```

```
              *** RESULTS ***

HEAT DUTY          BTU/HR                    -4.2409

COMPONENT = WATER
 STREAM   SUBSTREAM   SPLIT FRACTION
 10       MIXED            1.00000

COMPONENT = HYDROGEN
 STREAM   SUBSTREAM   SPLIT FRACTION
 10       MIXED            1.00000

COMPONENT = OXYGEN
 STREAM   SUBSTREAM   SPLIT FRACTION
 23       MIXED            1.00000

BLOCK:  M-100    MODEL: MIXER
------------------------------
 INLET STREAMS:       12        8
 OUTLET STREAM:        9
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

            *** MASS AND ENERGY BALANCE ***
                       IN          OUT       RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)         48.0449       48.0449        0.00000
   MASS(LB/HR   )       788.695       788.695       0.00000
   ENTHALPY(BTU/HR  )      -0.389629E+07  -0.389629E+07     0.00000

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

BLOCK:  P-100    MODEL: PUMP
----------------------------
 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)         42.7071       42.7071        0.00000
   MASS(LB/HR   )       769.380       769.380       0.00000
   ENTHALPY(BTU/HR  )      -0.530881E+07  -0.530726E+07   -0.292045E-03

              *** INPUT DATA ***
 EQUIPMENT TYPE: PUMP
 OUTLET PRESSURE  PSIA                     214.696
 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	12.3859
PRESSURE CHANGE PSI	199.996
NPSH AVAILABLE FT-LBF/LB	33.3642
FLUID POWER HP	0.18015
BRAKE POWER HP	0.60933
ELECTRICITY KW	0.45438
PUMP EFFICIENCY USED	0.29566
NET WORK REQUIRED HP	0.60933
HEAD DEVELOPED FT-LBF/LB	463.627

BLOCK: R-100 MODEL: RSTOIC

INLET STREAM: 9
OUTLET STREAM: NOTREAL
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	48.0449	67.2595	19.2146	0.211284E-15
MASS(LB/HR)	788.695	788.695		0.00000
ENTHALPY(BTU/HR)	-0.389629E+07	193993.		-1.04979

*** INPUT DATA ***
STOICHIOMETRY MATRIX:

REACTION # 1:
SUBSTREAM MIXED :
WATER -1.00 HYDROGEN 1.00 OXYGEN 0.500

REACTION EXTENT SPECS: NUMBER= 1
REACTION # 1: EXTENT= 38.43 LBMOL/HR

TWO PHASE TP FLASH

SPECIFIED TEMPERATURE F	1,472.00
PRESSURE DROP PSI	0.0
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000
SIMULTANEOUS REACTIONS	
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES	NO

*** RESULTS ***

OUTLET TEMPERATURE F	1472.0
OUTLET PRESSURE PSIA	19.200
HEAT DUTY BTU/HR	0.40903E+07
VAPOR FRACTION	1.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.71552E-01	0.71552E-01	0.71552E-01	MISSING
HYDROGEN	0.64277	0.64277	0.64277	MISSING
OXYGEN	0.28568	0.28568	0.28568	MISSING

BLOCK: S-100 MODEL: FSPLIT

INLET STREAM: 10
OUTLET STREAMS: 11 12
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	48.0449	48.0449	-0.147892E-15
MASS(LB/HR)	173.850	173.850	-0.163484E-15
ENTHALPY(BTU/HR)	-14689.7	-14689.7	0.247655E-15

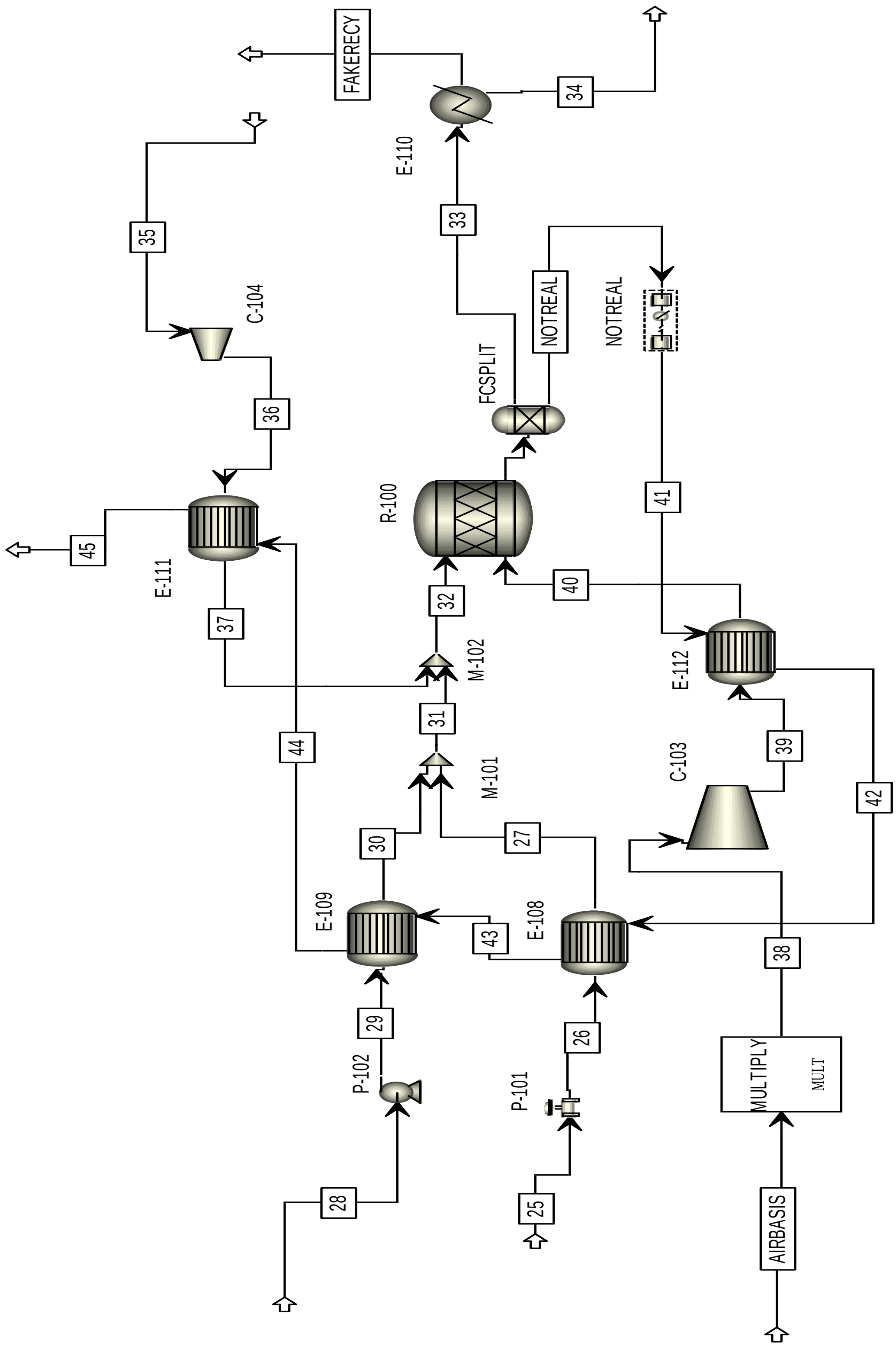
*** INPUT DATA ***

FRACTION OF FLOW STRM=12 FRAC= 0.11110

*** RESULTS ***

STREAM=	SPLIT=	KEY=	STREAM-ORDER=
11	0.88890	0	2
12	0.11110	0	1

ASPEN Results for Hydrogen System – Fuel Cell



STREAM	ID	25	26	27	28	29
FROM	:	----	P-101	E-108	----	P-102
TO	:	P-101	E-108	M-101	P-102	E-109
SUBSTREAM:	MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	LIQUID	LIQUID	
COMPONENTS:	LBMOL/HR					
WATER		0	0	0	4.6985	4.6985
HYDROGEN		42.2785	42.2785	42.2785	0	0
NITROGEN		0	0	0	0	0
OXYGEN		0	0	0	0	0
COMPONENTS:	LB/HR					
WATER		0	0	0	84.6446	84.6446
HYDROGEN		85.2284	85.2284	85.2284	0	0
NITROGEN		0	0	0	0	0
OXYGEN		0	0	0	0	0
TOTAL	FLOW:					
LBMOL/HR		42.2785	42.2785	42.2785	4.6985	4.6985
LB/HR		85.2284	85.2284	85.2284	84.6446	84.6446
CUFT/HR		2435.8733	1.4547+04	2.2140+04	1.3627	1.3627
STATE	VARIABLES:					
TEMP	F	75	75.4035	350	75	75.018
PRES	PSIA	100	16.7	16.6	14.6959	17.6959
VFRAC		1	1	1	0	0
LFRAC		0	0	0	1	1
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		-10.4163	-10.4163	1898.2321	3.7569	3.7569
BTU/LB		-5.1671	-5.1671	941.6394	-6900.1154	-6900.0852
BTU/HR		-440.3871	-440.3871	8.0254+04	-0.8406	-0.8406
ENTROPY:						
BTU/LBMOL-R		-3.8357	-0.2747	2.6147	-40.9705	-40.9699
BTU/LB-R		-1.9027	-0.1363	1.297	-2.2742	-2.2742
DENSITY:						
LBMOL/CUFT		1.7357-02	2.9063-03	1.9096-03	3.448	3.448
LB/CUFT		3.4989-02	5.8588-03	3.8495-03	62.1176	62.117
AVG	MW	2.0159	2.0159	2.0159	18.0153	18.0153

STREAM	ID	30	31	32	33	34
FROM	:	E-109	M-101	M-102	FCSPLIT	E-110
TO	:	M-101	M-102	R-100	E-110	----
SUBSTREAM:	MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	
COMPONENTS:	LBMOL/HR					
WATER		4.6985	4.6985	5.2858	47.5643	46.9784
HYDROGEN		0	42.2785	47.5643	5.2858	0
NITROGEN		0	0	0	0	0
OXYGEN		0	0	0	0	0
COMPONENTS:	LB/HR					
WATER		84.6446	84.6446	95.2252	856.884	846.3299
HYDROGEN		0	85.2284	95.8839	10.6555	0
NITROGEN		0	0	0	0	0
OXYGEN		0	0	0	0	0
TOTAL	FLOW:					
LBMOL/HR		4.6985	46.977	52.8501	52.8501	46.9784
LB/HR		84.6446	169.873	191.1091	867.5396	846.3299
CUFT/HR		2431.3504	2.4590+04	2.7894+04	6.5599+04	13.975
STATE	VARIABLES:					
TEMP	F	350	349.6808	356.3894	1472	180.5008
PRES	PSIA	16.6959	16.6	16.6	16.7	15.2
VFRAC		1	1	1	1	0
LFRAC		0	0	0	0	1
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		3.9823	-8469.9639	-8421.963	-4.1343	3.7898
BTU/LB		-5648.8833	-2342.2988	-2329.0439	-4955.3696	-6717.6923
BTU/HR		0.2185	1.0211	0.549	1.701	0.3146
ENTROPY:						
BTU/LBMOL-R		-7.5258	2.2461	2.3049	1.8251	-35.7959
BTU/LB-R		-0.4177	0.6211	0.6374	0.1112	-1.987
DENSITY:						
LBMOL/CUFT		1.9325-03	1.9104-03	1.8947-03	8.0565-04	3.3616
LB/CUFT		3.4814-02	6.9082-03	6.8513-03	1.3225-02	60.5602
AVG	MW	18.0153	3.6161	3.6161	16.4151	18.0153

STREAM	ID	35	36	37	38	39
FROM	:	----	C-104	E-111	MULTIPLY	C-103
TO	:	C-104	E-111	M-102	C-103	E-112
SUBSTREAM:	MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	
COMPONENTS:	LBMOL/HR					
WATER		0.5873	0.5873	0.5873	0	0
HYDROGEN		5.2858	5.2858	5.2858	0	0
NITROGEN		0	0	0	147.8309	147.8309
OXYGEN		0	0	0	39.2968	39.2968
COMPONENTS:	LB/HR					
WATER		10.5806	10.5806	10.5806	0	0
HYDROGEN		10.6555	10.6555	10.6555	0	0
NITROGEN		0	0	0	4141.2581	4141.2581
OXYGEN		0	0	0	1257.4512	1257.4512
TOTAL	FLOW:					
LBMOL/HR		5.8731	5.8731	5.8731	187.1277	187.1277
LB/HR		21.2361	21.2361	21.2361	5398.7093	5398.7093
CUFT/HR		2655.5828	2507.1521	3283.5819	7.3049+04	5.5975+04
STATE	VARIABLES:					
TEMP	F	180.5	204.3335	410	75	172.7647
PRES	PSIA	15.2	16.7	16.7	14.6959	22.6959
VFRAC		1	1	1	1	1
LFRAC		0	0	0	0	0
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		-9669.0716	-9500.6122	-8038.0209	-16.8436	665.4697
BTU/LB		-2674.102	-2627.5125	-2223.0147	-0.5838	23.0662
BTU/HR		-1.6788	-1.5798	-0.7208	-3151.9107	1.2453+05
ENTROPY:						
BTU/LBMOL-R		0.757	0.8284	2.7469	0.9895	1.2983
BTU/LB-R		0.2094	0.2291	0.7597	3.4297-02	4.5000-02
DENSITY:						
LBMOL/CUFT		2.2116-03	2.3425-03	1.7886-03	2.5617-03	3.3431-03
LB/CUFT		7.9968-03	8.4702-03	6.4674-03	7.3905-02	9.6449-02
AVG	MW	3.6158	3.6158	3.6158	28.8504	28.8504

STREAM	ID	40	41	42	43	44
FROM	:	E-112	NOTREAL	E-112	E-108	E-109
TO	:	R-100	E-112	E-108	E-109	E-111
SUBSTREAM:	MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	
COMPONENTS:	LBMOL/HR					
WATER		0	0	0	0	0
HYDROGEN		0	0	0	0	0
NITROGEN		147.8309	147.8309	147.8309	147.8309	147.8309
OXYGEN		39.2968	18.1576	18.1576	18.1576	18.1576
COMPONENTS:	LB/HR					
WATER		0	0	0	0	0
HYDROGEN		0	0	0	0	0
NITROGEN		4141.2581	4141.2581	4141.2581	4141.2581	4141.2581
OXYGEN		1257.4512	581.0207	581.0207	581.0207	581.0207
TOTAL	FLOW:					
LBMOL/HR		187.1277	165.9885	165.9885	165.9885	165.9885
LB/HR		5398.7093	4722.2788	4722.2788	4722.2788	4722.2788
CUFT/HR		8.5834+04	1.6161+05	1.5400+05	1.5211+05	1.5677+05
STATE	VARIABLES:					
TEMP	F	450	1472	1190.8829	1127.9424	1044.6739
PRES	PSIA	21.2959	21.3	19.1	18.6	17.1
VFRAC		1	1	1	1	1
LFRAC		0	0	0	0	0
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		2625.2681	1.0329+04	8119.3847	7633.2379	6995.1964
BTU/LB		90.9959	363.0571	285.397	268.3089	245.8817
BTU/HR		4.9126+05	1.7145+06	1.3477+06	1.2670+06	1.1611+06
ENTROPY:						
BTU/LBMOL-R		3.9928	9.2882	8.2692	8.0216	7.7758
BTU/LB-R		0.1384	0.3265	0.2907	0.282	0.2733
DENSITY:						
LBMOL/CUFT		2.1801-03	1.0271-03	1.0778-03	1.0912-03	1.0588-03
LB/CUFT		6.2897-02	2.9220-02	3.0664-02	3.1045-02	3.0121-02
AVG	MW	28.8504	28.4494	28.4494	28.4494	28.4494

STREAM	ID	45	AIRBASIS	FAKERECY	FCFAKE	NOTREAL
FROM	:	E-111	----	E-110	R-100	FCSPLIT
TO	:	----	MULTIPLY	----	FCSPLIT	NOTREAL
SUBSTREAM:	MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	
COMPONENTS:	LBMOL/HR					
WATER		0	0	0.5858	47.5643	0
HYDROGEN		0	0	5.2858	5.2858	0
NITROGEN		147.8309	79.5217	0	147.8309	147.8309
OXYGEN		18.1576	21.1387	0	18.1576	18.1576
COMPONENTS:	LB/HR					
WATER		0	0	10.5541	856.884	0
HYDROGEN		0	0	10.6555	10.6555	0
NITROGEN		4141.2581	2227.6805	0	4141.2581	4141.2581
OXYGEN		581.0207	676.4127	0	581.0207	581.0207
TOTAL	FLOW:					
LBMOL/HR		165.9885	100.6604	5.8716	218.8386	165.9885
LB/HR		4722.2788	2904.0932	21.2097	5589.8184	4722.2788
CUFT/HR		1.6077+05	3.9295+04	2654.9234	2.7173+05	2.0611+05
STATE	VARIABLES:					
TEMP	F	1037.8885	75	180.5008	1472	1472
PRES	PSIA	16.6	14.6959	15.2	16.7	16.7
VFRAC		1	1	1	1	1
LFRAC		0	0	0	0	0
SFRAC		0	0	0	0	0
ENTHALPY:						
BTU/LBMOL		6943.446	-16.8436	-9645.6802	2.819	1.0328+04
BTU/LB		244.0627	-0.5838	-2670.2935	-462.3493	363.0441
BTU/HR		1.1525+06	-1695.4872	-1.6636	3.4156	1.7144+06
ENTROPY:						
BTU/LBMOL-R		7.8003	0.9895	0.7584	8.9503	9.7714
BTU/LB-R		0.2742	3.4297-02	0.21	0.3504	0.3435
DENSITY:						
LBMOL/CUFT		1.0325-03	2.5617-03	2.2116-03	8.0537-04	8.0534-04
LB/CUFT		2.9374-02	7.3905-02	7.9888-03	2.0572-02	2.2912-02
AVG	MW	28.4494	28.8504	3.6122	25.5431	28.4494

Block Results – Hydrogen Fuel Cell

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BLOCK:  C-103    MODEL: COMPR
-----------------------------
  INLET STREAM:          38
  OUTLET STREAM:         39
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                *** MASS AND ENERGY BALANCE ***
                           IN          OUT       RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)          187.128       187.128       0.00000
      MASS(LB/HR   )          5398.71       5398.71       0.00000
      ENTHALPY(BTU/HR  )      -3151.91      124528.       -1.02531

                     *** INPUT DATA ***

  ISENTROPIC CENTRIFUGAL COMPRESSOR
   PRESSURE CHANGE  PSI                       8.00000
   ISENTROPIC EFFICIENCY                      0.72000
   MECHANICAL EFFICIENCY                      1.00000

                     *** RESULTS ***

   INDICATED  HORSEPOWER REQUIREMENT  HP              50.1800
   BRAKE      HORSEPOWER REQUIREMENT  HP              50.1800
   NET WORK REQUIRED                  HP              50.1800
   POWER LOSSES                       HP              0.0
   ISENTROPIC HORSEPOWER REQUIREMENT  HP              36.1296
   CALCULATED OUTLET PRES  PSIA                       22.6959
   CALCULATED OUTLET TEMP  F                          172.765
   ISENTROPIC TEMPERATURE  F                          145.482
   EFFICIENCY (POLYTR/ISENTR) USED                    0.72000
   OUTLET VAPOR FRACTION                              1.00000
   HEAD DEVELOPED,       FT-LBF/LB                    13,250.7
   MECHANICAL EFFICIENCY USED                         1.00000
   INLET HEAT CAPACITY RATIO                          1.40103
   INLET VOLUMETRIC FLOW RATE , CUFT/HR               73,049.4
   OUTLET VOLUMETRIC FLOW RATE, CUFT/HR               55,974.7
   INLET  COMPRESSIBILITY FACTOR                      0.99985
   OUTLET COMPRESSIBILITY FACTOR                      1.00030
   AV. ISENT. VOL. EXPONENT                           1.39998
   AV. ISENT. TEMP EXPONENT                           1.39844
   AV. ACTUAL VOL. EXPONENT                           1.63244
   AV. ACTUAL TEMP EXPONENT                           1.62968

BLOCK:  C-104    MODEL: COMPR
-----------------------------
  INLET STREAM:          35
  OUTLET STREAM:         36
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

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

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    MOLE(LBMOL/HR)          5.87311        5.87311        0.00000
    MASS(LB/HR   )          21.2361        21.2361        0.00000
    ENTHALPY(BTU/HR  )      -56787.6       -55798.2       -0.174225E-01

                    ***  INPUT DATA  ***

 ISENTROPIC CENTRIFUGAL COMPRESSOR
  PRESSURE CHANGE  PSI                          1.50000
  ISENTROPIC EFFICIENCY                         0.72000
  MECHANICAL EFFICIENCY                         1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  HP                  0.38884
  BRAKE      HORSEPOWER REQUIREMENT  HP                  0.38884
  NET WORK REQUIRED                  HP                  0.38884
  POWER LOSSES                       HP                  0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  HP                  0.27997
  CALCULATED OUTLET PRES  PSIA                           16.7000
  CALCULATED OUTLET TEMP  F                              204.333
  ISENTROPIC TEMPERATURE  F                              197.665
  EFFICIENCY (POLYTR/ISENTR) USED                        0.72000
  OUTLET VAPOR FRACTION                                  1.00000
  HEAD DEVELOPED,       FT-LBF/LB                        26,103.3
  MECHANICAL EFFICIENCY USED                             1.00000
  INLET HEAT CAPACITY RATIO                              1.39229
  INLET VOLUMETRIC FLOW RATE , CUFT/HR                   2,655.58
  OUTLET VOLUMETRIC FLOW RATE, CUFT/HR                   2,507.15
  INLET  COMPRESSIBILITY FACTOR                          1.00042
  OUTLET COMPRESSIBILITY FACTOR                          1.00046
  AV. ISENT. VOL. EXPONENT                               1.39198
  AV. ISENT. TEMP EXPONENT                               1.39110
  AV. ACTUAL VOL. EXPONENT                               1.63628
  AV. ACTUAL TEMP EXPONENT                               1.63505

BLOCK:  E-108    MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:          42
 OUTLET STREAM:         43
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
 COLD SIDE:
 ----------
 INLET STREAM:          26
 OUTLET STREAM:         27
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                            IN          OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          208.267        208.267        0.00000
    MASS(LB/HR   )          4807.51        4807.51        0.00000
    ENTHALPY(BTU/HR  )      0.134728E+07   0.134728E+07   0.00000

                    ***  INPUT DATA  ***
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```
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                   350.0000
  LMTD CORRECTION FACTOR                              1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE PRESSURE DROP       PSI                  0.5000
  COLD SIDE PRESSURE DROP       PSI                  0.1000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R          9.0300

                  ***  OVERALL RESULTS  ***

STREAMS:
              --------------------------------------
              |                            |
42       ----->|             HOT             |-----> 43
T=  1.1909D+03  |                           |      T=  1.1279D+03
P=  1.9100D+01  |                           |      P=  1.8600D+01
V=  1.0000D+00  |                           |      V=  1.0000D+00
              |                            |
27       <-----|             COLD            |<----- 26
T=  3.5000D+02  |                           |      T=  7.5403D+01
P=  1.6600D+01  |                           |      P=  1.6700D+01
V=  1.0000D+00  |                           |      V=  1.0000D+00
              --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            80694.7709
  CALCULATED (REQUIRED) AREA     SQFT                  9.4789
  ACTUAL EXCHANGER AREA         SQFT                  9.4789
  PER CENT OVER-DESIGN                          0.0000

HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R          9.0300
  UA (DIRTY)                  BTU/HR-R            85.5947

LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                            1.0000
  LMTD (CORRECTED)              F                 942.7543
  NUMBER OF SHELLS IN SERIES                         1

PRESSURE DROP:
```

HOTSIDE, TOTAL PSI 0.5000
COLDSIDE, TOTAL PSI 0.1000

PRESSURE DROP PARAMETER:
HOT SIDE: 4812.6
COLD SIDE: 0.44499E+06

BLOCK: E-109 MODEL: HEATX

HOT SIDE:

INLET STREAM: 43
OUTLET STREAM: 44
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE
COLD SIDE:

INLET STREAM: 29
OUTLET STREAM: 30
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	170.687	170.687	0.00000
MASS(LB/HR)	4806.92	4806.92	0.00000
ENTHALPY(BTU/HR)	682974.	682974.	-0.511360E-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 OUTLET TEMP
SPECIFIED VALUE F 350.0000
LMTD CORRECTION FACTOR 1.00000

PRESSURE SPECIFICATION:
HOT SIDE PRESSURE DROP PSI 1.5000
COLD SIDE PRESSURE DROP PSI 1.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
OVERALL COEFFICIENT BTU/HR-SQFT-R 20.6200

*** OVERALL RESULTS ***

STREAMS:

```
          |                         |
43      ----->|          HOT            |-----> 44
T=  1.1279D+03  |                       |      T=  1.0447D+03
P=  1.8600D+01  |                       |      P=  1.7100D+01
V=  1.0000D+00  |                       |      V=  1.0000D+00
          |                         |
30      <-----|          COLD           |<----- 29
T=  3.5000D+02  |                       |      T=  7.5018D+01
P=  1.6696D+01  |                       |      P=  1.7696D+01
V=  1.0000D+00  |                       |      V=  0.0000D+00
          -------------------------------------

DUTY AND AREA:
 CALCULATED HEAT DUTY          BTU/HR           105907.5437
 CALCULATED (REQUIRED) AREA    SQFT                  5.9017
 ACTUAL EXCHANGER AREA         SQFT                  5.9017
 PER CENT OVER-DESIGN                                0.0000

HEAT TRANSFER COEFFICIENT:
 AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R        20.6200
 UA (DIRTY)                    BTU/HR-R            121.6933

LOG-MEAN TEMPERATURE DIFFERENCE:
 LMTD CORRECTION FACTOR                              1.0000
 LMTD (CORRECTED)              F                   870.2826
 NUMBER OF SHELLS IN SERIES                           1

PRESSURE DROP:
 HOTSIDE, TOTAL                PSI                   1.5000
 COLDSIDE, TOTAL               PSI                   1.0000

PRESSURE DROP PARAMETER:
 HOT SIDE:                                  14308.
 COLD SIDE:                                 0.67570E+08

BLOCK:  E-110    MODEL: HEATER
------------------------------
 INLET STREAM:          33
 OUTLET STREAM:         FAKERECY
 OUTLET WATER STREAM:   34
 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)          52.8501        52.8501        0.00000
    MASS(LB/HR   )          867.540        867.540        0.00000
    ENTHALPY(BTU/HR  )     -0.429898E+07  -0.574202E+07   0.251312

              ***  INPUT DATA  ***
 TWO    PHASE  PV  FLASH
 FREE WATER CONSIDERED
 PRESSURE DROP                 PSI                   1.50000
 VAPOR FRACTION                                      0.11110
```

MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

OUTLET TEMPERATURE F 180.50
OUTLET PRESSURE PSIA 15.200
HEAT DUTY BTU/HR -0.14430E+07
OUTLET VAPOR FRACTION 0.11110
OUTLET: 1ST LIQUID/TOTAL LIQUID 0.0000
PRESSURE-DROP CORRELATION PARAMETER 0.35239E+06

V-L1-L2 PHASE EQUILIBRIUM :

COMP	F(I)	X1(I)	X2(I)	Y(I)	K1(I)	K2(I)
WATER	0.900	1.00	1.00	0.998E-01	0.431	0.998E-01
HYDROGEN	0.100	0.252E-05	0.00	0.900	0.154E+07	

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER U-1
RATE OF CONSUMPTION 4.8264+04 LB/HR
COST 0.4346 $/HR

BLOCK: E-111 MODEL: HEATX

HOT SIDE:

INLET STREAM: 44
OUTLET STREAM: 45
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE
COLD SIDE:

INLET STREAM: 36
OUTLET STREAM: 37
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	171.862	171.862	0.00000
MASS(LB/HR)	4743.51	4743.51	0.00000
ENTHALPY(BTU/HR)	0.110532E+07	0.110532E+07	0.210645E-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 OUTLET TEMP
  SPECIFIED VALUE              F              410.0000
  LMTD CORRECTION FACTOR                         1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE PRESSURE DROP       PSI              0.5000
  COLD SIDE PRESSURE DROP       PSI              0.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R          7.0800

                 ***  OVERALL RESULTS  ***

STREAMS:
            --------------------------------------
            |                             |
44       ----->|            HOT             |-----> 45
T=  1.0447D+03  |                         |      T=  1.0379D+03
P=  1.7100D+01  |                         |      P=  1.6600D+01
V=  1.0000D+00  |                         |      V=  1.0000D+00
            |                             |
37       <-----|            COLD            |<----- 36
T=  4.1000D+02  |                         |      T=  2.0433D+02
P=  1.6700D+01  |                         |      P=  1.6700D+01
V=  1.0000D+00  |                         |      V=  1.0000D+00
            --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            8589.9667
  CALCULATED (REQUIRED) AREA     SQFT                  1.6629
  ACTUAL EXCHANGER AREA          SQFT                  1.6629
  PER CENT OVER-DESIGN                           0.0000

HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R          7.0800
  UA (DIRTY)                  BTU/HR-R           11.7735

LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                         1.0000
  LMTD (CORRECTED)             F               729.6023
  NUMBER OF SHELLS IN SERIES                      1

PRESSURE DROP:
  HOTSIDE, TOTAL              PSI              0.5000
  COLDSIDE, TOTAL              PSI              0.0000

PRESSURE DROP PARAMETER:
  HOT SIDE:                          4639.4
  COLD SIDE:                          0.0000

BLOCK:  E-112    MODEL: HEATX
```

```
------------------------------
 HOT SIDE:
 ---------
 INLET STREAM:          41
 OUTLET STREAM:         42
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE
 COLD SIDE:
 ----------
 INLET STREAM:          39
 OUTLET STREAM:         40
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                          IN             OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)           353.116        353.116        0.00000
    MASS(LB/HR   )           10121.0        10121.0        0.00000
    ENTHALPY(BTU/HR  )       0.183898E+07    0.183898E+07     0.00000

                   ***  INPUT DATA  ***

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

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

 FLOW DIRECTION AND SPECIFICATION:
   COUNTERCURRENT   HEAT EXCHANGER
   SPECIFIED COLD OUTLET TEMP
   SPECIFIED VALUE              F                450.0000
   LMTD CORRECTION FACTOR                              1.00000

 PRESSURE SPECIFICATION:
   HOT  SIDE PRESSURE DROP       PSI                  2.2000
   COLD SIDE PRESSURE DROP       PSI                  1.4000

 HEAT TRANSFER COEFFICIENT SPECIFICATION:
   OVERALL COEFFICIENT          BTU/HR-SQFT-R          14.4300

                  ***  OVERALL RESULTS  ***

 STREAMS:
               --------------------------------------
               |                            |
 41       ----->|              HOT              |-----> 42
 T=  1.4720D+03  |                            |      T=  1.1909D+03
 P=  2.1300D+01  |                            |      P=  1.9100D+01
 V=  1.0000D+00  |                            |      V=  1.0000D+00
               |                            |
 40       <-----|              COLD             |<----- 39
 T=  4.5000D+02  |                            |      T=  1.7276D+02
```

```
P=  2.1296D+01  |                         |      P=  2.2696D+01
V=  1.0000D+00  |                         |      V=  1.0000D+00
           -------------------------------------

DUTY AND AREA:
 CALCULATED HEAT DUTY          BTU/HR            366732.6066
 CALCULATED (REQUIRED) AREA     SQFT                  24.9149
 ACTUAL EXCHANGER AREA         SQFT                  24.9149
 PER CENT OVER-DESIGN                              0.0000

HEAT TRANSFER COEFFICIENT:
 AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R         14.4300
 UA (DIRTY)                  BTU/HR-R            359.5214

LOG-MEAN TEMPERATURE DIFFERENCE:
 LMTD CORRECTION FACTOR                            1.0000
 LMTD (CORRECTED)              F                1020.0579
 NUMBER OF SHELLS IN SERIES                            1

PRESSURE DROP:
 HOTSIDE, TOTAL               PSI                 2.2000
 COLDSIDE, TOTAL               PSI                 1.4000

PRESSURE DROP PARAMETER:
 HOT SIDE:                               20538.
 COLD SIDE:                               25444.

BLOCK:  FCSPLIT  MODEL: SEP
---------------------------
 INLET STREAM:          FCFAKE
 OUTLET STREAMS:        33          NOTREAL
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                         IN             OUT       RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)           218.839        218.839        0.00000
   MASS(LB/HR   )           5589.82        5589.82       -0.162706E-15
   ENTHALPY(BTU/HR  )      -0.258445E+07   -0.258458E+07    0.523891E-04


                 ***  INPUT DATA  ***

FLASH SPECS FOR STREAM 33
TWO    PHASE  TP  FLASH
PRESSURE DROP         PSI                        0.0
MAXIMUM NO. ITERATIONS                               30
CONVERGENCE TOLERANCE                                  0.000100000

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

FRACTION OF FEED
```

```
  SUBSTREAM= MIXED
    STREAM= 33       CPT= WATER     FRACTION=         1.00000
                     HYDROGEN                1.00000
                     NITROGEN               0.0
                     OXYGEN                 0.0


                  ***  RESULTS  ***

 HEAT DUTY           BTU/HR                        -135.40

 COMPONENT = WATER
  STREAM     SUBSTREAM    SPLIT FRACTION
  33         MIXED               1.00000

 COMPONENT = HYDROGEN
  STREAM     SUBSTREAM    SPLIT FRACTION
  33         MIXED               1.00000

 COMPONENT = NITROGEN
  STREAM     SUBSTREAM    SPLIT FRACTION
  NOTREAL    MIXED               1.00000

 COMPONENT = OXYGEN
  STREAM     SUBSTREAM    SPLIT FRACTION
  NOTREAL    MIXED               1.00000

BLOCK:  M-101    MODEL: MIXER
-----------------------------
 INLET STREAMS:        30        27
 OUTLET STREAM:        31
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                          IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          46.9770        46.9770        0.00000
    MASS(LB/HR   )          169.873        169.873      -0.167312E-15
    ENTHALPY(BTU/HR  )       -397893.       -397893.        0.146290E-15

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

BLOCK:  M-102    MODEL: MIXER
-----------------------------
 INLET STREAMS:        31        37
 OUTLET STREAM:        32
 PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                          IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          52.8501        52.8501        0.00000
```

```
    MASS(LB/HR   )          191.109        191.109       0.148720E-15
    ENTHALPY(BTU/HR  )       -445102.       -445102.       -0.261548E-15

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

BLOCK:  MULTIPLY MODEL: MULT
----------------------------
  INLET STREAM:         AIRBASIS
  OUTLET STREAM:         38

                   ***  INPUT DATA  ***
  MULTIPLICATION FACTOR:  1.8590

BLOCK:  NOTREAL  MODEL: MCOMPR
------------------------------
  INLET STREAMS:    NOTREAL      TO STAGE   1
  OUTLET STREAMS:   41         FROM STAGE   1
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                         IN            OUT       RELATIVE DIFF.
   TOTAL BALANCE
    MOLE(LBMOL/HR)          165.988        165.988        0.00000
    MASS(LB/HR   )          4722.28        4722.28        0.00000
    ENTHALPY(BTU/HR  )       0.171440E+07    0.171446E+07    -0.358408E-04

                   ***  INPUT DATA  ***

  ISENTROPIC CENTRIFUGAL COMPRESSOR
  NUMBER OF STAGES                                 1
  FINAL PRESSURE, PSIA                            21.3000

             COMPRESSOR SPECIFICATIONS PER STAGE

  STAGE                 MECHANICAL     ISENTROPIC
  NUMBER                  EFFICIENCY     EFFICIENCY


    1                    1.000         0.7200

             COOLER SPECIFICATIONS PER STAGE

  STAGE     PRESSURE DROP     TEMPERATURE
  NUMBER    PSI              F

    1      0.000            1472.

                   ***  RESULTS  ***

  FINAL PRESSURE, PSIA                            21.3000
  TOTAL WORK REQUIRED, HP                              87.2031
  TOTAL COOLING DUTY , BTU/HR                         -221,821.
```

*** PROFILE ***

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE PSIA	PRESSURE RATIO	OUTLET TEMPERATURE F
1	21.30	1.275	1639.

STAGE NUMBER	INDICATED HORSEPOWER HP	BRAKE HORSEPOWER HP
1	87.20	87.20

STAGE NUMBER	HEAD DEVELOPED FT-LBF/LB	VOLUMETRIC FLOW CUFT/HR
1	0.2633E+05	0.2061E+06

COOLER PROFILE

STAGE NUMBER	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	COOLING LOAD BTU/HR	VAPOR FRACTION
1	1472.	21.30	-.2218E+06	1.000

BLOCK: P-101 MODEL: VALVE

INLET STREAM: 25
OUTLET STREAM: 26
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	42.2785	42.2785	0.00000
MASS(LB/HR)	85.2284	85.2284	0.00000
ENTHALPY(BTU/HR)	-440.387	-440.387	0.00000

*** INPUT DATA ***

VALVE OUTLET PRESSURE	PSIA	16.7000
VALVE FLOW COEF CALC.		NO

FLASH SPECIFICATIONS:

NPHASE	2
MAX NUMBER OF ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000

*** RESULTS ***

VALVE PRESSURE DROP	PSI	83.3000

```
BLOCK:  P-102    MODEL: PUMP
----------------------------
  INLET STREAM:          28
  OUTLET STREAM:         29
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                   ***  MASS AND ENERGY BALANCE  ***
                               IN            OUT       RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(LBMOL/HR)           4.69849        4.69849        0.00000
      MASS(LB/HR   )           84.6446        84.6446        0.00000
      ENTHALPY(BTU/HR  )       -584058.       -584055.       -0.438076E-05

                       ***  INPUT DATA  ***
   PRESSURE CHANGE  PSI                              3.00000
   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                          1.36265
   PRESSURE CHANGE  PSI                              3.00000
   NPSH AVAILABLE   FT-LBF/LB                          33.3548
   FLUID POWER  HP                              0.00029731
   BRAKE POWER  HP                               0.0010056
   ELECTRICITY  KW                              0.00074986
   PUMP EFFICIENCY USED                              0.29566
   NET WORK REQUIRED  HP                             0.0010056
   HEAD DEVELOPED FT-LBF/LB                             6.95455

BLOCK:  R-100    MODEL: RSTOIC
------------------------------
  INLET STREAMS:         32         40
  OUTLET STREAM:         FCFAKE
  PROPERTY OPTION SET:   RK-SOAVE  STANDARD RKS EQUATION OF STATE

                   ***  MASS AND ENERGY BALANCE  ***
                          IN         OUT       GENERATION   RELATIVE DIFF.
  TOTAL BALANCE
  MOLE(LBMOL/HR)        239.978       218.839      -21.1392     -0.118435E-15
  MASS(LB/HR   )        5589.82       5589.82                     0.00000
  ENTHALPY(BTU/HR  )     46158.9     -0.258445E+07                1.01786

                       ***  INPUT DATA  ***
  STOICHIOMETRY MATRIX:

   REACTION #   1:
    SUBSTREAM MIXED   :
    WATER      1.00    HYDROGEN  -1.00    OXYGEN   -0.500


  REACTION EXTENT SPECS: NUMBER=    1
```

REACTION # 1: EXTENT= 42.28 LBMOL/HR

TWO PHASE TP FLASH

SPECIFIED TEMPERATURE F	1,472.00
SPECIFIED PRESSURE PSIA	16.7000
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000
SIMULTANEOUS REACTIONS	
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES	NO

*** RESULTS ***

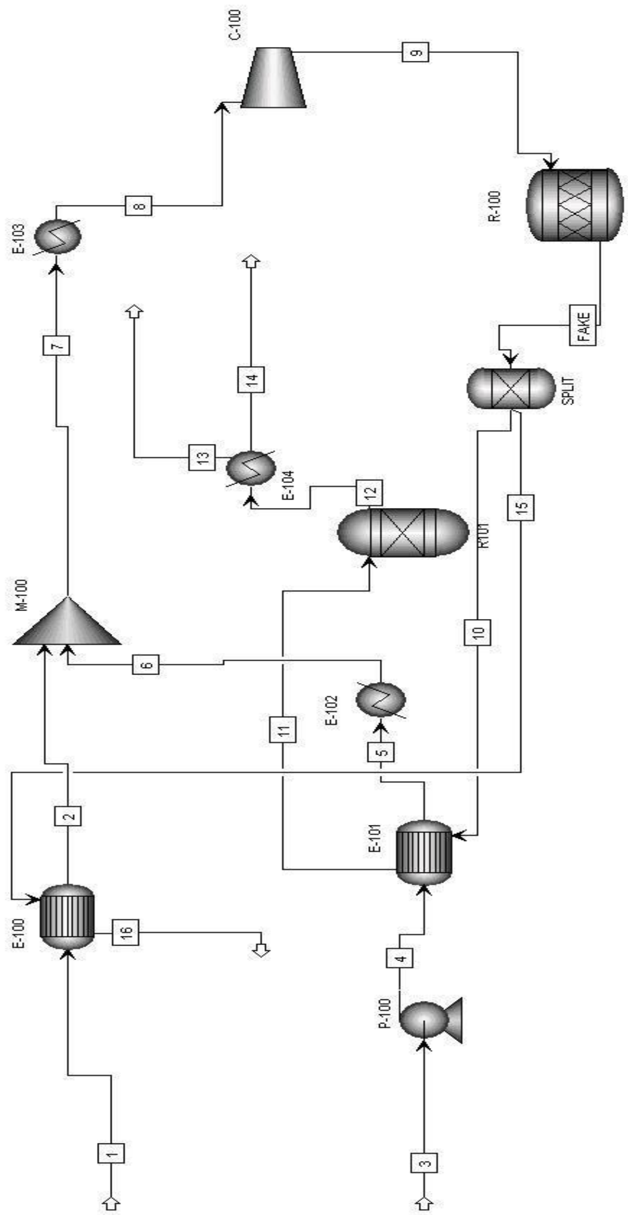
OUTLET TEMPERATURE	F	1472.0
OUTLET PRESSURE	PSIA	16.700
HEAT DUTY	BTU/HR	-0.26306E+07
VAPOR FRACTION		1.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
WATER	0.21735	0.21735	0.21735	MISSING
HYDROGEN	0.24154E-01	0.24154E-01	0.24154E-01	MISSING
NITROGEN	0.67552	0.67552	0.67552	MISSING
OXYGEN	0.82972E-01	0.82972E-01	0.82972E-01	MISSING

Methane System

Electrolysis



1 10 11 12 13

STREAM ID	1	10	11	12	13
FROM :	----	SPLIT	E-101	R101	E-104
TO :	E-100	E-101	R101	E-104	----
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID
COMPONENTS: LBMOL/HR					
HYDROGEN	3.5274	32.1831	32.1831	7.1525-02	0.0
CARBO-01	8.8185	0.8818	0.8818	0.4599	0.0
CARBO-02	2.2046	10.1413	10.1413	1.3373-05	0.0
WATER	0.0	0.8863	0.8863	11.8714	11.7901
METHANE	0.0	0.0	0.0	10.5632	0.0
OXYGEN	0.0	0.0	0.0	0.0	0.0
NITROGEN	0.0	0.0	0.0	0.0	0.0
COMPONENTS: LB/HR					
HYDROGEN	7.1108	64.8772	64.8772	0.1442	0.0
CARBO-01	388.1000	38.8100	38.8100	20.2400	0.0
CARBO-02	61.7524	284.0609	284.0609	3.7457-04	0.0
WATER	0.0	15.9662	15.9662	213.8668	212.4028
METHANE	0.0	0.0	0.0	169.4629	0.0
OXYGEN	0.0	0.0	0.0	0.0	0.0
NITROGEN	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
LBMOL/HR	14.5505	44.0925	44.0925	22.9660	11.7901
LB/HR	456.9632	403.7143	403.7143	403.7143	212.4028
CUFT/HR	587.2702	5651.8064	2656.3688	1435.3881	3.4245
STATE VARIABLES:					
TEMP F	77.0000	1292.0000	200.0000	400.0000	100.0000
PRES PSIA	140.0000	146.9595	145.0000	143.5000	143.5000
VFRAC	1.0000	1.0000	1.0000	1.0000	0.0
LFRAC	0.0	0.0	0.0	0.0	1.0000
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-1.0981+05	-7617.8258	-1.5541+04	-6.9224+04	-1.2246+05
BTU/LB	-3496.5942	-831.9959	-1697.3923	-3937.9458	-6797.7066
BTU/HR	-1.5978+06	-3.3589+05	-6.8526+05	-1.5898+06	-1.4439+06
ENTROPY:					

BTU/LBMOL-R	0.9153	10.0614	3.1356	-13.3226	-38.2146
BTU/LB-R	2.9144-02	1.0989	0.3425	-0.7579	-2.1212
DENSITY:					
LBMOL/CUFT	2.4777-02	7.8015-03	1.6599-02	1.6000-02	3.4428
LB/CUFT	0.7781	7.1431-02	0.1520	0.2813	62.0239
AVG MW	31.4053	9.1561	9.1561	17.5787	18.0153

14 15 16 2 3

STREAM ID	14	15	16	2	3
FROM :	E-104	SPLIT	E-100	E-100	----
TO :	----	E-100	----	M-100	P-100
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID
COMPONENTS: LBMOL/HR					
HYDROGEN	7.1525-02	0.0	0.0	3.5274	0.0
CARBO-01	0.4599	0.0	0.0	8.8185	0.0
CARBO-02	1.3373-05	0.0	0.0	2.2046	0.0
WATER	8.1265-02	0.0	0.0	0.0	29.5419
METHANE	10.5632	0.0	0.0	0.0	0.0
OXYGEN	0.0	18.2962	18.2962	0.0	0.0
NITROGEN	0.0	0.0	0.0	0.0	0.0
COMPONENTS: LB/HR					
HYDROGEN	0.1442	0.0	0.0	7.1108	0.0
CARBO-01	20.2400	0.0	0.0	388.1000	0.0
CARBO-02	3.7457-04	0.0	0.0	61.7524	0.0
WATER	1.4640	0.0	0.0	0.0	532.2064
METHANE	169.4629	0.0	0.0	0.0	0.0
OXYGEN	0.0	585.4553	585.4553	0.0	0.0
NITROGEN	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
LBMOL/HR	11.1759	18.2962	18.2962	14.5505	29.5419
LB/HR	191.3115	585.4553	585.4553	456.9632	532.2064
CUFT/HR	970.5203	2346.5351	2022.3383	1026.1486	8.5457
STATE VARIABLES:					
TEMP F	100.0000	1292.0000	978.2161	440.3300	76.7300
PRES PSIA	143.5000	146.9595	140.0000	137.0000	140.0000
VFRAC	1.0000	1.0000	1.0000	1.0000	0.0
LFRAC	0.0	0.0	0.0	0.0	1.0000

SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-3.7869+04	9362.8943	6792.5139	-1.0658+05	-1.2288+05
BTU/LB	-2212.2291	292.6014	212.2740	-3393.6798	-6820.8941
BTU/HR	-4.2322+05	1.7131+05	1.2428+05	-1.5508+06	-3.6301+06
ENTROPY:					
BTU/LBMOL-R	-21.9259	4.3752	2.8556	5.5365	-38.9766
BTU/LB-R	-1.2808	0.1367	8.9241-02	0.1763	-2.1635
DENSITY:					
LBMOL/CUFT	1.1515-02	7.7971-03	9.0470-03	1.4180-02	3.4569
LB/CUFT	0.1971	0.2495	0.2895	0.4453	62.2777
AVG MW	17.1182	31.9988	31.9988	31.4053	18.0153

4 5 6 7 8

STREAM ID	4	5	6	7	8
FROM :	P-100	E-101	E-102	M-100	E-103
TO :	E-101	E-102	M-100	E-103	C-100

MAX CONV. ERROR:	0.0	0.0	0.0	8.3275-08	0.0
SUBSTREAM: MIXED					
PHASE:	LIQUID	MIXED	VAPOR	VAPOR	VAPOR
COMPONENTS: LBMOL/HR					
HYDROGEN	0.0	0.0	0.0	3.5274	3.5274
CARBO-01	0.0	0.0	0.0	8.8185	8.8185
CARBO-02	0.0	0.0	0.0	2.2046	2.2046
WATER	29.5419	29.5419	29.5419	29.5419	29.5419
METHANE	0.0	0.0	0.0	0.0	0.0
OXYGEN	0.0	0.0	0.0	0.0	0.0
NITROGEN	0.0	0.0	0.0	0.0	0.0
COMPONENTS: LB/HR					
HYDROGEN	0.0	0.0	0.0	7.1108	7.1108
CARBO-01	0.0	0.0	0.0	388.1000	388.1000
CARBO-02	0.0	0.0	0.0	61.7524	61.7524
WATER	532.2064	532.2064	532.2064	532.2064	532.2064
METHANE	0.0	0.0	0.0	0.0	0.0
OXYGEN	0.0	0.0	0.0	0.0	0.0
NITROGEN	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					

LBMOL/HR	29.5419	29.5419	29.5419	44.0925	44.0925
LB/HR	532.2064	532.2064	532.2064	989.1696	989.1696
CUFT/HR	8.5456	767.5455	1749.5683	2779.8194	7048.7253
STATE VARIABLES:					
TEMP F	76.7593	351.5895	351.5907	377.9480	1805.0000
PRES PSIA	144.0000	137.0000	137.0000	137.0000	137.0000
VFRAC	0.0	0.4356	1.0000	1.0000	1.0000
LFRAC	1.0000	0.5644	0.0	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-1.2288+05	-1.1105+05	-1.0222+05	-1.0366+05	-8.9480+04
BTU/LB	-6820.8539	-6164.3925	-5673.8540	-4620.4904	-3988.5757
BTU/HR	-3.6301+06	-3.2807+06	-3.0197+06	-4.5704+06	-3.9454+06
ENTROPY:					
BTU/LBMOL-R	-38.9757	-23.0435	-12.1471	-5.0404	4.7294
BTU/LB-R	-2.1635	-1.2791	-0.6743	-0.2247	0.2108
DENSITY:					
LBMOL/CUFT	3.4570	3.8489-02	1.6885-02	1.5862-02	6.2554-03
LB/CUFT	62.2783	0.6934	0.3042	0.3558	0.1403
AVG MW	18.0153	18.0153	18.0153	22.4340	22.4340

9 FAKE

STREAM ID	9	FAKE
FROM :	C-100	R-100
TO :	R-100	SPLIT
SUBSTREAM: MIXED		
PHASE:	VAPOR	VAPOR
COMPONENTS: LBMOL/HR		
HYDROGEN	3.5274	32.1831
CARBO-01	8.8185	0.8818
CARBO-02	2.2046	10.1413
WATER	29.5419	0.8863
METHANE	0.0	0.0
OXYGEN	0.0	18.2962
NITROGEN	0.0	0.0
COMPONENTS: LB/HR		
HYDROGEN	7.1108	64.8772
CARBO-01	388.1000	38.8100

CARBO-02	61.7524	284.0609
WATER	532.2064	15.9662
METHANE	0.0	0.0
OXYGEN	0.0	585.4553
NITROGEN	0.0	0.0
TOTAL FLOW:		
LBMOL/HR	44.0925	62.3886
LB/HR	989.1696	989.1696
CUFT/HR	6614.1663	7998.4604
STATE VARIABLES:		
TEMP F	1845.7350	1292.0000
PRES PSIA	146.9595	146.9595
VFRAC	1.0000	1.0000
LFRAC	0.0	0.0
SFRAC	0.0	0.0
ENTHALPY:		
BTU/LBMOL	-8.9038+04	-2637.7030
BTU/LB	-3968.9016	-166.3644
BTU/HR	-3.9259+06	-1.6456+05
ENTROPY:		
BTU/LBMOL-R	4.7831	9.5956
BTU/LB-R	0.2132	0.6052
DENSITY:		
LBMOL/CUFT	6.6664-03	7.8001-03
LB/CUFT	0.1496	0.1237
AVG MW	22.4340	15.8550

*** INPUT DATA ***

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

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

FLOW DIRECTION AND SPECIFICATION:
COUNTERCURRENT HEAT EXCHANGER

```
  SPECIFIED MIN OUTLET TEMP APPR
  SPECIFIED VALUE              F                  18.0000
  LMTD CORRECTION FACTOR                           1.00000

 PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE      PSIA              143.0000
  COLD SIDE OUTLET PRESSURE      PSIA              143.2000

 HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R       40.4100




                ***  OVERALL RESULTS  ***

 STREAMS:
            --------------------------------------
            |                                    |
 28   ----->|           HOT                      |-----> 29
 T=  1.5620D+03  |                               |   T=  9.2178D+02
 P=  1.4696D+02  |                               |   P=  1.4300D+02
 V=  1.0000D+00  |                               |   V=  1.0000D+00
            |                                    |
 21   <-----|           COLD                     |<----- 20
 T=  9.0378D+02  |                               |   T=  7.7007D+01
 P=  1.4320D+02  |                               |   P=  1.4796D+02
 V=  1.0000D+00  |                               |   V=  0.0000D+00
            --------------------------------------

 DUTY AND AREA:
  CALCULATED HEAT DUTY           BTU/HR          284986.1148
  CALCULATED (REQUIRED) AREA     SQFT                 9.4331
  ACTUAL EXCHANGER AREA          SQFT                 9.4331
  PER CENT OVER-DESIGN                                0.0000

 HEAT TRANSFER COEFFICIENT:
```

AVERAGE COEFFICIENT (DIRTY) BTU/HR-SQFT-R 40.4100
UA (DIRTY) BTU/HR-R 381.1911

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR 1.0000
LMTD (CORRECTED) F 747.6200
NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:
HOTSIDE, TOTAL PSI 3.9595
COLDSIDE, TOTAL PSI 4.7595

PRESSURE DROP PARAMETER:
HOT SIDE: 0.51164E+07
COLD SIDE: 0.29778E+09

BLOCK: E-107 MODEL: HEATX

HOT SIDE:

INLET STREAM: 33
OUTLET STREAM: 34
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 22
OUTLET STREAM: 23
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	157.311	157.311	0.00000
MASS(LB/HR)	4221.74	4221.74	0.00000
ENTHALPY(BTU/HR)	102724.	102724.	0.198325E-14

*** 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              1472.0000
  LMTD CORRECTION FACTOR                        1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE     PSIA           143.5000
  COLD SIDE OUTLET PRESSURE     PSIA           139.9000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT         BTU/HR-SQFT-R        21.2900

                  ***  OVERALL RESULTS  ***

STREAMS:
             --------------------------------------
             |                            |
33      ----->|          HOT          |-----> 34
T=  1.5620D+03  |                      |      T=  1.3826D+03
P=  1.4696D+02  |                      |      P=  1.4350D+02
V=  1.0000D+00  |                      |      V=  1.0000D+00
             |                            |
23      <-----|          COLD         |<----- 22
T=  1.4720D+03  |                      |      T=  7.9188D+02
P=  1.3990D+02  |                      |      P=  1.4320D+02
V=  1.0000D+00  |                      |      V=  1.0000D+00
             --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR           192974.4104
  CALCULATED (REQUIRED) AREA    SQFT                 34.0610
  ACTUAL EXCHANGER AREA         SQFT                 34.0610
  PER CENT OVER-DESIGN                            0.0000
```

HEAT TRANSFER COEFFICIENT:
AVERAGE COEFFICIENT (DIRTY) BTU/HR-SQFT-R 21.2900
UA (DIRTY) BTU/HR-R 725.1580

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR 1.0000
LMTD (CORRECTED) F 266.1136
NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:
HOTSIDE, TOTAL PSI 3.4595
COLDSIDE, TOTAL PSI 3.3000

PRESSURE DROP PARAMETER:
HOT SIDE: 0.32436E+06
COLD SIDE: 0.22263E+08

BLOCK: E-108 MODEL: HEATER

INLET STREAM: 30
OUTLET STREAM: 31
OUTLET WATER STREAM: 32
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
FREE WATER OPTION SET: SYSOP12 ASME STEAM TABLE
SOLUBLE WATER OPTION: THE MAIN PROPERTY OPTION SET (SRK).

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	43.7245	43.7245	0.00000
MASS(LB/HR)	999.331	999.331	0.113763E-15
ENTHALPY(BTU/HR)	-0.451367E+07	-0.529325E+07	0.147278

*** INPUT DATA ***
TWO PHASE TP FLASH
FREE WATER CONSIDERED
SPECIFIED TEMPERATURE F 100.000
SPECIFIED PRESSURE PSIA 140.000
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***

OUTLET TEMPERATURE	F	100.00
OUTLET PRESSURE	PSIA	140.00
HEAT DUTY	BTU/HR	-0.77958E+06
OUTLET VAPOR FRACTION		0.33922
OUTLET: 1ST LIQUID/TOTAL LIQUID		0.0000
PRESSURE-DROP CORRELATION PARAMETER		0.0000

V-L1-L2 PHASE EQUILIBRIUM :

COMP	F(I)	X1(I)	X2(I)	Y(I)	K1(I)	K2(I)
HYDROGEN	0.846E-01	0.205E-01	0.00	0.249	75.5	
CARBO-01	0.230	0.853	0.00	0.677	4.93	
CARBO-02	0.225E-01	0.131E-01	0.00	0.664E-01	31.5	
WATER	0.663	0.113	1.00	0.746E-02	0.410	0.746E-02

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER U-1
RATE OF CONSUMPTION 2.6074+04 LB/HR
COST 0.2365 $/HR

BLOCK: E-109 MODEL: HEATX

HOT SIDE:

INLET STREAM: 34
OUTLET STREAM: 35
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 26
OUTLET STREAM: 27
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	289.429	289.429	0.00000
MASS(LB/HR)	8289.65	8289.65	0.00000
ENTHALPY(BTU/HR)	0.205141E+07	0.205141E+07	0.226995E-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 MIN OUTLET TEMP APPR
SPECIFIED VALUE F 18.0000
LMTD CORRECTION FACTOR 1.00000

PRESSURE SPECIFICATION:
HOT SIDE OUTLET PRESSURE PSIA 140.5000
COLD SIDE OUTLET PRESSURE PSIA 147.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
OVERALL COEFFICIENT BTU/HR-SQFT-R 29.4300

*** OVERALL RESULTS ***

STREAMS:

```
            -------------------------------------
            |                          |
34    ----->|          HOT             |-----> 35
T=  1.3826D+03  |                      |    T=  1.0631D+03
P=  1.4350D+02  |                      |    P=  1.4050D+02
V=  1.0000D+00  |                      |    V=  1.0000D+00
            |                          |
```

```
27      <-----|          COLD          |<----- 26
T=  1.0451D+03  |                       |      T=  7.5751D+02
P=  1.4700D+02  |                       |      P=  1.5000D+02
V=  1.0000D+00  |                       |      V=  1.0000D+00
              --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR          335565.2889
  CALCULATED (REQUIRED) AREA    SQFT                35.4925
  ACTUAL EXCHANGER AREA         SQFT                35.4925
  PER CENT OVER-DESIGN                               0.0000

HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R       29.4300
  UA (DIRTY)                    BTU/HR-R          1044.5432

LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                             1.0000
  LMTD (CORRECTED)              F                  321.2555
  NUMBER OF SHELLS IN SERIES                              1

PRESSURE DROP:
  HOTSIDE, TOTAL                PSI                  3.0000
  COLDSIDE, TOTAL               PSI                  3.0000

PRESSURE DROP PARAMETER:
  HOT SIDE:                                     0.31584E+06
  COLD SIDE:                                    0.30727E+06

BLOCK:  M-101    MODEL: MIXER
------------------------------
 INLET STREAMS:        18        21
 OUTLET STREAM:        22
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                          IN          OUT        RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)          22.2053       22.2053       0.00000
   MASS(LB/HR   )          384.388       384.388       0.00000
   ENTHALPY(BTU/HR  )   -0.139030E+07  -0.139030E+07  0.167468E-15
```

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

BLOCK:  P-101    MODEL: PUMP
----------------------------
 INLET STREAM:         19
 OUTLET STREAM:        20
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

            ***  MASS AND ENERGY BALANCE  ***
                          IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          11.0231        11.0231        0.00000
    MASS(LB/HR   )          198.584        198.584        0.00000
    ENTHALPY(BTU/HR  )     -0.135447E+07   -0.135446E+07   -0.147350E-05

              ***  INPUT DATA  ***
  PRESSURE CHANGE  PSI                       1.00000
  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              3.18875
  PRESSURE CHANGE  PSI                       1.00000
  NPSH AVAILABLE   FT-LBF/LB                 339.175
  FLUID POWER  HP                            0.00023191
  BRAKE POWER  HP                            0.00078438
  ELECTRICITY  KW                            0.00058491
  PUMP EFFICIENCY USED                       0.29566
  NET WORK REQUIRED  HP                      0.00078438
  HEAD DEVELOPED FT-LBF/LB                   2.31226
```

BLOCK: R-100 MODEL: RSTOIC

INLET STREAMS: FAKE1 27
OUTLET STREAM: FAKE2
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	198.048	178.830	-19.2177	0.00000
MASS(LB/HR)	4836.68	4836.68		0.00000
ENTHALPY(BTU/HR)	934314.	-0.265712E+07		1.35163

*** INPUT DATA ***
STOICHIOMETRY MATRIX:

REACTION # 1:
SUBSTREAM MIXED :
HYDROGEN -2.00 WATER 2.00 OXYGEN -1.00

REACTION # 2:
SUBSTREAM MIXED :
CARBO-01 2.00 CARBO-02 -2.00 OXYGEN -1.00

REACTION EXTENT SPECS: NUMBER= 2
REACTION # 1: EXTENT= 14.33 LBMOL/HR
REACTION # 2: EXTENT= 4.888 LBMOL/HR

TWO PHASE TP FLASH	
SPECIFIED TEMPERATURE F	1,562.00
SPECIFIED PRESSURE PSIA	146.959
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000
SIMULTANEOUS REACTIONS	
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES	NO

*** RESULTS ***

OUTLET TEMPERATURE F 1562.0
OUTLET PRESSURE PSIA 146.96
HEAT DUTY BTU/HR -0.35914E+07
VAPOR FRACTION 1.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
HYDROGEN	0.20680E-01	0.20680E-01	0.20680E-01	MISSING
CARBO-01	0.56136E-01	0.56136E-01	0.56136E-01	MISSING
CARBO-02	0.55043E-02	0.55043E-02	0.55043E-02	MISSING
WATER	0.16218	0.16218	0.16218	MISSING
OXYGEN	0.73758E-01	0.73758E-01	0.73758E-01	MISSING
NITROGEN	0.68174	0.68174	0.68174	MISSING

BLOCK: REFORMER MODEL: RSTOIC

INLET STREAM: 24
OUTLET STREAM: FAKE1
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	22.2053	43.7245	21.5193	0.00000
MASS(LB/HR)	384.388	384.388		-0.147880E-15
ENTHALPY(BTU/HR)	-0.119148E+07	-152618.		-0.871909

*** INPUT DATA ***
STOICHIOMETRY MATRIX:

REACTION # 1:
SUBSTREAM MIXED :
HYDROGEN 3.00 CARBO-02 1.00 WATER -1.00 METHANE -1.00

REACTION CONVERSION SPECS: NUMBER= 1
REACTION # 1:
SUBSTREAM:MIXED KEY COMP:METHANE CONV FRAC: 1.000

TWO PHASE TP FLASH

SPECIFIED TEMPERATURE F	1,472.00
SPECIFIED PRESSURE PSIA	146.959
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000
SIMULTANEOUS REACTIONS	
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES	NO

*** RESULTS ***

OUTLET TEMPERATURE	F	1472.0
OUTLET PRESSURE	PSIA	146.96
HEAT DUTY	BTU/HR	0.10389E+07
VAPOR FRACTION		1.0000

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT LBMOL/HR
1	10.760

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
HYDROGEN	0.74005	0.74005	0.74005	MISSING
CARBO-01	0.60259E-02	0.60259E-02	0.60259E-02	MISSING
CARBO-02	0.24608	0.24608	0.24608	MISSING
WATER	0.78449E-02	0.78449E-02	0.78449E-02	MISSING

BLOCK: SEP MODEL: SEP

INLET STREAM: FAKE2

OUTLET STREAMS: 33 28

PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	178.830	178.830	0.00000
MASS(LB/HR)	4836.68	4836.68	0.00000
ENTHALPY(BTU/HR)	-0.265712E+07	-0.265715E+07	0.981577E-05

*** INPUT DATA ***

FLASH SPECS FOR STREAM 33
TWO PHASE TP FLASH
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

FLASH SPECS FOR STREAM 28
TWO PHASE TP FLASH
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

FRACTION OF FEED
SUBSTREAM= MIXED
STREAM= 33 CPT= OXYGEN FRACTION= 1.00000
NITROGEN 1.00000

*** RESULTS ***

HEAT DUTY BTU/HR -26.082

COMPONENT = HYDROGEN

STREAM	SUBSTREAM	SPLIT FRACTION
28	MIXED	1.00000

COMPONENT = CARBO-01

STREAM	SUBSTREAM	SPLIT FRACTION
28	MIXED	1.00000

COMPONENT = CARBO-02

```
  STREAM     SUBSTREAM    SPLIT FRACTION
  28         MIXED              1.00000

 COMPONENT = WATER
  STREAM     SUBSTREAM    SPLIT FRACTION
  28         MIXED              1.00000

 COMPONENT = OXYGEN
  STREAM     SUBSTREAM    SPLIT FRACTION
  33         MIXED              1.00000

 COMPONENT = NITROGEN
  STREAM     SUBSTREAM    SPLIT FRACTION
  33         MIXED              1.00000

BLOCK:  T-100    MODEL: COMPR
-----------------------------
 INLET STREAM:         35
 OUTLET STREAM:        36
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                         IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          135.106        135.106        0.00000
    MASS(LB/HR   )          3837.35        3837.35        0.00000
    ENTHALPY(BTU/HR  )       964482.        465398.       0.517464

                    ***  INPUT DATA  ***

 ISENTROPIC TURBINE
  OUTLET PRESSURE  PSIA                          14.6959
  ISENTROPIC EFFICIENCY                           0.72000
  MECHANICAL EFFICIENCY                           1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  HP              -196.148
  BRAKE      HORSEPOWER REQUIREMENT  HP              -196.148
  NET WORK REQUIRED                 HP              -196.148
  POWER LOSSES                      HP               0.0
```

ISENTROPIC HORSEPOWER REQUIREMENT HP	-272.427
CALCULATED OUTLET TEMP F	565.743
ISENTROPIC TEMPERATURE F	364.052
EFFICIENCY (POLYTR/ISENTR) USED	0.72000
OUTLET VAPOR FRACTION	1.00000
HEAD DEVELOPED, FT-LBF/LB	-140,567.
MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.35217
INLET VOLUMETRIC FLOW RATE , CUFT/HR	15,769.5
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR	101,212.
INLET COMPRESSIBILITY FACTOR	1.00356
OUTLET COMPRESSIBILITY FACTOR	1.00046
AV. ISENT. VOL. EXPONENT	1.37652
AV. ISENT. TEMP EXPONENT	1.37391
AV. ACTUAL VOL. EXPONENT	1.21434
AV. ACTUAL TEMP EXPONENT	1.21233

BLOCK: C-100 MODEL: COMPR

INLET STREAM: 8
OUTLET STREAM: 9
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	44.0925	44.0925	0.00000
MASS(LB/HR)	989.170	989.170	0.00000
ENTHALPY(BTU/HR)	-0.394538E+07	-0.392592E+07	-0.493260E-02

*** INPUT DATA ***

ISENTROPIC CENTRIFUGAL COMPRESSOR

OUTLET PRESSURE PSIA	146.959
ISENTROPIC EFFICIENCY	0.72000
MECHANICAL EFFICIENCY	1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP	7.64845
BRAKE HORSEPOWER REQUIREMENT HP	7.64845
NET WORK REQUIRED HP	7.64845
POWER LOSSES HP	0.0

ISENTROPIC HORSEPOWER REQUIREMENT HP	5.50688
CALCULATED OUTLET TEMP F	1,845.74
ISENTROPIC TEMPERATURE F	1,834.39
EFFICIENCY (POLYTR/ISENTR) USED	0.72000
OUTLET VAPOR FRACTION	1.00000
HEAD DEVELOPED, FT-LBF/LB	11,023.0
MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.02254
INLET VOLUMETRIC FLOW RATE , CUFT/HR	7,048.73
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR	6,614.17
INLET COMPRESSIBILITY FACTOR	0.90117
OUTLET COMPRESSIBILITY FACTOR	0.89106
AV. ISENT. VOL. EXPONENT	1.07207
AV. ISENT. TEMP EXPONENT	1.22507
AV. ACTUAL VOL. EXPONENT	1.10282
AV. ACTUAL TEMP EXPONENT	1.34055

BLOCK: E-100 MODEL: HEATX

HOT SIDE:

INLET STREAM: 15
OUTLET STREAM: 16
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 1
OUTLET STREAM: 2
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	32.8467	32.8467	0.00000
MASS(LB/HR)	1042.42	1042.42	0.00000
ENTHALPY(BTU/HR)	-0.142651E+07	-0.142651E+07	0.00000

*** INPUT DATA ***

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

FLASH SPECS FOR COLD SIDE:
TWO PHASE FLASH

```
MAXIMUM NO. ITERATIONS                          30
CONVERGENCE TOLERANCE                            0.000100000

FLOW DIRECTION AND SPECIFICATION:
  COUNTERCURRENT   HEAT EXCHANGER
  SPECIFIED COLD OUTLET TEMP
  SPECIFIED VALUE              F              440.3300
  LMTD CORRECTION FACTOR                          1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE     PSIA              140.0000
  COLD SIDE OUTLET PRESSURE     PSIA              137.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT        BTU/HR-SQFT-R        21.2600

                  ***  OVERALL RESULTS  ***

STREAMS:
              --------------------------------------
              |                                    |
15       ----->|             HOT                   |-----> 16
T=  1.2920D+03  |                                  |      T=  9.7822D+02
P=  1.4696D+02  |                                  |      P=  1.4000D+02
V=  1.0000D+00  |                                  |      V=  1.0000D+00
              |                                    |
2        <-----|             COLD                  |<----- 1
T=  4.4033D+02  |                                  |      T=  7.7000D+01
P=  1.3700D+02  |                                  |      P=  1.4000D+02
V=  1.0000D+00  |                                  |      V=  1.0000D+00
              --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            47028.0992
  CALCULATED (REQUIRED) AREA    SQFT                  2.5246
  ACTUAL EXCHANGER AREA         SQFT                  2.5246
  PER CENT OVER-DESIGN                            0.0000

HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R        21.2600
  UA (DIRTY)                   BTU/HR-R          53.6722

LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                          1.0000
  LMTD (CORRECTED)             F              876.2096
  NUMBER OF SHELLS IN SERIES                        1
```

```
 PRESSURE DROP:
  HOTSIDE, TOTAL            PSI                 6.9595
  COLDSIDE, TOTAL           PSI                 3.0000

 PRESSURE DROP PARAMETER:
  HOT SIDE:                              0.37858E+08
  COLD SIDE:                             0.56616E+08

BLOCK:  E-101    MODEL: HEATX
-----------------------------
 HOT SIDE:
 ---------
 INLET STREAM:        10
 OUTLET STREAM:       11
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE
 COLD SIDE:
 ----------
 INLET STREAM:        4
 OUTLET STREAM:       5
 PROPERTY OPTION SET:   SRK      SOAVE-REDLICH-KWONG EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                       IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          73.6344       73.6344       0.00000
    MASS(LB/HR   )         935.921       935.921       0.00000
    ENTHALPY(BTU/HR  )     -0.396599E+07   -0.396599E+07     0.00000

                ***  INPUT DATA  ***

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

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

 FLOW DIRECTION AND SPECIFICATION:
  COUNTERCURRENT   HEAT EXCHANGER
  SPECIFIED HOT OUTLET TEMP
  SPECIFIED VALUE            F               200.0000
  LMTD CORRECTION FACTOR                          1.00000
```

```
PRESSURE SPECIFICATION:
 HOT  SIDE OUTLET PRESSURE      PSIA                  145.0000
 COLD SIDE OUTLET PRESSURE      PSIA                  137.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
 OVERALL COEFFICIENT            BTU/HR-SQFT-R          57.8900

              ***  OVERALL RESULTS  ***

STREAMS:
          --------------------------------------
          |                             |
10    ----->|          HOT              |-----> 11
T=  1.2920D+03  |                       |    T=  2.0000D+02
P=  1.4696D+02  |                       |    P=  1.4500D+02
V=  1.0000D+00  |                       |    V=  1.0000D+00
          |                             |
5     <-----|          COLD             |<----- 4
T=  3.5159D+02  |                       |    T=  7.6759D+01
P=  1.3700D+02  |                       |    P=  1.4400D+02
V=  4.3561D-01  |                       |    V=  0.0000D+00
          --------------------------------------

DUTY AND AREA:
 CALCULATED HEAT DUTY           BTU/HR            349372.9194
 CALCULATED (REQUIRED) AREA     SQFT                  15.0084
 ACTUAL EXCHANGER AREA          SQFT                  15.0084
 PER CENT OVER-DESIGN                                  0.0000

HEAT TRANSFER COEFFICIENT:
 AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R          57.8900
 UA (DIRTY)                     BTU/HR-R              868.8375

LOG-MEAN TEMPERATURE DIFFERENCE:
 LMTD CORRECTION FACTOR                                1.0000
 LMTD (CORRECTED)               F                     402.1154
 NUMBER OF SHELLS IN SERIES                                 1

PRESSURE DROP:
 HOTSIDE, TOTAL                 PSI                    1.9595
 COLDSIDE, TOTAL                PSI                    7.0000

PRESSURE DROP PARAMETER:
 HOT SIDE:                                        0.81284E+07
 COLD SIDE:                                       0.23580E+09
```

```
BLOCK:  E-102    MODEL: HEATER
------------------------------
 INLET STREAM:          5
 OUTLET STREAM:         6
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                        IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          29.5419        29.5419        0.00000
    MASS(LB/HR   )          532.206        532.206        0.00000
    ENTHALPY(BTU/HR  )     -0.328073E+07  -0.301966E+07   -0.795761E-01

                 ***  INPUT DATA  ***
 TWO    PHASE  PV  FLASH
 SPECIFIED PRESSURE                PSIA                 137.000
 VAPOR FRACTION                                        1.00000
 MAXIMUM NO. ITERATIONS                                   30
 CONVERGENCE TOLERANCE                                     0.000100000



                  ***  RESULTS  ***
 OUTLET TEMPERATURE    F                            351.59
 OUTLET PRESSURE       PSIA                        137.00
 HEAT DUTY             BTU/HR                    0.26107E+06
 OUTLET VAPOR FRACTION                                1.0000
 PRESSURE-DROP CORRELATION PARAMETER                       0.0000



 V-L PHASE EQUILIBRIUM :

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

              ***  ASSOCIATED  UTILITIES  ***

 UTILITY ID FOR GAS                     U-6
 RATE OF CONSUMPTION                      12.2215  LB/HR
 COST                             0.9211  $/HR

BLOCK:  E-103    MODEL: HEATER
------------------------------
 INLET STREAM:          7
```

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

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	44.0925	44.0925	0.00000
MASS(LB/HR)	989.170	989.170	0.229863E-15
ENTHALPY(BTU/HR)	-0.457045E+07	-0.394538E+07	-0.136764

*** INPUT DATA ***

TWO PHASE TP FLASH

SPECIFIED TEMPERATURE	F	1,805.00
SPECIFIED PRESSURE	PSIA	137.000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

*** RESULTS ***

OUTLET TEMPERATURE	F	1805.0
OUTLET PRESSURE	PSIA	137.00
HEAT DUTY	BTU/HR	0.62507E+06
OUTLET VAPOR FRACTION		1.0000
PRESSURE-DROP CORRELATION PARAMETER		-0.24164E-07

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
HYDROGEN	0.80000E-01	0.80000E-01	0.80000E-01	MISSING
CARBO-01	0.20000	0.20000	0.20000	MISSING
CARBO-02	0.50000E-01	0.50000E-01	0.50000E-01	MISSING
WATER	0.67000	0.67000	0.67000	MISSING

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR GAS U-5
RATE OF CONSUMPTION 29.2618 LB/HR
COST 2.2053 $/HR

BLOCK: E-104 MODEL: HEATER

INLET STREAM: 12
OUTLET STREAM: 14

OUTLET WATER STREAM: 13
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
FREE WATER OPTION SET: SYSOP12 ASME STEAM TABLE
SOLUBLE WATER OPTION: THE MAIN PROPERTY OPTION SET (SRK).

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	22.9660	22.9660	0.00000
MASS(LB/HR)	403.714	403.714	0.140801E-15
ENTHALPY(BTU/HR)	-0.158980E+07	-0.186708E+07	0.148506

*** INPUT DATA ***

TWO PHASE TP FLASH
FREE WATER CONSIDERED

SPECIFIED TEMPERATURE	F	100.000
SPECIFIED PRESSURE	PSIA	143.500
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

*** RESULTS ***

OUTLET TEMPERATURE	F	100.00
OUTLET PRESSURE	PSIA	143.50
HEAT DUTY	BTU/HR	-0.27727E+06
OUTLET VAPOR FRACTION		0.48663
OUTLET: 1ST LIQUID/TOTAL LIQUID		0.0000
PRESSURE-DROP CORRELATION PARAMETER		0.0000

V-L1-L2 PHASE EQUILIBRIUM :

COMP	F(I)	X1(I)	X2(I)	Y(I)	K1(I)	K2(I)
HYDROGEN	0.311E-02	0.854E-03	0.00	0.640E-02	87.4	
CARBO-01	0.200E-01	0.942E-01	0.00	0.412E-01	5.09	
CARBO-02	0.582E-06	0.426E-06	0.00	0.120E-05	32.8	
WATER	0.517	0.173	1.00	0.727E-02	0.489	0.727E-02
METHANE	0.460	0.731	0.00	0.945	15.1	

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER	U-1
RATE OF CONSUMPTION	9273.6797 LB/HR
COST	8.4129-02 $/HR

```
BLOCK:  M-100    MODEL: MIXER
-----------------------------
 INLET STREAMS:        2          6
 OUTLET STREAM:        7
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                           IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          44.0925        44.0925        0.00000
    MASS(LB/HR   )          989.170        989.170      -0.114932E-15
    ENTHALPY(BTU/HR  )      -0.457045E+07   -0.457045E+07    0.832748E-07

                 ***  INPUT DATA  ***
 TWO    PHASE      FLASH
 MAXIMUM NO. ITERATIONS                                30
 CONVERGENCE TOLERANCE                                 0.000100000
 OUTLET PRESSURE   PSIA                             137.000

BLOCK:  P-100    MODEL: PUMP
----------------------------
 INLET STREAM:         3
 OUTLET STREAM:        4
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                           IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          29.5419        29.5419        0.00000
    MASS(LB/HR   )          532.206        532.206        0.00000
    ENTHALPY(BTU/HR  )      -0.363012E+07   -0.363010E+07   -0.589366E-05

                 ***  INPUT DATA  ***
  PRESSURE CHANGE  PSI                              4.00000
  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                       8.54569
  PRESSURE CHANGE  PSI                              4.00000
```

```
 NPSH AVAILABLE   FT-LBF/LB                    323.070
 FLUID POWER  HP                             0.0024860
 BRAKE POWER  HP                              0.0084084
 ELECTRICITY  KW                             0.0062702
 PUMP EFFICIENCY USED                           0.29566
 NET WORK REQUIRED  HP                          0.0084084
 HEAD DEVELOPED FT-LBF/LB                          9.24889

BLOCK:  R-100    MODEL: RSTOIC
------------------------------
 INLET STREAM:         9
 OUTLET STREAM:        FAKE
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                   IN         OUT      GENERATION   RELATIVE DIFF.
 TOTAL BALANCE
 MOLE(LBMOL/HR)        44.0925       62.3886       18.2962      0.227780E-15
 MASS(LB/HR   )        989.170       989.170                   0.114932E-15
 ENTHALPY(BTU/HR  )   -0.392592E+07  -164563.                  -0.958083

                  ***  INPUT DATA  ***
 STOICHIOMETRY MATRIX:

  REACTION #   1:
   SUBSTREAM MIXED   :
   HYDROGEN   1.00    WATER     -1.00    OXYGEN    0.500

  REACTION #   2:
   SUBSTREAM MIXED   :
   CARBO-01  -1.00    CARBO-02   1.00    OXYGEN    0.500


 REACTION CONVERSION SPECS: NUMBER=    2
   REACTION #   1:
   SUBSTREAM:MIXED    KEY COMP:WATER    CONV FRAC: 0.9700
   REACTION #   2:
   SUBSTREAM:MIXED    KEY COMP:CARBO-01 CONV FRAC: 0.9000



 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE F                    1,292.00
 SPECIFIED PRESSURE    PSIA                 146.959
 MAXIMUM NO. ITERATIONS                        30
```

CONVERGENCE TOLERANCE 0.000100000
SIMULTANEOUS REACTIONS
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES NO

*** RESULTS ***

OUTLET TEMPERATURE	F	1292.0
OUTLET PRESSURE	PSIA	146.96
HEAT DUTY	BTU/HR	0.37614E+07
VAPOR FRACTION		1.0000

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT LBMOL/HR
1	28.656
2	7.9366

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
HYDROGEN	0.51585	0.51585	0.51585	MISSING
CARBO-01	0.14135E-01	0.14135E-01	0.14135E-01	MISSING
CARBO-02	0.16255	0.16255	0.16255	MISSING
WATER	0.14205E-01	0.14205E-01	0.14205E-01	MISSING
OXYGEN	0.29326	0.29326	0.29326	MISSING

BLOCK: R101 MODEL: RGIBBS

INLET STREAM: 11
OUTLET STREAM: 12
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	44.0925	22.9660	-21.1264	0.805742E-16
MASS(LB/HR)	403.714	403.714		0.112641E-14
ENTHALPY(BTU/HR)	-685262.	-0.158980E+07		0.568965

*** INPUT DATA ***

EQUILIBRIUM SPECIFICATIONS:
ONLY CHEMICAL EQUILIBRIUM IS CONSIDERED, THE FLUID PHASE IS VAPOR

SYSTEM TEMPERATURE F 400.00
TEMPERATURE FOR FREE ENERGY EVALUATION F 400.00
SYSTEM PRESSURE PSIA 143.50

FLUID PHASE SPECIES IN PRODUCT LIST:
HYDROGEN CARBO-01 CARBO-02 WATER METHANE OXYGEN NITROGEN

ATOM MATRIX:

ELEMENT	H	C	N	O
HYDROGEN	2.00	0.00	0.00	0.00
CARBO-01	0.00	1.00	0.00	2.00
CARBO-02	0.00	1.00	0.00	1.00
WATER	2.00	0.00	0.00	1.00
METHANE	4.00	1.00	0.00	0.00
OXYGEN	0.00	0.00	0.00	2.00
NITROGEN	0.00	0.00	2.00	0.00

*** RESULTS ***

TEMPERATURE	F	400.00
PRESSURE	PSIA	143.50
HEAT DUTY	BTU/HR	-0.90454E+06
VAPOR FRACTION		1.0000
NUMBER OF FLUID PHASES		1

FLUID PHASE MOLE FRACTIONS:

PHASE VAPOR
OF TYPE VAPOR
PHASE FRACTION 1.000000
PLACED IN STREAM 12

HYDROGEN	0.3114360E-02
CARBO-01	0.2002512E-01
CARBO-02	0.5822737E-06
METHANE	0.4599486
OXYGEN	0.000000
WATER	0.5169113

LBMOL/HR 22.96605

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER	U-4
RATE OF CONSUMPTION	3.0254+04 LB/HR
COST	0.2745 $/HR

BLOCK: SPLIT MODEL: SEP

```
---------------------------
 INLET STREAM:         FAKE
 OUTLET STREAMS:       10         15
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                               IN             OUT       RELATIVE DIFF.
  TOTAL BALANCE
     MOLE(LBMOL/HR)          62.3886        62.3886        0.00000
     MASS(LB/HR   )          989.170        989.170       -0.114932E-15
     ENTHALPY(BTU/HR  )      -164563.       -164584.        0.127246E-03

                      ***  INPUT DATA  ***

 FLASH SPECS FOR STREAM 10
 TWO    PHASE  TP  FLASH
 PRESSURE DROP        PSI                        0.0
 MAXIMUM NO. ITERATIONS                           30
 CONVERGENCE TOLERANCE                               0.000100000

 FLASH SPECS FOR STREAM 15
 TWO    PHASE  TP  FLASH
 PRESSURE DROP        PSI                        0.0
 MAXIMUM NO. ITERATIONS                           30
 CONVERGENCE TOLERANCE                               0.000100000

 FRACTION OF FEED
   SUBSTREAM= MIXED
     STREAM= 10       CPT= HYDROGEN  FRACTION=          1.00000
                           CARBO-01                 1.00000
                           CARBO-02                 1.00000
                           WATER                   1.00000
                           METHANE                  1.00000

                       ***  RESULTS  ***

 HEAT DUTY           BTU/HR                      -20.943

 COMPONENT = HYDROGEN
  STREAM     SUBSTREAM    SPLIT FRACTION
  10         MIXED               1.00000

 COMPONENT = CARBO-01
  STREAM     SUBSTREAM    SPLIT FRACTION
```

10	MIXED	1.00000

COMPONENT = CARBO-02

STREAM	SUBSTREAM	SPLIT FRACTION
10	MIXED	1.00000

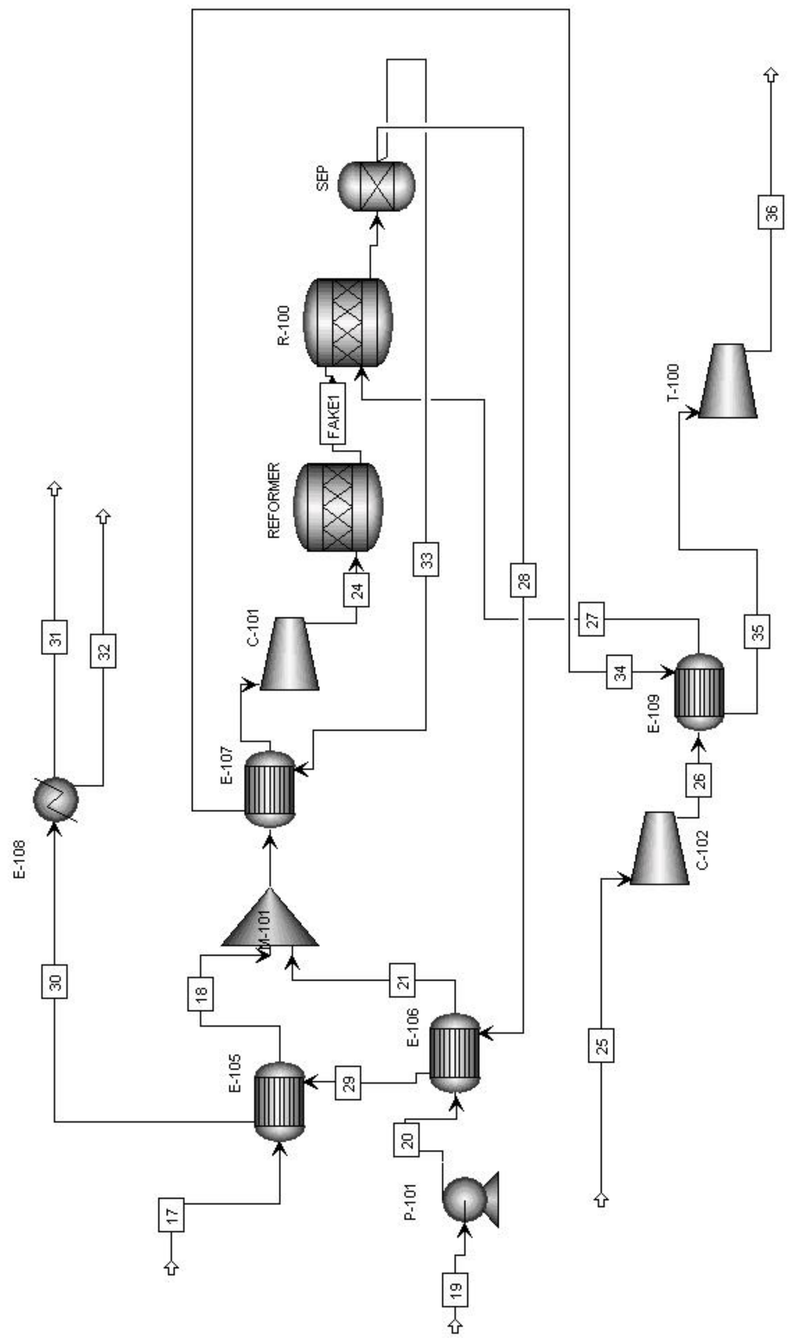
COMPONENT = WATER

STREAM	SUBSTREAM	SPLIT FRACTION
10	MIXED	1.00000

COMPONENT = OXYGEN

STREAM	SUBSTREAM	SPLIT FRACTION
15	MIXED	1.00000

Fuel Cell


SEP
R-100
FAKE1
REFORMER
T-100
C-101
C-102
E-105
E-106
E-107
E-108
E-109
M-101
P-101
17
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36

		17	18	19	20	21
From			E-105		P-101	E-106
To		E-105	M-101	P-101	E-106	M-101
Substream: MIXED						
Phase:		Mixed	Vapor	Liquid	Liquid	Vapor
Component Mole Flow						
HYDROGEN	LBMOL/HR	0.0794972	0.0794972	0	0	0
CARBO-01	LBMOL/HR	0.2634785	0.2634785	0	0	0
CARBO-02	LBMOL/HR	8.82E-06	8.82E-06	0	0	0
WATER	LBMOL/HR	0.07953	0.07953	11.02311	11.02311	11.02311
METHANE	LBMOL/HR	10.75963	10.75963	0	0	0
OXYGEN	LBMOL/HR	0	0	0	0	0
NITROGEN	LBMOL/HR	0	0	0	0	0
Component Mass Flow						
HYDROGEN	LB/HR	0.1602568	0.1602568	0	0	0
CARBO-01	LB/HR	11.59564	11.59564	0	0	0
CARBO-02	LB/HR	2.47E-04	2.47E-04	0	0	0
WATER	LB/HR	1.432755	1.432755	198.5845	198.5845	198.5845
METHANE	LB/HR	172.6142	172.6142	0	0	0
OXYGEN	LB/HR	0	0	0	0	0
NITROGEN	LB/HR	0	0	0	0	0
Mole Flow	LBMOL/HR	11.18214	11.18214	11.02311	11.02311	11.02311
Mass Flow	LB/HR	185.8031	185.8031	198.5845	198.5845	198.5845
Volume Flow	CUFT/HR	806.4467	988.2593	3.188746	3.188739	1116.675
Temperature	F	76.73	716.4141	77	77.00726	903.7819
Pressure	PSIA	143.5	143.2	146.9595	147.9595	143.2
Vapor Fraction		0.9954974	1	0	0	1
Liquid Fraction		4.50E-03	0	1	1	0
Solid Fraction		0	0	0	0	0
Molar Enthalpy	BTU/LBMOL	-35711.83	-28690.38	-1.23E+05	-1.23E+05	-97021.44
Mass Enthalpy	BTU/LB	-2149.237	-1726.667	-6820.606	-6820.596	-5385.508
Enthalpy Flow	BTU/HR	-3.99E+05	-3.21E+05	-1.35E+06	-1.35E+06	-1.07E+06
Molar Entropy	BTU/LBMOL-R	-22.94787	-14.53711	-38.96767	-38.96743	-7.31966
Mass Entropy	BTU/LB-R	-1.381067	-0.8748835	-2.163034	-2.163021	-0.4063029
Molar Density	LBMOL/CUFT	0.0138659	0.0113149	3.45688	3.456887	9.87E-03
Mass Density	LB/CUFT	0.2303972	0.1880104	62.27667	62.2768	0.1778355
Average Molecular Weight		16.61605	16.61605	18.01528	18.01528	18.01528

		22	23	24	25	26
From		M-101	E-107	C-101		C-102
To		E-107	C-101	REFORMER	C-102	E-109
Substream: MIXED						
Phase:		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
HYDROGEN	LBMOL/HR	0.0794972	0.0794972	0.0794972	0	0
CARBO-01	LBMOL/HR	0.2634785	0.2634785	0.2634785	0	0
CARBO-02	LBMOL/HR	8.82E-06	8.82E-06	8.82E-06	0	0
WATER	LBMOL/HR	11.10264	11.10264	11.10264	0	0
METHANE	LBMOL/HR	10.75963	10.75963	10.75963	0	0
OXYGEN	LBMOL/HR	0	0	0	32.40795	32.40795
NITROGEN	LBMOL/HR	0	0	0	121.9156	121.9156
Component Mass Flow						
HYDROGEN	LB/HR	0.1602568	0.1602568	0.1602568	0	0
CARBO-01	LB/HR	11.59564	11.59564	11.59564	0	0
CARBO-02	LB/HR	2.47E-04	2.47E-04	2.47E-04	0	0
WATER	LB/HR	200.0172	200.0172	200.0172	0	0
METHANE	LB/HR	172.6142	172.6142	172.6142	0	0
OXYGEN	LB/HR	0	0	0	1037.016	1037.016
NITROGEN	LB/HR	0	0	0	3415.281	3415.281
Mole Flow	LBMOL/HR	22.20526	22.20526	22.20526	154.3236	154.3236
Mass Flow	LB/HR	384.3875	384.3875	384.3875	4452.297	4452.297
Volume Flow	CUFT/HR	2073.582	3291.94	3149.171	60468.83	13496.23
Temperature	F	791.8847	1472	1490.824	77	757.5131
Pressure	PSIA	143.2	139.9	146.9595	14.69595	150
Vapor Fraction		1	1	1	1	1
Liquid Fraction		0	0	0	0	0
Solid Fraction		0	0	0	0	0
Molar Enthalpy	BTU/LBMOL	-62611.22	-53920.74	-53657.39	-2.891061	4868.771
Mass Enthalpy	BTU/LB	-3616.918	-3114.887	-3099.674	-0.1002087	168.7592
Enthalpy Flow	BTU/HR	-1.39E+06	-1.20E+06	-1.19E+06	-446.1589	7.51E+05
Molar Entropy	BTU/LBMOL-R	-9.589959	-4.038206	-4.000351	1.01556	2.231081
Mass Entropy	BTU/LB-R	-0.5539917	-0.2332786	-0.2310919	0.0352008	0.0773327
Molar Density	LBMOL/CUFT	0.0107086	6.75E-03	7.05E-03	2.55E-03	0.0114345
Mass Density	LB/CUFT	0.1853736	0.1167662	0.1220599	0.0736296	0.3298919
Average Molecular Weight		17.31065	17.31065	17.31065	28.8504	28.8504

		27	28	29	30	31
From		E-109	SEP	E-106	E-105	E-108
To		R-100	E-106	E-105	E-108	
Substream: MIXED						
Phase:		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
HYDROGEN	LBMOL/HR	0	3.698293	3.698293	3.698293	3.698293
CARBO-01	LBMOL/HR	0	10.03878	10.03878	10.03878	10.03878
CARBO-02	LBMOL/HR	0	0.984342	0.984342	0.984342	0.984342
WATER	LBMOL/HR	0	29.00311	29.00311	29.00311	0.1107146
METHANE	LBMOL/HR	0	0	0	0	0
OXYGEN	LBMOL/HR	32.40795	0	0	0	0
NITROGEN	LBMOL/HR	121.9156	0	0	0	0
Component Mass Flow						
HYDROGEN	LB/HR	0	7.455314	7.455314	7.455314	7.455314
CARBO-01	LB/HR	0	441.8045	441.8045	441.8045	441.8045
CARBO-02	LB/HR	0	27.57181	27.57181	27.57181	27.57181
WATER	LB/HR	0	522.4991	522.4991	522.4991	1.994555
METHANE	LB/HR	0	0	0	0	0
OXYGEN	LB/HR	1037.016	0	0	0	0
NITROGEN	LB/HR	3415.281	0	0	0	0
Mole Flow	LBMOL/HR	154.3236	43.72452	43.72452	43.72452	14.83212
Mass Flow	LB/HR	4452.297	999.3307	999.3307	999.3307	478.8262
Volume Flow	CUFT/HR	17014.55	6261.941	4512.764	3968.827	1318.523
Temperature	F	1045.068	1562	921.7797	734.4267	100
Pressure	PSIA	147	146.9595	143	140	140
Vapor Fraction		1	1	1	1	1
Liquid Fraction		0	0	0	0	0
Solid Fraction		0	0	0	0	0
Molar Enthalpy	BTU/LBMOL	7043.198	-94916.28	-1.01E+05	-1.03E+05	-1.18E+05
Mass Enthalpy	BTU/LB	244.1283	-4152.948	-4438.125	-4516.693	-3665.223
Enthalpy Flow	BTU/HR	1.09E+06	-4.15E+06	-4.44E+06	-4.51E+06	-1.76E+06
Molar Entropy	BTU/LBMOL-R	3.874103	2.943068	-0.8682465	-2.222841	-0.716656
Mass Entropy	BTU/LB-R	0.1342825	0.1287704	-0.037989	-0.0972577	-0.0221991
Molar Density	LBMOL/CUFT	9.07E-03	6.98E-03	9.69E-03	0.0110169	0.011249
Mass Density	LB/CUFT	0.2616758	0.159588	0.2214454	0.251795	0.3631534
Average Molecular Weight		28.8504	22.85516	22.85516	22.85516	32.28305

From		32	33	34	35
To	E-108	SEP	E-107	E-109	
Substream: MIXED		E-107	E-109	T-100	
Phase:					
Component Mole Flow	Liquid	Vapor	Vapor	Vapor	
HYDROGEN	LBMOL/HR				
CARBO-01	LBMOL/HR	0	0	0	0
CARBO-02	LBMOL/HR	0	0	0	0
WATER	LBMOL/HR	0	0	0	0
METHANE	LBMOL/HR	28.89239	0	0	0
OXYGEN	LBMOL/HR	0	0	0	0
NITROGEN	LBMOL/HR	0	13.19026	13.19026	13.19026
Component Mass Flow		0	121.9156	121.9156	121.9156
HYDROGEN	LB/HR				
CARBO-01	LB/HR	0	0	0	0
CARBO-02	LB/HR	0	0	0	0
WATER	LB/HR	0	0	0	0
METHANE	LB/HR	520.5046	0	0	0
OXYGEN	LB/HR	0	0	0	0
NITROGEN	LB/HR	0	422.0724	422.0724	422.0724
Mole Flow	LBMOL/HR	0	3415.281	3415.281	3415.281
Mass Flow	LB/HR	28.89239	135.1059	135.1059	135.1059
Volume Flow	CUFT/HR	520.5046	3837.354	3837.354	3837.354
Temperature	F	8.39209	20002.21	18670.26	15769.47
Pressure	PSIA	100	1562	1382.571	1063.052
Vapor Fraction		140	146.9595	143.5	140.5
Liquid Fraction		0	1	1	1
Solid Fraction		1	0	0	0
Molar Enthalpy	BTU/LBMOL	0	0	0	0
Mass Enthalpy	BTU/LB	-1.22E+05	11050.75	9622.434	7138.713
Enthalpy Flow	BTU/HR	-6797.716	389.0759	338.7875	251.3404
Molar Entropy	BTU/LBMOL-R	-3.54E+06	1.49E+06	1.30E+06	9.64E+05
Mass Entropy	BTU/LB-R	-38.21459	5.760495	5.068185	3.630363
Molar Density	LBMOL/CUFT	-2.121232	0.202816	0.1784411	0.1278182
Mass Density	LB/CUFT	3.442813	6.75E-03	7.24E-03	8.57E-03
Average Molecular Weight		62.02323	0.1918465	0.2055329	0.2433406
		18.01528	28.40256	28.40256	28.40256

		36	FAKE1	FAKE2
From		T-100	REFORMER	R-100
To			R-100	SEP
Substream: MIXED				
Phase:		Vapor	Vapor	Vapor
Component Mole Flow				
HYDROGEN	LBMOL/HR	0	32.35839	3.698293
CARBO-01	LBMOL/HR	0	0.2634785	10.03878
CARBO-02	LBMOL/HR	0	10.75964	0.984342
WATER	LBMOL/HR	0	0.3430132	29.00311
METHANE	LBMOL/HR	0	0	0
OXYGEN	LBMOL/HR	13.19026	0	13.19026
NITROGEN	LBMOL/HR	121.9156	0	121.9156
Component Mass Flow				
HYDROGEN	LB/HR	0	65.23063	7.455314
CARBO-01	LB/HR	0	11.59564	441.8045
CARBO-02	LB/HR	0	301.3818	27.57181
WATER	LB/HR	0	6.17948	522.4991
METHANE	LB/HR	0	0	0
OXYGEN	LB/HR	422.0724	0	422.0724
NITROGEN	LB/HR	3415.281	0	3415.281
Mole Flow	LBMOL/HR	135.1059	43.72452	178.8304
Mass Flow	LB/HR	3837.354	384.3875	4836.684
Volume Flow	CUFT/HR	1.01E+05	6179.753	26264.48
Temperature	F	565.7429	1472	1562
Pressure	PSIA	14.69595	146.9595	146.9595
Vapor Fraction		1	1	1
Liquid Fraction		0	0	0
Solid Fraction		0	0	0
Molar Enthalpy	BTU/LBMOL	3444.689	-3490.44	-14858.33
Mass Enthalpy	BTU/LB	121.2809	-397.0415	-549.3682
Enthalpy Flow	BTU/HR	4.65E+05	-1.53E+05	-2.66E+06
Molar Entropy	BTU/LBMOL-R	5.189795	10.99768	6.17623
Mass Entropy	BTU/LB-R	0.1827228	1.250999	0.2283584
Molar Density	LBMOL/CUFT	1.33E-03	7.08E-03	6.81E-03
Mass Density	LB/CUFT	0.0379139	0.0622011	0.1841531
Average Molecular Weight		28.40256	8.791121	27.04621

BLOCK: C-101 MODEL: COMPR

INLET STREAM: 23
OUTLET STREAM: 24
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	22.2053	22.2053	0.00000
MASS(LB/HR)	384.388	384.388	0.00000
ENTHALPY(BTU/HR)	-0.119732E+07	-0.119148E+07	-0.488396E-02

*** INPUT DATA ***

ISENTROPIC CENTRIFUGAL COMPRESSOR

OUTLET PRESSURE PSIA	146.959
ISENTROPIC EFFICIENCY	0.72000
MECHANICAL EFFICIENCY	1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP	2.29823
BRAKE HORSEPOWER REQUIREMENT HP	2.29823
NET WORK REQUIRED HP	2.29823
POWER LOSSES HP	0.0
ISENTROPIC HORSEPOWER REQUIREMENT HP	1.65472
CALCULATED OUTLET TEMP F	1,490.82
ISENTROPIC TEMPERATURE F	1,485.58
EFFICIENCY (POLYTR/ISENTR) USED	0.72000
OUTLET VAPOR FRACTION	1.00000
HEAD DEVELOPED, FT-LBF/LB	8,523.57
MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.16636
INLET VOLUMETRIC FLOW RATE , CUFT/HR	3,291.94
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR	3,149.17
INLET COMPRESSIBILITY FACTOR	1.00052
OUTLET COMPRESSIBILITY FACTOR	0.99572
AV. ISENT. VOL. EXPONENT	1.07742
AV. ISENT. TEMP EXPONENT	1.16586
AV. ACTUAL VOL. EXPONENT	1.11032
AV. ACTUAL TEMP EXPONENT	1.24531

```
BLOCK:  C-102    MODEL: COMPR
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  INLET STREAM:          25
  OUTLET STREAM:         26
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                              IN           OUT       RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(LBMOL/HR)           154.324        154.324        0.00000
     MASS(LB/HR   )          4452.30        4452.30         0.00000
     ENTHALPY(BTU/HR  )       -446.159       751366.        -1.00059

                    ***  INPUT DATA  ***

  ISENTROPIC CENTRIFUGAL COMPRESSOR
   OUTLET PRESSURE  PSIA                            150.000
   ISENTROPIC EFFICIENCY                            0.72000
   MECHANICAL EFFICIENCY                            1.00000

                    ***  RESULTS  ***

   INDICATED  HORSEPOWER REQUIREMENT  HP                295.473
   BRAKE      HORSEPOWER REQUIREMENT  HP                295.473
   NET WORK REQUIRED                  HP                295.473
   POWER LOSSES                       HP                0.0
   ISENTROPIC HORSEPOWER REQUIREMENT  HP                212.741
   CALCULATED OUTLET TEMP  F                            757.513
   ISENTROPIC TEMPERATURE  F                            571.995
   EFFICIENCY (POLYTR/ISENTR) USED                      0.72000
   OUTLET VAPOR FRACTION                                1.00000
   HEAD DEVELOPED,       FT-LBF/LB                      94,608.9
   MECHANICAL EFFICIENCY USED                           1.00000
   INLET HEAT CAPACITY RATIO                            1.40099
   INLET VOLUMETRIC FLOW RATE , CUFT/HR                 60,468.8
   OUTLET VOLUMETRIC FLOW RATE, CUFT/HR                 13,496.2
   INLET  COMPRESSIBILITY FACTOR                        0.99985
   OUTLET COMPRESSIBILITY FACTOR                        1.00429
   AV. ISENT. VOL. EXPONENT                             1.39536
   AV. ISENT. TEMP EXPONENT                             1.39146
   AV. ACTUAL VOL. EXPONENT                             1.54900
```

AV. ACTUAL TEMP EXPONENT 1.54443

BLOCK: E-105 MODEL: HEATX

HOT SIDE:

INLET STREAM: 29
OUTLET STREAM: 30
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 17
OUTLET STREAM: 18
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	54.9067	54.9067	0.00000
MASS(LB/HR)	1185.13	1185.13	0.00000
ENTHALPY(BTU/HR)	-0.483449E+07	-0.483449E+07	0.00000

*** INPUT DATA ***

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

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

FLOW DIRECTION AND SPECIFICATION:
COUNTERCURRENT HEAT EXCHANGER
SPECIFIED MIN OUTLET TEMP APPR
SPECIFIED VALUE F 18.0000
LMTD CORRECTION FACTOR 1.00000

PRESSURE SPECIFICATION:

```
  HOT  SIDE OUTLET PRESSURE      PSIA              140.0000
  COLD SIDE OUTLET PRESSURE      PSIA              143.2000

 HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R         24.4600

                    ***  OVERALL RESULTS  ***

 STREAMS:
                --------------------------------------
                |                            |
 29      ----->|           HOT              |-----> 30
 T=  9.2178D+02  |                            |      T=  7.3443D+02
 P=  1.4300D+02  |                            |      P=  1.4000D+02
 V=  1.0000D+00  |                            |      V=  1.0000D+00
                |                            |
 18      <-----|           COLD             |<----- 17
 T=  7.1641D+02  |                            |      T=  7.6730D+01
 P=  1.4320D+02  |                            |      P=  1.4350D+02
 V=  1.0000D+00  |                            |      V=  9.9550D-01
                --------------------------------------

 DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            78514.8737
  CALCULATED (REQUIRED) AREA    SQFT                  8.2599
  ACTUAL EXCHANGER AREA         SQFT                  8.2599
  PER CENT OVER-DESIGN                               0.0000

 HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R         24.4600
  UA (DIRTY)                  BTU/HR-R            202.0369

 LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                             1.0000
  LMTD (CORRECTED)              F                 388.6166
  NUMBER OF SHELLS IN SERIES                           1

 PRESSURE DROP:
  HOTSIDE, TOTAL               PSI                 3.0000
  COLDSIDE, TOTAL              PSI                 0.3000
```

PRESSURE DROP PARAMETER:
HOT SIDE: 0.49247E+07
COLD SIDE: 0.12518E+08

BLOCK: E-106 MODEL: HEATX

HOT SIDE:

INLET STREAM: 28
OUTLET STREAM: 29
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 20
OUTLET STREAM: 21
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	54.7476	54.7476	0.00000
MASS(LB/HR)	1197.92	1197.92	0.00000
ENTHALPY(BTU/HR)	-0.550463E+07	-0.550463E+07	0.338378E-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 MIN OUTLET TEMP APPR
SPECIFIED VALUE F 18.0000
LMTD CORRECTION FACTOR 1.00000

```
PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE      PSIA              143.0000
  COLD SIDE OUTLET PRESSURE      PSIA              143.2000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R       40.4100

                 ***  OVERALL RESULTS  ***

STREAMS:
              --------------------------------------
              |                            |
28      ----->|           HOT              |-----> 29
T=  1.5620D+03  |                          |      T=  9.2178D+02
P=  1.4696D+02  |                          |      P=  1.4300D+02
V=  1.0000D+00  |                          |      V=  1.0000D+00
              |                            |
21      <-----|           COLD             |<----- 20
T=  9.0378D+02  |                          |      T=  7.7007D+01
P=  1.4320D+02  |                          |      P=  1.4796D+02
V=  1.0000D+00  |                          |      V=  0.0000D+00
              --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR           284986.1148
  CALCULATED (REQUIRED) AREA    SQFT                  9.4331
  ACTUAL EXCHANGER AREA         SQFT                  9.4331
  PER CENT OVER-DESIGN                                0.0000

HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R        40.4100
  UA (DIRTY)                     BTU/HR-R            381.1911

LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                              1.0000
  LMTD (CORRECTED)               F                  747.6200
  NUMBER OF SHELLS IN SERIES                           1

PRESSURE DROP:
  HOTSIDE, TOTAL                 PSI                  3.9595
```

COLDSIDE, TOTAL PSI 4.7595

PRESSURE DROP PARAMETER:
HOT SIDE: 0.51164E+07
COLD SIDE: 0.29778E+09

BLOCK: E-107 MODEL: HEATX

HOT SIDE:

INLET STREAM: 33
OUTLET STREAM: 34
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 22
OUTLET STREAM: 23
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	157.311	157.311	0.00000
MASS(LB/HR)	4221.74	4221.74	0.00000
ENTHALPY(BTU/HR)	102724.	102724.	0.198325E-14

*** 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                 1472.0000
  LMTD CORRECTION FACTOR                          1.00000

 PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE      PSIA            143.5000
  COLD SIDE OUTLET PRESSURE      PSIA            139.9000

 HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R       21.2900

                  ***  OVERALL RESULTS  ***

 STREAMS:
              --------------------------------------
              |                            |
 33      ----->|         HOT             |-----> 34
 T=  1.5620D+03  |                          |     T=  1.3826D+03
 P=  1.4696D+02  |                          |     P=  1.4350D+02
 V=  1.0000D+00  |                          |     V=  1.0000D+00
              |                            |
 23      <-----|         COLD            |<----- 22
 T=  1.4720D+03  |                          |     T=  7.9188D+02
 P=  1.3990D+02  |                          |     P=  1.4320D+02
 V=  1.0000D+00  |                          |     V=  1.0000D+00
              --------------------------------------

 DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR          192974.4104
  CALCULATED (REQUIRED) AREA    SQFT               34.0610
  ACTUAL EXCHANGER AREA         SQFT               34.0610
  PER CENT OVER-DESIGN                              0.0000

 HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R      21.2900
  UA (DIRTY)                    BTU/HR-R          725.1580

 LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                            1.0000
  LMTD (CORRECTED)              F                 266.1136
  NUMBER OF SHELLS IN SERIES                        1
```

PRESSURE DROP:

HOTSIDE, TOTAL	PSI	3.4595
COLDSIDE, TOTAL	PSI	3.3000

PRESSURE DROP PARAMETER:

HOT SIDE:	0.32436E+06
COLD SIDE:	0.22263E+08

BLOCK: E-108 MODEL: HEATER

INLET STREAM: 30

OUTLET STREAM: 31

OUTLET WATER STREAM: 32

PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

FREE WATER OPTION SET: SYSOP12 ASME STEAM TABLE

SOLUBLE WATER OPTION: THE MAIN PROPERTY OPTION SET (SRK).

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	43.7245	43.7245	0.00000
MASS(LB/HR)	999.331	999.331	0.113763E-15
ENTHALPY(BTU/HR)	-0.451367E+07	-0.529325E+07	0.147278

*** INPUT DATA ***

TWO PHASE TP FLASH

FREE WATER CONSIDERED

SPECIFIED TEMPERATURE	F	100.000
SPECIFIED PRESSURE	PSIA	140.000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

*** RESULTS ***

OUTLET TEMPERATURE	F	100.00
OUTLET PRESSURE	PSIA	140.00
HEAT DUTY	BTU/HR	-0.77958E+06
OUTLET VAPOR FRACTION		0.33922
OUTLET: 1ST LIQUID/TOTAL LIQUID		0.0000
PRESSURE-DROP CORRELATION PARAMETER		0.0000

V-L1-L2 PHASE EQUILIBRIUM :

COMP	F(I)	X1(I)	X2(I)	Y(I)	K1(I)	K2(I)
HYDROGEN	0.846E-01	0.205E-01	0.00	0.249	75.5	
CARBO-01	0.230	0.853	0.00	0.677	4.93	
CARBO-02	0.225E-01	0.131E-01	0.00	0.664E-01	31.5	
WATER	0.663	0.113	1.00	0.746E-02	0.410	0.746E-02

*** ASSOCIATED UTILITIES ***

UTILITY ID FOR WATER U-1
RATE OF CONSUMPTION 2.6074+04 LB/HR
COST 0.2365 $/HR

BLOCK: E-109 MODEL: HEATX

HOT SIDE:

INLET STREAM: 34
OUTLET STREAM: 35
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 26
OUTLET STREAM: 27
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	289.429	289.429	0.00000
MASS(LB/HR)	8289.65	8289.65	0.00000
ENTHALPY(BTU/HR)	0.205141E+07	0.205141E+07	0.226995E-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 MIN OUTLET TEMP APPR
SPECIFIED VALUE F 18.0000
LMTD CORRECTION FACTOR 1.00000

PRESSURE SPECIFICATION:
HOT SIDE OUTLET PRESSURE PSIA 140.5000
COLD SIDE OUTLET PRESSURE PSIA 147.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
OVERALL COEFFICIENT BTU/HR-SQFT-R 29.4300

*** OVERALL RESULTS ***

STREAMS:

```
            --------------------------------------
            |                            |
34     ----->|          HOT             |-----> 35
T=  1.3826D+03  |                        |     T=  1.0631D+03
P=  1.4350D+02  |                        |     P=  1.4050D+02
V=  1.0000D+00  |                        |     V=  1.0000D+00
            |                            |
27     <-----|          COLD            |<----- 26
T=  1.0451D+03  |                        |     T=  7.5751D+02
P=  1.4700D+02  |                        |     P=  1.5000D+02
V=  1.0000D+00  |                        |     V=  1.0000D+00
            --------------------------------------
```

DUTY AND AREA:
CALCULATED HEAT DUTY BTU/HR 335565.2889
CALCULATED (REQUIRED) AREA SQFT 35.4925
ACTUAL EXCHANGER AREA SQFT 35.4925

PER CENT OVER-DESIGN 0.0000

HEAT TRANSFER COEFFICIENT:
AVERAGE COEFFICIENT (DIRTY) BTU/HR-SQFT-R 29.4300
UA (DIRTY) BTU/HR-R 1044.5432

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR 1.0000
LMTD (CORRECTED) F 321.2555
NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:
HOTSIDE, TOTAL PSI 3.0000
COLDSIDE, TOTAL PSI 3.0000

PRESSURE DROP PARAMETER:
HOT SIDE: 0.31584E+06
COLD SIDE: 0.30727E+06

BLOCK: M-101 MODEL: MIXER

INLET STREAMS: 18 21
OUTLET STREAM: 22
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	22.2053	22.2053	0.00000
MASS(LB/HR)	384.388	384.388	0.00000
ENTHALPY(BTU/HR)	-0.139030E+07	-0.139030E+07	0.167468E-15

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

BLOCK: P-101 MODEL: PUMP

INLET STREAM: 19

OUTLET STREAM: 20
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	11.0231	11.0231	0.00000
MASS(LB/HR)	198.584	198.584	0.00000
ENTHALPY(BTU/HR)	-0.135447E+07	-0.135446E+07	-0.147350E-05

*** INPUT DATA ***

PRESSURE CHANGE PSI 1.00000
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 3.18875
PRESSURE CHANGE PSI 1.00000
NPSH AVAILABLE FT-LBF/LB 339.175
FLUID POWER HP 0.00023191
BRAKE POWER HP 0.00078438
ELECTRICITY KW 0.00058491
PUMP EFFICIENCY USED 0.29566
NET WORK REQUIRED HP 0.00078438
HEAD DEVELOPED FT-LBF/LB 2.31226

BLOCK: R-100 MODEL: RSTOIC

INLET STREAMS: FAKE1 27
OUTLET STREAM: FAKE2
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	198.048	178.830	-19.2177	0.00000

MASS(LB/HR) 4836.68 4836.68 0.00000
ENTHALPY(BTU/HR) 934314. -0.265712E+07 1.35163

*** INPUT DATA ***

STOICHIOMETRY MATRIX:

REACTION # 1:
SUBSTREAM MIXED :
HYDROGEN -2.00 WATER 2.00 OXYGEN -1.00

REACTION # 2:
SUBSTREAM MIXED :
CARBO-01 2.00 CARBO-02 -2.00 OXYGEN -1.00

REACTION EXTENT SPECS: NUMBER= 2
REACTION # 1: EXTENT= 14.33 LBMOL/HR
REACTION # 2: EXTENT= 4.888 LBMOL/HR

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F 1,562.00
SPECIFIED PRESSURE PSIA 146.959
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000
SIMULTANEOUS REACTIONS
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES NO

*** RESULTS ***

OUTLET TEMPERATURE F 1562.0
OUTLET PRESSURE PSIA 146.96
HEAT DUTY BTU/HR -0.35914E+07
VAPOR FRACTION 1.0000

V-L PHASE EQUILIBRIUM :

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

HYDROGEN	0.20680E-01	0.20680E-01	0.20680E-01	MISSING
CARBO-01	0.56136E-01	0.56136E-01	0.56136E-01	MISSING
CARBO-02	0.55043E-02	0.55043E-02	0.55043E-02	MISSING
WATER	0.16218	0.16218	0.16218	MISSING
OXYGEN	0.73758E-01	0.73758E-01	0.73758E-01	MISSING
NITROGEN	0.68174	0.68174	0.68174	MISSING

BLOCK: REFORMER MODEL: RSTOIC

INLET STREAM: 24

OUTLET STREAM: FAKE1

PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	22.2053	43.7245	21.5193	0.00000
MASS(LB/HR)	384.388	384.388		-0.147880E-15
ENTHALPY(BTU/HR)	-0.119148E+07	-152618.		-0.871909

*** INPUT DATA ***

STOICHIOMETRY MATRIX:

REACTION # 1:

SUBSTREAM MIXED :

HYDROGEN 3.00 CARBO-02 1.00 WATER -1.00 METHANE -1.00

REACTION CONVERSION SPECS: NUMBER= 1

REACTION # 1:

SUBSTREAM:MIXED KEY COMP:METHANE CONV FRAC: 1.000

TWO PHASE TP FLASH	
SPECIFIED TEMPERATURE F	1,472.00
SPECIFIED PRESSURE PSIA	146.959
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000
SIMULTANEOUS REACTIONS	

GENERATE COMBUSTION REACTIONS FOR FEED SPECIES NO

*** RESULTS ***

OUTLET TEMPERATURE	F	1472.0
OUTLET PRESSURE	PSIA	146.96
HEAT DUTY	BTU/HR	0.10389E+07
VAPOR FRACTION		1.0000

REACTION EXTENTS:

REACTION NUMBER	REACTION EXTENT LBMOL/HR
1	10.760

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
HYDROGEN	0.74005	0.74005	0.74005	MISSING
CARBO-01	0.60259E-02	0.60259E-02	0.60259E-02	MISSING
CARBO-02	0.24608	0.24608	0.24608	MISSING
WATER	0.78449E-02	0.78449E-02	0.78449E-02	MISSING

BLOCK: SEP MODEL: SEP

INLET STREAM: FAKE2
OUTLET STREAMS: 33 28
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	178.830	178.830	0.00000
MASS(LB/HR)	4836.68	4836.68	0.00000
ENTHALPY(BTU/HR)	-0.265712E+07	-0.265715E+07	0.981577E-05

*** INPUT DATA ***

FLASH SPECS FOR STREAM 33
TWO PHASE TP FLASH
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

FLASH SPECS FOR STREAM 28
TWO PHASE TP FLASH
PRESSURE DROP PSI 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

FRACTION OF FEED
SUBSTREAM= MIXED
STREAM= 33 CPT= OXYGEN FRACTION= 1.00000
NITROGEN 1.00000

*** RESULTS ***

HEAT DUTY BTU/HR -26.082

COMPONENT = HYDROGEN

STREAM	SUBSTREAM	SPLIT FRACTION
28	MIXED	1.00000

COMPONENT = CARBO-01

STREAM	SUBSTREAM	SPLIT FRACTION
28	MIXED	1.00000

COMPONENT = CARBO-02

STREAM	SUBSTREAM	SPLIT FRACTION
28	MIXED	1.00000

COMPONENT = WATER

STREAM	SUBSTREAM	SPLIT FRACTION
28	MIXED	1.00000

COMPONENT = OXYGEN

STREAM	SUBSTREAM	SPLIT FRACTION
33	MIXED	1.00000

COMPONENT = NITROGEN

STREAM	SUBSTREAM	SPLIT FRACTION
33	MIXED	1.00000

BLOCK: T-100 MODEL: COMPR

INLET STREAM: 35
OUTLET STREAM: 36
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	135.106	135.106	0.00000
MASS(LB/HR)	3837.35	3837.35	0.00000
ENTHALPY(BTU/HR)	964482.	465398.	0.517464

*** INPUT DATA ***

ISENTROPIC TURBINE

OUTLET PRESSURE PSIA	14.6959
ISENTROPIC EFFICIENCY	0.72000
MECHANICAL EFFICIENCY	1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP	-196.148
BRAKE HORSEPOWER REQUIREMENT HP	-196.148
NET WORK REQUIRED HP	-196.148
POWER LOSSES HP	0.0
ISENTROPIC HORSEPOWER REQUIREMENT HP	-272.427
CALCULATED OUTLET TEMP F	565.743
ISENTROPIC TEMPERATURE F	364.052
EFFICIENCY (POLYTR/ISENTR) USED	0.72000
OUTLET VAPOR FRACTION	1.00000
HEAD DEVELOPED, FT-LBF/LB	-140,567.
MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.35217
INLET VOLUMETRIC FLOW RATE , CUFT/HR	15,769.5
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR	101,212.

INLET COMPRESSIBILITY FACTOR	1.00356
OUTLET COMPRESSIBILITY FACTOR	1.00046
AV. ISENT. VOL. EXPONENT	1.37652
AV. ISENT. TEMP EXPONENT	1.37391
AV. ACTUAL VOL. EXPONENT	1.21434
AV. ACTUAL TEMP EXPONENT	1.21233

BLOCK: C-101 MODEL: COMPR

INLET STREAM: 23
OUTLET STREAM: 24
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	22.2053	22.2053	0.00000
MASS(LB/HR)	384.388	384.388	0.00000
ENTHALPY(BTU/HR)	-0.119732E+07	-0.119148E+07	-0.488396E-02

*** INPUT DATA ***

ISENTROPIC CENTRIFUGAL COMPRESSOR

OUTLET PRESSURE PSIA	146.959
ISENTROPIC EFFICIENCY	0.72000
MECHANICAL EFFICIENCY	1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP	2.29823
BRAKE HORSEPOWER REQUIREMENT HP	2.29823
NET WORK REQUIRED HP	2.29823
POWER LOSSES HP	0.0
ISENTROPIC HORSEPOWER REQUIREMENT HP	1.65472
CALCULATED OUTLET TEMP F	1,490.82
ISENTROPIC TEMPERATURE F	1,485.58
EFFICIENCY (POLYTR/ISENTR) USED	0.72000
OUTLET VAPOR FRACTION	1.00000
HEAD DEVELOPED, FT-LBF/LB	8,523.57
MECHANICAL EFFICIENCY USED	1.00000
INLET HEAT CAPACITY RATIO	1.16636
INLET VOLUMETRIC FLOW RATE , CUFT/HR	3,291.94
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR	3,149.17
INLET COMPRESSIBILITY FACTOR	1.00052
OUTLET COMPRESSIBILITY FACTOR	0.99572
AV. ISENT. VOL. EXPONENT	1.07742
AV. ISENT. TEMP EXPONENT	1.16586
AV. ACTUAL VOL. EXPONENT	1.11032
AV. ACTUAL TEMP EXPONENT	1.24531

```
BLOCK:  C-102    MODEL: COMPR
-----------------------------
  INLET STREAM:         25
  OUTLET STREAM:        26
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                         IN           OUT       RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(LBMOL/HR)          154.324        154.324        0.00000
     MASS(LB/HR   )          4452.30        4452.30        0.00000
     ENTHALPY(BTU/HR  )     -446.159        751366.       -1.00059

                   ***  INPUT DATA  ***

  ISENTROPIC CENTRIFUGAL COMPRESSOR
   OUTLET PRESSURE  PSIA                        150.000
   ISENTROPIC EFFICIENCY                        0.72000
   MECHANICAL EFFICIENCY                        1.00000

                   ***  RESULTS  ***

   INDICATED  HORSEPOWER REQUIREMENT  HP              295.473
   BRAKE      HORSEPOWER REQUIREMENT  HP              295.473
   NET WORK REQUIRED                  HP              295.473
   POWER LOSSES                       HP              0.0
   ISENTROPIC HORSEPOWER REQUIREMENT  HP              212.741
   CALCULATED OUTLET TEMP  F                          757.513
   ISENTROPIC TEMPERATURE  F                          571.995
   EFFICIENCY (POLYTR/ISENTR) USED                    0.72000
   OUTLET VAPOR FRACTION                              1.00000
   HEAD DEVELOPED,       FT-LBF/LB                    94,608.9
   MECHANICAL EFFICIENCY USED                         1.00000
   INLET HEAT CAPACITY RATIO                          1.40099
   INLET VOLUMETRIC FLOW RATE , CUFT/HR               60,468.8
   OUTLET VOLUMETRIC FLOW RATE, CUFT/HR               13,496.2
   INLET  COMPRESSIBILITY FACTOR                      0.99985
   OUTLET COMPRESSIBILITY FACTOR                      1.00429
   AV. ISENT. VOL. EXPONENT                           1.39536
   AV. ISENT. TEMP EXPONENT                           1.39146
   AV. ACTUAL VOL. EXPONENT                           1.54900
   AV. ACTUAL TEMP EXPONENT                           1.54443

BLOCK:  E-105    MODEL: HEATX
-----------------------------
  HOT SIDE:
  ---------
  INLET STREAM:         29
  OUTLET STREAM:        30
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE
  COLD SIDE:
  ----------
  INLET STREAM:         17
  OUTLET STREAM:        18
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE
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            ***  MASS AND ENERGY BALANCE  ***
                        IN          OUT       RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)          54.9067       54.9067       0.00000
   MASS(LB/HR   )        1185.13       1185.13       0.00000
   ENTHALPY(BTU/HR  )     -0.483449E+07  -0.483449E+07    0.00000

               ***  INPUT DATA  ***

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

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

FLOW DIRECTION AND SPECIFICATION:
  COUNTERCURRENT   HEAT EXCHANGER
  SPECIFIED MIN OUTLET TEMP APPR
  SPECIFIED VALUE              F               18.0000
  LMTD CORRECTION FACTOR                         1.00000

PRESSURE SPECIFICATION:
  HOT  SIDE OUTLET PRESSURE      PSIA              140.0000
  COLD SIDE OUTLET PRESSURE      PSIA              143.2000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
  OVERALL COEFFICIENT          BTU/HR-SQFT-R         24.4600

              ***  OVERALL RESULTS  ***

STREAMS:
          --------------------------------------
          |                                    |
29     ----->|            HOT              |-----> 30
T=  9.2178D+02  |                            |      T=  7.3443D+02
P=  1.4300D+02  |                            |      P=  1.4000D+02
V=  1.0000D+00  |                            |      V=  1.0000D+00
          |                                    |
18     <-----|            COLD             |<----- 17
T=  7.1641D+02  |                            |      T=  7.6730D+01
P=  1.4320D+02  |                            |      P=  1.4350D+02
V=  1.0000D+00  |                            |      V=  9.9550D-01
          --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            78514.8737
  CALCULATED (REQUIRED) AREA     SQFT                 8.2599
  ACTUAL EXCHANGER AREA         SQFT                 8.2599
  PER CENT OVER-DESIGN                        0.0000

HEAT TRANSFER COEFFICIENT:
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   AVERAGE COEFFICIENT (DIRTY)    BTU/HR-SQFT-R          24.4600
   UA (DIRTY)                    BTU/HR-R             202.0369

  LOG-MEAN TEMPERATURE DIFFERENCE:
   LMTD CORRECTION FACTOR                              1.0000
   LMTD (CORRECTED)              F                  388.6166
   NUMBER OF SHELLS IN SERIES                            1

  PRESSURE DROP:
   HOTSIDE, TOTAL              PSI                  3.0000
   COLDSIDE, TOTAL              PSI                  0.3000

  PRESSURE DROP PARAMETER:
   HOT SIDE:                                 0.49247E+07
   COLD SIDE:                                 0.12518E+08

BLOCK:  E-106    MODEL: HEATX
-----------------------------
  HOT SIDE:
  ---------
  INLET STREAM:         28
  OUTLET STREAM:        29
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE
  COLD SIDE:
  ----------
  INLET STREAM:         20
  OUTLET STREAM:        21
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                         IN            OUT       RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(LBMOL/HR)          54.7476        54.7476        0.00000
     MASS(LB/HR   )          1197.92        1197.92        0.00000
     ENTHALPY(BTU/HR  )      -0.550463E+07   -0.550463E+07    0.338378E-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 MIN OUTLET TEMP APPR
   SPECIFIED VALUE              F                  18.0000
   LMTD CORRECTION FACTOR                              1.00000

  PRESSURE SPECIFICATION:
   HOT  SIDE OUTLET PRESSURE      PSIA                 143.0000
```

COLD SIDE OUTLET PRESSURE PSIA 143.2000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
OVERALL COEFFICIENT BTU/HR-SQFT-R 40.4100

*** OVERALL RESULTS ***

STREAMS:

```
          --------------------------------------
          |                                    |
28   ----->|          HOT                 |-----> 29
T=  1.5620D+03 |                          |    T=  9.2178D+02
P=  1.4696D+02 |                          |    P=  1.4300D+02
V=  1.0000D+00 |                          |    V=  1.0000D+00
          |                                    |
21   <-----|          COLD                |<----- 20
T=  9.0378D+02 |                          |    T=  7.7007D+01
P=  1.4320D+02 |                          |    P=  1.4796D+02
V=  1.0000D+00 |                          |    V=  0.0000D+00
          --------------------------------------
```

DUTY AND AREA:
CALCULATED HEAT DUTY BTU/HR 284986.1148
CALCULATED (REQUIRED) AREA SQFT 9.4331
ACTUAL EXCHANGER AREA SQFT 9.4331
PER CENT OVER-DESIGN 0.0000

HEAT TRANSFER COEFFICIENT:
AVERAGE COEFFICIENT (DIRTY) BTU/HR-SQFT-R 40.4100
UA (DIRTY) BTU/HR-R 381.1911

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR 1.0000
LMTD (CORRECTED) F 747.6200
NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:
HOTSIDE, TOTAL PSI 3.9595
COLDSIDE, TOTAL PSI 4.7595

PRESSURE DROP PARAMETER:
HOT SIDE: 0.51164E+07
COLD SIDE: 0.29778E+09

BLOCK: E-107 MODEL: HEATX

HOT SIDE:

INLET STREAM: 33
OUTLET STREAM: 34
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
COLD SIDE:

INLET STREAM: 22
OUTLET STREAM: 23
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

```
              ***  MASS AND ENERGY BALANCE  ***
                           IN          OUT      RELATIVE DIFF.
 TOTAL BALANCE
   MOLE(LBMOL/HR)          157.311       157.311       0.00000
   MASS(LB/HR   )          4221.74       4221.74       0.00000
   ENTHALPY(BTU/HR  )      102724.       102724.       0.198325E-14

              ***  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              1472.0000
   LMTD CORRECTION FACTOR                     1.00000

 PRESSURE SPECIFICATION:
   HOT  SIDE OUTLET PRESSURE     PSIA          143.5000
   COLD SIDE OUTLET PRESSURE     PSIA          139.9000

 HEAT TRANSFER COEFFICIENT SPECIFICATION:
   OVERALL COEFFICIENT        BTU/HR-SQFT-R      21.2900

              ***  OVERALL RESULTS  ***

 STREAMS:
            --------------------------------------
            |                          |
 33    ----->|          HOT            |-----> 34
 T=  1.5620D+03 |                      |    T=  1.3826D+03
 P=  1.4696D+02 |                      |    P=  1.4350D+02
 V=  1.0000D+00 |                      |    V=  1.0000D+00
            |                          |
 23    <-----|          COLD           |<----- 22
 T=  1.4720D+03 |                      |    T=  7.9188D+02
 P=  1.3990D+02 |                      |    P=  1.4320D+02
 V=  1.0000D+00 |                      |    V=  1.0000D+00
            --------------------------------------

 DUTY AND AREA:
   CALCULATED HEAT DUTY        BTU/HR        192974.4104
   CALCULATED (REQUIRED) AREA     SQFT           34.0610
   ACTUAL EXCHANGER AREA        SQFT             34.0610
   PER CENT OVER-DESIGN                      0.0000

 HEAT TRANSFER COEFFICIENT:
```

AVERAGE COEFFICIENT (DIRTY) BTU/HR-SQFT-R 21.2900
UA (DIRTY) BTU/HR-R 725.1580

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR 1.0000
LMTD (CORRECTED) F 266.1136
NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:
HOTSIDE, TOTAL PSI 3.4595
COLDSIDE, TOTAL PSI 3.3000

PRESSURE DROP PARAMETER:
HOT SIDE: 0.32436E+06
COLD SIDE: 0.22263E+08

BLOCK: E-108 MODEL: HEATER

INLET STREAM: 30
OUTLET STREAM: 31
OUTLET WATER STREAM: 32
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE
FREE WATER OPTION SET: SYSOP12 ASME STEAM TABLE
SOLUBLE WATER OPTION: THE MAIN PROPERTY OPTION SET (SRK).

*** MASS AND ENERGY BALANCE ***

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(LBMOL/HR)	43.7245	43.7245	0.00000
MASS(LB/HR)	999.331	999.331	0.113763E-15
ENTHALPY(BTU/HR)	-0.451367E+07	-0.529325E+07	0.147278

*** INPUT DATA ***
TWO PHASE TP FLASH
FREE WATER CONSIDERED
SPECIFIED TEMPERATURE F 100.000
SPECIFIED PRESSURE PSIA 140.000
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000

*** RESULTS ***
OUTLET TEMPERATURE F 100.00
OUTLET PRESSURE PSIA 140.00
HEAT DUTY BTU/HR -0.77958E+06
OUTLET VAPOR FRACTION 0.33922
OUTLET: 1ST LIQUID/TOTAL LIQUID 0.0000
PRESSURE-DROP CORRELATION PARAMETER 0.0000

V-L1-L2 PHASE EQUILIBRIUM :

COMP	F(I)	X1(I)	X2(I)	Y(I)	K1(I)	K2(I)
HYDROGEN	0.846E-01	0.205E-01	0.00	0.249	75.5	

```
    CARBO-01     0.230     0.853      0.00     0.677      4.93
    CARBO-02     0.225E-01 0.131E-01  0.00     0.664E-01  31.5
    WATER       0.663     0.113      1.00     0.746E-02 0.410     0.746E-02

               ***  ASSOCIATED  UTILITIES  ***

 UTILITY ID FOR WATER                    U-1
 RATE OF CONSUMPTION                 2.6074+04  LB/HR
 COST                            0.2365  $/HR

BLOCK:  E-109    MODEL: HEATX
------------------------------
  HOT SIDE:
  ---------
  INLET STREAM:         34
  OUTLET STREAM:        35
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE
  COLD SIDE:
  ----------
  INLET STREAM:         26
  OUTLET STREAM:        27
  PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                          IN            OUT       RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(LBMOL/HR)          289.429        289.429        0.00000
     MASS(LB/HR   )       8289.65        8289.65        0.00000
     ENTHALPY(BTU/HR  )       0.205141E+07    0.205141E+07    0.226995E-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 MIN OUTLET TEMP APPR
    SPECIFIED VALUE              F                  18.0000
    LMTD CORRECTION FACTOR                          1.00000

  PRESSURE SPECIFICATION:
    HOT  SIDE OUTLET PRESSURE      PSIA               140.5000
    COLD SIDE OUTLET PRESSURE      PSIA                147.0000

  HEAT TRANSFER COEFFICIENT SPECIFICATION:
    OVERALL COEFFICIENT           BTU/HR-SQFT-R          29.4300

              ***  OVERALL RESULTS  ***
```

```
STREAMS:
              --------------------------------------
              |                            |
34     ----->|          HOT           |-----> 35
T=  1.3826D+03  |                         |    T=  1.0631D+03
P=  1.4350D+02  |                         |    P=  1.4050D+02
V=  1.0000D+00  |                         |    V=  1.0000D+00
              |                            |
27     <-----|          COLD          |<----- 26
T=  1.0451D+03  |                         |    T=  7.5751D+02
P=  1.4700D+02  |                         |    P=  1.5000D+02
V=  1.0000D+00  |                         |    V=  1.0000D+00
              --------------------------------------

DUTY AND AREA:
  CALCULATED HEAT DUTY          BTU/HR            335565.2889
  CALCULATED (REQUIRED) AREA    SQFT                 35.4925
  ACTUAL EXCHANGER AREA         SQFT                 35.4925
  PER CENT OVER-DESIGN                                0.0000

HEAT TRANSFER COEFFICIENT:
  AVERAGE COEFFICIENT (DIRTY)   BTU/HR-SQFT-R        29.4300
  UA (DIRTY)                    BTU/HR-R           1044.5432

LOG-MEAN TEMPERATURE DIFFERENCE:
  LMTD CORRECTION FACTOR                              1.0000
  LMTD (CORRECTED)              F                   321.2555
  NUMBER OF SHELLS IN SERIES                           1

PRESSURE DROP:
  HOTSIDE, TOTAL                PSI                   3.0000
  COLDSIDE, TOTAL               PSI                   3.0000

PRESSURE DROP PARAMETER:
  HOT SIDE:                                  0.31584E+06
  COLD SIDE:                                 0.30727E+06

BLOCK:  M-101    MODEL: MIXER
-----------------------------
 INLET STREAMS:       18        21
 OUTLET STREAM:        22
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                            IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          22.2053       22.2053       0.00000
    MASS(LB/HR   )          384.388       384.388       0.00000
    ENTHALPY(BTU/HR  )   -0.139030E+07  -0.139030E+07   0.167468E-15

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

```
BLOCK:  P-101    MODEL: PUMP
----------------------------
 INLET STREAM:          19
 OUTLET STREAM:         20
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                        IN          OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          11.0231       11.0231        0.00000
    MASS(LB/HR   )         198.584       198.584        0.00000
    ENTHALPY(BTU/HR  )   -0.135447E+07  -0.135446E+07  -0.147350E-05

                 ***  INPUT DATA  ***
  PRESSURE CHANGE  PSI                          1.00000
  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                      3.18875
  PRESSURE CHANGE  PSI                          1.00000
  NPSH AVAILABLE   FT-LBF/LB                      339.175
  FLUID POWER  HP                             0.00023191
  BRAKE POWER  HP                             0.00078438
  ELECTRICITY  KW                             0.00058491
  PUMP EFFICIENCY USED                          0.29566
  NET WORK REQUIRED  HP                         0.00078438
  HEAD DEVELOPED FT-LBF/LB                        2.31226

BLOCK:  R-100    MODEL: RSTOIC
------------------------------
 INLET STREAMS:         FAKE1      27
 OUTLET STREAM:         FAKE2
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                      IN         OUT       GENERATION   RELATIVE DIFF.
 TOTAL BALANCE
 MOLE(LBMOL/HR)        198.048       178.830      -19.2177       0.00000
 MASS(LB/HR   )       4836.68       4836.68                    0.00000
 ENTHALPY(BTU/HR  )     934314.    -0.265712E+07                1.35163

                 ***  INPUT DATA  ***
 STOICHIOMETRY MATRIX:

  REACTION #   1:
   SUBSTREAM MIXED   :
   HYDROGEN  -2.00    WATER      2.00    OXYGEN    -1.00

  REACTION #   2:
```

SUBSTREAM MIXED :
CARBO-01 2.00 CARBO-02 -2.00 OXYGEN -1.00

REACTION EXTENT SPECS: NUMBER= 2
REACTION # 1: EXTENT= 14.33 LBMOL/HR
REACTION # 2: EXTENT= 4.888 LBMOL/HR

TWO PHASE TP FLASH	
SPECIFIED TEMPERATURE F	1,562.00
SPECIFIED PRESSURE PSIA	146.959
MAXIMUM NO. ITERATIONS	30
CONVERGENCE TOLERANCE	0.000100000
SIMULTANEOUS REACTIONS	
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES	NO

*** RESULTS ***

OUTLET TEMPERATURE	F	1562.0
OUTLET PRESSURE	PSIA	146.96
HEAT DUTY	BTU/HR	-0.35914E+07
VAPOR FRACTION		1.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
HYDROGEN	0.20680E-01	0.20680E-01	0.20680E-01	MISSING
CARBO-01	0.56136E-01	0.56136E-01	0.56136E-01	MISSING
CARBO-02	0.55043E-02	0.55043E-02	0.55043E-02	MISSING
WATER	0.16218	0.16218	0.16218	MISSING
OXYGEN	0.73758E-01	0.73758E-01	0.73758E-01	MISSING
NITROGEN	0.68174	0.68174	0.68174	MISSING

BLOCK: REFORMER MODEL: RSTOIC

INLET STREAM: 24
OUTLET STREAM: FAKE1
PROPERTY OPTION SET: SRK SOAVE-REDLICH-KWONG EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

	IN	OUT	GENERATION	RELATIVE DIFF.
TOTAL BALANCE				
MOLE(LBMOL/HR)	22.2053	43.7245	21.5193	0.00000
MASS(LB/HR)	384.388	384.388		-0.147880E-15
ENTHALPY(BTU/HR)	-0.119148E+07	-152618.		-0.871909

*** INPUT DATA ***
STOICHIOMETRY MATRIX:

REACTION # 1:
SUBSTREAM MIXED :
HYDROGEN 3.00 CARBO-02 1.00 WATER -1.00 METHANE -1.00

```
REACTION CONVERSION SPECS: NUMBER=    1
  REACTION #   1:
  SUBSTREAM:MIXED    KEY COMP:METHANE  CONV FRAC:  1.000



TWO    PHASE  TP  FLASH
SPECIFIED TEMPERATURE F                    1,472.00
SPECIFIED PRESSURE    PSIA                 146.959
MAXIMUM NO. ITERATIONS                       30
CONVERGENCE TOLERANCE                          0.000100000
SIMULTANEOUS REACTIONS
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES          NO

                    ***  RESULTS  ***
OUTLET TEMPERATURE    F                      1472.0
OUTLET PRESSURE       PSIA                  146.96
HEAT DUTY            BTU/HR               0.10389E+07
VAPOR FRACTION                            1.0000



REACTION EXTENTS:

  REACTION         REACTION
  NUMBER           EXTENT
                 LBMOL/HR
  1               10.760

V-L PHASE EQUILIBRIUM :

  COMP            F(I)          X(I)          Y(I)          K(I)
  HYDROGEN        0.74005       0.74005       0.74005       MISSING
  CARBO-01        0.60259E-02   0.60259E-02   0.60259E-02   MISSING
  CARBO-02        0.24608       0.24608       0.24608       MISSING
  WATER           0.78449E-02   0.78449E-02   0.78449E-02   MISSING

BLOCK:  SEP      MODEL: SEP
----------------------------
 INLET STREAM:         FAKE2
 OUTLET STREAMS:       33         28
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                            IN            OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(LBMOL/HR)          178.830       178.830       0.00000
    MASS(LB/HR   )          4836.68       4836.68       0.00000
    ENTHALPY(BTU/HR  )      -0.265712E+07   -0.265715E+07   0.981577E-05


                  ***  INPUT DATA  ***
```

```
 FLASH SPECS FOR STREAM 33
 TWO    PHASE  TP  FLASH
 PRESSURE DROP        PSI                      0.0
 MAXIMUM NO. ITERATIONS                            30
 CONVERGENCE TOLERANCE                               0.000100000

 FLASH SPECS FOR STREAM 28
 TWO    PHASE  TP  FLASH
 PRESSURE DROP        PSI                      0.0
 MAXIMUM NO. ITERATIONS                            30
 CONVERGENCE TOLERANCE                               0.000100000

 FRACTION OF FEED
  SUBSTREAM= MIXED
   STREAM= 33      CPT= OXYGEN    FRACTION=        1.00000
                 NITROGEN               1.00000


              ***  RESULTS  ***

 HEAT DUTY           BTU/HR                    -26.082

 COMPONENT = HYDROGEN
  STREAM    SUBSTREAM    SPLIT FRACTION
  28        MIXED             1.00000

 COMPONENT = CARBO-01
  STREAM    SUBSTREAM    SPLIT FRACTION
  28        MIXED             1.00000

 COMPONENT = CARBO-02
  STREAM    SUBSTREAM    SPLIT FRACTION
  28        MIXED             1.00000

 COMPONENT = WATER
  STREAM    SUBSTREAM    SPLIT FRACTION
  28        MIXED             1.00000

 COMPONENT = OXYGEN
  STREAM    SUBSTREAM    SPLIT FRACTION
  33        MIXED             1.00000

 COMPONENT = NITROGEN
  STREAM    SUBSTREAM    SPLIT FRACTION
  33        MIXED             1.00000

BLOCK:  T-100    MODEL: COMPR
-----------------------------
 INLET STREAM:         35
 OUTLET STREAM:        36
 PROPERTY OPTION SET:   SRK       SOAVE-REDLICH-KWONG EQUATION OF STATE

             ***  MASS AND ENERGY BALANCE  ***
                     IN           OUT       RELATIVE DIFF.
  TOTAL BALANCE
   MOLE(LBMOL/HR)          135.106        135.106        0.00000
```

```
MASS(LB/HR   )          3837.35       3837.35       0.00000
ENTHALPY(BTU/HR  )       964482.       465398.       0.517464

               ***  INPUT DATA  ***

ISENTROPIC TURBINE
 OUTLET PRESSURE  PSIA                       14.6959
 ISENTROPIC EFFICIENCY                        0.72000
 MECHANICAL EFFICIENCY                          1.00000

               ***  RESULTS  ***

 INDICATED  HORSEPOWER REQUIREMENT  HP              -196.148
 BRAKE      HORSEPOWER REQUIREMENT  HP              -196.148
 NET WORK REQUIRED               HP            -196.148
 POWER LOSSES                 HP               0.0
 ISENTROPIC HORSEPOWER REQUIREMENT  HP              -272.427
 CALCULATED OUTLET TEMP  F                      565.743
 ISENTROPIC TEMPERATURE  F                     364.052
 EFFICIENCY (POLYTR/ISENTR) USED                    0.72000
 OUTLET VAPOR FRACTION                         1.00000
 HEAD DEVELOPED,       FT-LBF/LB              -140,567.
 MECHANICAL EFFICIENCY USED                        1.00000
 INLET HEAT CAPACITY RATIO                      1.35217
 INLET VOLUMETRIC FLOW RATE , CUFT/HR              15,769.5
 OUTLET VOLUMETRIC FLOW RATE, CUFT/HR              101,212.
 INLET  COMPRESSIBILITY FACTOR                     1.00356
 OUTLET COMPRESSIBILITY FACTOR                      1.00046
 AV. ISENT. VOL. EXPONENT                     1.37652
 AV. ISENT. TEMP EXPONENT                      1.37391
 AV. ACTUAL VOL. EXPONENT                      1.21434
 AV. ACTUAL TEMP EXPONENT                       1.21233
```

Material Safety Data Sheets

Hydrogen

International Chemical Safety Cards

HYDROGEN

ICSC: 0001

HYDROGEN
(cylinder)
H_2
Molecular mass: 2.0

CAS # 1333-74-0
RTECS # MW8900000
ICSC # 0001
UN # 1049
EC # 001-001-00-9

TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/ SYMPTOMS	PREVENTION	FIRST AID/ FIRE FIGHTING
FIRE	Extremely flammable. Many reactions may cause fire or explosion.	NO open flames, NO sparks, and NO smoking.	Shut off supply; if not possible and no risk to surroundings, let the fire burn itself out; (see notes) water spray, powder, carbon dioxide.
EXPLOSION	Gas/air mixtures are explosive.	Closed system, ventilation, explosion-proof electrical equipment and lighting. Use non-sparking handtools. Do not handle cylinders with oily hands.	In case of fire: keep cylinder cool by spraying with water.Combat fire from a sheltered position.
EXPOSURE			
• INHALATION	Dizziness. Asphyxia. Laboured breathing. Unconsciousness.	Closed system and ventilation.	Fresh air, rest. Refer for medical attention.
• SKIN	ON CONTACT WITH LIQUID: FROSTBITE.	Cold-insulating gloves. Protective clothing.	ON FROSTBITE: rinse with plenty of water, do NOT remove clothes. Refer for medical attention.
• EYES		Safety goggles, or face shield.	
• INGESTION			

SPILLAGE DISPOSAL	STORAGE	PACKAGING & LABELLING
Evacuate danger area! Consult an	Fireproof. Cool.	

expert! Ventilation. Remove vapour with fine water spray.

F+ symbol
R: 12
S: 9-16-33
UN Hazard Class: 2.1

SEE IMPORTANT INFORMATION ON BACK

ICSC: 0001

International Chemical Safety Cards

HYDROGEN

ICSC: 0001

IMPORTANT DATA

PHYSICAL STATE; APPEARANCE:
ODOURLESS , COLOURLESS COMPRESSED LIQUEFIED GAS

PHYSICAL DANGERS:
The gas mixes well with air, explosive mixtures are easily formed. The gas is lighter than air.

CHEMICAL DANGERS:
Heating may cause violent combustion or explosion. Reacts violently with air, oxygen, chlorine, fluorine, strong oxidants causing fire and explosion hazard. Metal catalysts, such as platinum and nickel, greatly enhance these reactions.

OCCUPATIONAL EXPOSURE LIMITS (OELs):
TLV not established

ROUTES OF EXPOSURE:
The substance can be absorbed into the body by inhalation.

INHALATION RISK:
On loss of containment this liquid evaporates very quickly causing supersaturation of the air with serious risk of suffocation when in confined areas.

EFFECTS OF SHORT-TERM EXPOSURE:
The liquid may cause frostbite. Exposure could cause dizzines, high voice. Exposure may result in suffocation.

EFFECTS OF LONG-TERM OR REPEATED EXPOSURE:

PHYSICAL PROPERTIES

Boiling point: - 253°C
Relative vapour density (air = 1): 0.07
Flash point: flammable gas

Auto-ignition temperature: 500-571°C
Explosive limits, vol% in air: 4-76%

ENVIRONMENTAL DATA

NOTES

Addition of small amounts of a flammable substance or an increase in the oxygen content of the air strongly enhances combustibility. High concentrations in the air cause a deficiency of oxygen with the risk of unconsciousness or death. Check oxygen content before entering area. No odour warning if toxic concentrations are present. Measure hydrogen concentrations with suitable gas detector (a normal flammable gas detector is not suited for the purpose). After use for welding, turn valve off; regularly check tubing, etc., and test for leaks with soap and water. The measures mentioned in section PREVENTION are applicable to production, filling of cylinders, and storage of the gas.

Transport Emergency Card: TEC (R)-20
NFPA Code: H0; F4; R0;

ADDITIONAL INFORMATION

ICSC: 0001 **HYDROGEN**

IMPORTANT LEGAL NOTICE:	Neither the CEC or the IPCS nor any person acting on behalf of the CEC or the IPCS is responsible for the use which might be made of this information. This card contains the collective views of the IPCS Peer Review Committee and may not reflect in all cases all the detailed requirements included in national legislation on the subject. The user should verify compliance of the cards with the relevant legislation in the country of use.

Water

Material Safety Data Sheet
Water

ACC# 00339

Section 1 - Chemical Product and Company Identification

MSDS Name: Water
Catalog Numbers: AC327390000, AC327390010, AC327390050
Synonyms:
Company Identification:
Acros Organics N.V.
One Reagent Lane
Fair Lawn, NJ 07410
For information in North America, call: 800-ACROS-01
For emergencies in the US, call CHEMTREC: 800-424-9300

Section 2 - Composition, Information on Ingredients

CAS#	Chemical Name	Percent	EINECS/ELINCS
7732-18-5	Water	100	231-791-2

Section 3 - Hazards Identification

EMERGENCY OVERVIEW

Appearance: water-white liquid.
Expected to be non-hazardous.
Target Organs: None.

Potential Health Effects
Eye: Non-irritating to the eyes.
Skin: Non-irritating to the skin.
Ingestion: No hazard expected in normal industrial use.
Inhalation: No hazard expected in normal industrial use.
Chronic: None

Section 4 - First Aid Measures

Eyes: No specific treatment is necessary, since this material is not likely to be hazardous.
Skin: No specific treatment is necessary, since this material is not likely to be hazardous.
Ingestion: No specific treatment is necessary, since this material is expected to be non-hazardous.
Inhalation: No specific treatment is necessary since this material is not likely to be hazardous by inhalation.
Notes to Physician: Treat symptomatically and supportively.

Section 5 - Fire Fighting Measures

General Information: Material will not burn.
Extinguishing Media: Not available.
Flash Point: Not applicable.
Autoignition Temperature: Not applicable.
Explosion Limits, Lower: Not available.
Upper: Not available.
NFPA Rating: (estimated) Health: 0; Flammability: 0; Instability: 0

Section 6 - Accidental Release Measures

General Information: Use proper personal protective equipment as indicated in Section 8.
Spills/Leaks: Absorb spill with inert material (e.g. vermiculite, sand or earth), then place in suitable container.

Section 7 - Handling and Storage

Handling: No special handling procedures are required.
Storage: No special storage requirements.

Section 8 - Exposure Controls, Personal Protection

Engineering Controls: There are no special ventilation requirements.
Exposure Limits

Chemical Name	ACGIH	NIOSH	OSHA - Final PELs
Water	none listed	none listed	none listed

OSHA Vacated PELs: Water: No OSHA Vacated PELs are listed for this chemical.
Personal Protective Equipment
Eyes: Eye protection is not normally required.
Skin: Protective garments not normally required.
Clothing: Protective garments not normally required.
Respirators: Respirator protection is not normally required.

Section 9 - Physical and Chemical Properties

Physical State: Liquid
Appearance: colorless - Clear - water-white
Odor: odorless
pH: Not available.
Vapor Pressure: 17.5 mm Hg @ 20 deg C.
Vapor Density: Not available.
Evaporation Rate: Not available.
Viscosity: 1 cP @ 20C
Boiling Point: 100 deg C
Freezing/Melting Point: Not available.
Decomposition Temperature: Not available.
Solubility: Not available.
Specific Gravity/Density:1.000
Molecular Formula:H2O
Molecular Weight:18.0134

Section 10 - Stability and Reactivity

Chemical Stability: Stable.
Conditions to Avoid: None reported.
Incompatibilities with Other Materials: None.
Hazardous Decomposition Products: None.
Hazardous Polymerization: Will not occur.

Section 11 - Toxicological Information

RTECS#:
CAS# 7732-18-5: ZC0110000
LD50/LC50:
CAS# 7732-18-5:
Oral, rat: LD50 = >90 mL/kg;<br.

Carcinogenicity:
CAS# 7732-18-5: Not listed by ACGIH, IARC, NTP, or CA Prop 65.

Epidemiology: No data available.
Teratogenicity: No data available.
Reproductive Effects: No data available.
Mutagenicity: No data available.
Neurotoxicity: No data available.
Other Studies:</br.

Section 12 - Ecological Information

Ecotoxicity: No data available. No information available.
Environmental: Nonhazardous to the environment.
Physical: No information available.
Other: No information available.

Section 13 - Disposal Considerations

Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. US EPA guidelines for the classification determination are listed in 40 CFR Parts 261.3. Additionally, waste generators must consult state and local hazardous waste regulations to ensure complete and accurate classification.
RCRA P-Series: None listed.
RCRA U-Series: None listed.

Section 14 - Transport Information

	US DOT	Canada TDG

Shipping Name:	Please contact Fisher Scientific for shipping information	No information available.
Hazard Class:		
UN Number:		
Packing Group:		

Section 15 - Regulatory Information

US FEDERAL

TSCA
CAS# 7732-18-5 is listed on the TSCA inventory.
Health & Safety Reporting List
None of the chemicals are on the Health & Safety Reporting List.
Chemical Test Rules
None of the chemicals in this product are under a Chemical Test Rule.
Section 12b
None of the chemicals are listed under TSCA Section 12b.
TSCA Significant New Use Rule
None of the chemicals in this material have a SNUR under TSCA.
CERCLA Hazardous Substances and corresponding RQs
None of the chemicals in this material have an RQ.
SARA Section 302 Extremely Hazardous Substances
None of the chemicals in this product have a TPQ.
Section 313 No chemicals are reportable under Section 313.
Clean Air Act:
This material does not contain any hazardous air pollutants.
This material does not contain any Class 1 Ozone depletors.
This material does not contain any Class 2 Ozone depletors.
Clean Water Act:
None of the chemicals in this product are listed as Hazardous Substances under the CWA.
None of the chemicals in this product are listed as Priority Pollutants under the CWA.
None of the chemicals in this product are listed as Toxic Pollutants under the CWA.
OSHA:
None of the chemicals in this product are considered highly hazardous by OSHA.
STATE
CAS# 7732-18-5 is not present on state lists from CA, PA, MN, MA, FL, or NJ.

California Prop 65

California No Significant Risk Level: None of the chemicals in this product are listed.

European/International Regulations
European Labeling in Accordance with EC Directives
Hazard Symbols:

Not available.

Risk Phrases:

Safety Phrases:

WGK (Water Danger/Protection)

CAS# 7732-18-5: No information available.

Canada - DSL/NDSL

CAS# 7732-18-5 is listed on Canada's DSL List.

Canada - WHMIS

WHMIS: Not available.

Canadian Ingredient Disclosure List

Section 16 - Additional Information

MSDS Creation Date: 1/12/1999
Revision #3 Date: 3/18/2003

Oxygen

International Chemical Safety Cards

OXYGEN

ICSC: 0138

OXYGEN
Oxygen, compressed
O_2
Molecular mass: 32.0

CAS # 7782-44-7
RTECS # RS2060000
ICSC # 0138
UN # 1072
EC # 008-001-00-8

TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/ SYMPTOMS	PREVENTION	FIRST AID/ FIRE FIGHTING
FIRE	Not combustible but enhances combustion of other substances. Many reactions may cause fire or explosion. Heating will cause rise in pressure with risk of bursting.	NO open flames, NO sparks, and NO smoking. NO contact with flammable substances. NO contact with fuels and other combustible materials.	In case of fire in the surroundings: all extinguishing agents allowed.
EXPLOSION	Risk of fire and explosion on contact with combustible materials such as oils or fats.		In case of fire: keep cylinder cool by spraying with water. Combat fire from a sheltered position.
EXPOSURE			
• INHALATION			
• SKIN			
• EYES	Redness.	Safety goggles.	First rinse with plenty of water for several minutes (remove contact lenses if easily possible), then take to a doctor.
• INGESTION			

SPILLAGE DISPOSAL	STORAGE	PACKAGING & LABELLING
Evacuate danger area! Consult an expert! Ventilation.	Fireproof. Separated from combustible and reducing substances. Cool.	O symbol R: 8-34 S: 21 UN Hazard Class: 2.2

SEE IMPORTANT INFORMATION ON BACK

ICSC: 0138

International Chemical Safety Cards

OXYGEN

ICSC: 0138

IMPORTANT DATA

PHYSICAL STATE; APPEARANCE:
COMPRESSED GAS.

PHYSICAL DANGERS:
The gas is heavier than air.

CHEMICAL DANGERS:
The substance is a strong oxidant and reacts violently with combustible and reducing materials, with risks of fire and explosion hazard.

OCCUPATIONAL EXPOSURE LIMITS (OELs):
TLV not established.

ROUTES OF EXPOSURE:
The substance can be absorbed into the body by inhalation and through the skin.

INHALATION RISK:

EFFECTS OF SHORT-TERM EXPOSURE:

EFFECTS OF LONG-TERM OR REPEATED EXPOSURE:
Lungs may be affected by inhalation of high concentrations. Symptoms may be delayed.

PHYSICAL PROPERTIES

Boiling point: -183°C
Melting point: -218.8°C
Solubility in water: moderate (3.1 ml/100 ml at 20°C)
Relative vapour density (air = 1): 1.43
Octanol/water partition coefficient as log Pow: 0.65

ENVIRONMENTAL DATA

NOTES

Do NOT use in the vicinity of a fire or a hot surface, or during welding. Also consult ICSC # 0880.

Transport Emergency Card: TEC (R)-842

ADDITIONAL INFORMATION

ICSC: 0138 **OXYGEN**

IMPORTANT LEGAL NOTICE:

Nitrogen

International Chemical Safety Cards

NITROGEN (GASEOUS)

ICSC: 1198

NITROGEN (GASEOUS)
Azote
Nitrogen (Compressed)
(cylinder)
N_2
Molecular mass: 28.01

CAS # 7727-37-9
RTECS # QW9700000
ICSC # 1198
UN # 1066

TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/ SYMPTOMS	PREVENTION	FIRST AID/ FIRE FIGHTING
FIRE	Not combustible.		In case of fire in the surroundings: all extinguishing agents allowed.
EXPLOSION			In case of fire: keep cylinder cool by spraying with water.
EXPOSURE			
• INHALATION	Unconsciousness. Weakness. Death. See Notes.	Ventilation. Breathing protection.	Fresh air, rest. Artificial respiration if indicated. Oxygen may be beneficial if administered by a trained person on physician's advice. Refer for medical attention.
• SKIN			
• EYES			
• INGESTION			

SPILLAGE DISPOSAL	STORAGE	PACKAGING & LABELLING
Ventilation (extra personal protection: self-contained breathing apparatus).	Cool. Keep in a well-ventilated room.	UN Hazard Class: 2.2

SEE IMPORTANT INFORMATION ON BACK

ICSC: 1198

International Chemical Safety Cards

NITROGEN (GASEOUS)

ICSC: 1198

IMPORTANT DATA	**PHYSICAL STATE; APPEARANCE:** ODOURLESS, COLOURLESS, TASTELESS, COMPRESSED GAS. **PHYSICAL DANGERS:** Gas mixes readily with air. **CHEMICAL DANGERS:** Reacts with oxygen and hydrogen on sparking forming nitric oxide and ammonia. Combines directly with lithium and at red heat with calcium, srontium and barium to form nitrides. Forms cyanides when heated with carbon in presence of alkalies or barium oxides. **OCCUPATIONAL EXPOSURE LIMITS (OELs):** TLV not established.	**ROUTES OF EXPOSURE:** The substance can be absorbed into the body by inhalation. **INHALATION RISK:** A harmful concentration of this gas in the air will be reached very quickly on loss of containment. On loss of containment this gas can cause suffocation by lowering the oxygen content of the air in confined areas. See Notes. **EFFECTS OF SHORT-TERM EXPOSURE:** **EFFECTS OF LONG-TERM OR REPEATED EXPOSURE:**
PHYSICAL PROPERTIES	Boiling point: -195.8°C Melting point: -210°C	Solubility in water: none Relative vapour density (air = 1): 0.97
ENVIRONMENTAL DATA		

NOTES

High concentrations in the air cause a deficiency of oxygen with the risk of unconsciousness or death. Check oxygen content before entering area. Effects are the result of oxygen deficiency. Do not attempt rescue without air supplied respirator.

Transport Emergency Card: TEC (R)-20G01

ADDITIONAL INFORMATION

ICSC: 1198 **NITROGEN (GASEOUS)**

Carbon Monoxide

International Chemical Safety Cards

CARBON MONOXIDE

ICSC: 0023

CARBON MONOXIDE
Carbon oxide
Carbonic oxide
(cylinder)
CO
Molecular mass: 28.0

CAS # 630-08-0
RTECS # FG3500000
ICSC # 0023
UN # 1016
EC # 006-001-00-2

TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/ SYMPTOMS	PREVENTION	FIRST AID/ FIRE FIGHTING
FIRE	Extremely flammable.	NO open flames, NO sparks, and NO smoking.	Shut off supply; if not possible and no risk to surroundings, let the fire burn itself out; in other cases extinguish with carbon dioxide, water spray, powder.
EXPLOSION	Gas/air mixtures are explosive.	Closed system, ventilation, explosion-proof electrical equipment and lighting. Use non-sparking handtools.	In case of fire: keep cylinder cool by spraying with water. Combat fire from a sheltered position.
EXPOSURE		AVOID EXPOSURE OF	IN ALL CASES

		(PREGNANT) WOMEN!	CONSULT A DOCTOR!
• INHALATION	Confusion. Dizziness. Headache. Nausea. Unconsciousness.Weakness.	Ventilation, local exhaust, or breathing protection.	Fresh air, rest. Artificial respiration if indicated. Refer for medical attention.
• SKIN			
• EYES			
• INGESTION			

SPILLAGE DISPOSAL	STORAGE	PACKAGING & LABELLING
Evacuate danger area! Consult an expert! Ventilation (extra personal protection: self-contained breathing apparatus).	Fireproof. Cool.	F+ symbol T symbol R: 61-12-23-48/23 S: 53-45 Note: E UN Hazard Class: 2.3 UN Subsidiary Risks: 2.1

SEE IMPORTANT INFORMATION ON BACK

ICSC: 0023

International Chemical Safety Cards

CARBON MONOXIDE

ICSC: 0023

I M P O R T A N T	**PHYSICAL STATE; APPEARANCE:** ODOURLESS, TASTELESS, COLOURLESS COMPRESSED GAS. **PHYSICAL DANGERS:** The gas mixes well with air, explosive mixtures are easily formed. The gas penetrates easily through walls and ceilings. **CHEMICAL DANGERS:** In the presence of finely dispersed metal powders the substance forms toxic and flammable carbonyls. May react vigorously with oxygen, acetylene, chlorine, fluorine, nitrous oxide. **OCCUPATIONAL EXPOSURE LIMITS (OELs):**	**ROUTES OF EXPOSURE:** The substance can be absorbed into the body by inhalation. **INHALATION RISK:** A harmful concentration of this gas in the air will be reached very quickly on loss of containment. **EFFECTS OF SHORT-TERM EXPOSURE:** The substance may cause effects on the blood, cardiovascular system and central nervous system. Exposure at high levels may result in lowering of consciousness and death. Medical observation is indicated. **EFFECTS OF LONG-TERM OR**

D A T A	TLV: 25 ppm; 29 mg/m^3 (as TWA) (ACGIH 1994-1995). MAK: 30 ppm; 33 mg/m^3; Pregnancy: B (harmful effect probable in spite of observance of MAK) (1993).	**REPEATED EXPOSURE:** The substance may have effects on the nervous system and the cardiovascular system , resulting in neurological and cardiac disorders). Suspected to cause reproductive effects such as neurological problems, low birth weight, increased still births, and congenital heart problems.
PHYSICAL PROPERTIES	Boiling point: -191°C Melting point: -205°C Solubility in water, ml/100 ml at 20°C: 2.3 Relative vapour density (air = 1): 0.97	Flash point: Flammable Gas Auto-ignition temperature: 605°C Explosive limits, vol% in air: 12.5-74.2
ENVIRONMENTAL DATA		

N O T E S

Carbon monoxide is a product of incomplete combustion of coal, oil, wood. It is present in vehicle exhaust and tobacco smoke. Depending on the degree of exposure, periodic medical examination is indicated. No odour warning if toxic concentrations are present.

Transport Emergency Card: TEC (R)-827
NFPA Code: H3; F4; R0

ADDITIONAL INFORMATION

ICSC: 0023 **CARBON MONOXIDE**

IMPORTANT LEGAL NOTICE:

Neither the CEC or the IPCS nor any person acting on behalf of the CEC or the IPCS is responsible for the use which might be made of this information. This card contains the collective views of the IPCS Peer Review Committee and may not reflect in all cases all the detailed requirements included in national legislation on the subject. The user should verify compliance of the cards with the relevant legislation in the country of use.

Carbon Dioxide

International Chemical Safety Cards

CARBON DIOXIDE

ICSC: 0021

CARBON DIOXIDE
Carbonic acid gas
Carbonic anhydride
(cylinder)
CO_2
Molecular mass: 44.0

CAS # 124-38-9
RTECS # FF6400000
ICSC # 0021
UN # 1013

TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/ SYMPTOMS	PREVENTION	FIRST AID/ FIRE FIGHTING
FIRE	Not combustible.		In case of fire in the surroundings: all extinguishing agents allowed.
EXPLOSION	Containers may burst in the heat of a fire!		In case of fire: keep cylinder cool by spraying with water. Combat fire from a sheltered position.
EXPOSURE			
• INHALATION	Dizziness. Headache. Elevated blood pressure. Tachycardia.	Ventilation.	Fresh air, rest. Artificial respiration if indicated. Refer for medical attention.
• SKIN	ON CONTACT WITH LIQUID: FROSTBITE.	Cold-insulating gloves. Protective clothing.	ON FROSTBITE: rinse with plenty of water, do NOT remove clothes. Refer for medical attention.
• EYES	On contact with liquid: frostbite.	Safety goggles, or face shield.	First rinse with plenty of water for several minutes (remove contact lenses if easily possible), then take to a doctor.
• INGESTION			

SPILLAGE DISPOSAL	STORAGE	PACKAGING & LABELLING
Ventilation. NEVER direct water jet on liquid (extra personal protection: self-contained breathing apparatus).	Fireproof if in building. Cool.	UN Hazard Class: 2.2

SEE IMPORTANT INFORMATION ON BACK

ICSC: 0021

International Chemical Safety Cards

CARBON DIOXIDE

ICSC: 0021

IMPORTANT DATA

PHYSICAL STATE; APPEARANCE:
ODOURLESS, COLOURLESS, COMPRESSED LIQUEFIED GAS.

PHYSICAL DANGERS:
The gas is heavier than air and may accumulate in low ceiling spaces causing deficiency of oxygen. Build up of static electricity can occur at fast flow rates and may ignite any explosive mixtures present. Free-flowing liquid condenses to form extremely cold dry ice.

CHEMICAL DANGERS:
The substance decomposes on heating above 2000°C producing toxic carbon monoxide. Reacts violently with strong bases and alkali metals. Various metal dusts such as magnesium, zirconium, titanium, aluminium, chromium and manganese are ignitable and explosive when suspended and heated in carbon dioxide.

OCCUPATIONAL EXPOSURE LIMITS (OELs):
TLV: 5000 ppm; 9000 mg/m^3 (as TWA); 30,000 ppm; 54,000 mg/m^3 (as STEL) (ACGIH 1994-1995).
MAK: 5000 ppm; 9000 mg/m^3 (1993).

ROUTES OF EXPOSURE:
The substance can be absorbed into the body by inhalation.

INHALATION RISK:
On loss of containment this liquid evaporates very quickly causing supersaturation of the air with serious risk of suffocation when in confined areas.

EFFECTS OF SHORT-TERM EXPOSURE:
Inhalation of high concentrations of this gas may cause hyperventilation and unconciousness.Rapid evaporation of the liquid may cause frostbite.

EFFECTS OF LONG-TERM OR REPEATED EXPOSURE:
The substance may have effects on the metabolism.

PHYSICAL PROPERTIES

Sublimation point: -79°C
Solubility in water, ml/100 ml at 20°C: 88
Vapour pressure, kPa at 20°C: 5720
Relative vapour density (air = 1): 1.5

ENVIRONMENTAL DATA

NOTES

Carbon dioxide is given off by many fermentation processes (wine, beer, etc.) and is a major component of flue gas. High concentrations in the air cause a deficiency of oxygen with the risk of unconsciousness or death. Check oxygen content before entering area. No odour warning if toxic concentrations are present. Turn leaking cylinder with the leak up to prevent escape of gas in liquid state. Other UN classification numbers for transport are: UN 1845 carbon dioxide, dry ice; UN 2187 carbon dioxide refrigerated liquid.

Transport Emergency Card: TEC (R)-11-1 (in cylinders); 11-2 (refrigerated gas)

ADDITIONAL INFORMATION

ICSC: 0021 **CARBON DIOXIDE**

IMPORTANT LEGAL NOTICE:	Neither the CEC or the IPCS nor any person acting on behalf of the CEC or the IPCS is responsible for the use which might be made of this information. This card contains the collective views of the IPCS Peer Review Committee and may not reflect in all cases all the detailed requirements included in national legislation on the subject. The user should verify compliance of the cards with the relevant legislation in the country of use.

Methane

International Chemical Safety Cards

METHANE

ICSC: 0291

METHANE
(cylinder)
CH_4
Molecular mass: 16.0

CAS # 74-82-8
RTECS # PA1490000
ICSC # 0291
UN # 1971;1972
EC # 601-001-00-4

TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/ SYMPTOMS	PREVENTION	FIRST AID/ FIRE FIGHTING
FIRE	Extremely flammable.	NO open flames, NO sparks, and NO smoking.	Shut off supply; if not possible and no risk to surroundings, let the fire burn itself out; in other cases extinguish with water spray, powder, carbon dioxide
EXPLOSION	Gas/air mixtures are explosive.	Closed system, ventilation, explosion-proof electrical equipment and lighting.	In case of fire: keep cylinder cool by spraying with water.Combat fire from a sheltered position.
EXPOSURE			
• **INHALATION**	Unconsciousness.	Ventilation. Breathing protection if high concentration.	Fresh air, rest. Artificial respiration if indicated. Refer for medical attention.
• **SKIN**	Serious frostbite.	Cold-insulating gloves.	ON FROSTBITE: rinse with plenty of water, do NOT remove clothes. Refer for medical attention.
• **EYES**			
• **INGESTION**			

SPILLAGE DISPOSAL	STORAGE	PACKAGING & LABELLING
Evacuate danger area! Consult an expert! Ventilation (extra personal protection: self-contained breathing apparatus).	Fireproof. Cool. Ventilation along the floor and ceiling.	F symbol R: 12 S: 9-16-33 UN Hazard Class: 2.1

SEE IMPORTANT INFORMATION ON BACK

ICSC: 0291 Prepared in the context of cooperation between the International Programme on Chemical Safety & the

International Chemical Safety Cards

METHANE

ICSC: 0291

IMPORTANT DATA	**PHYSICAL STATE; APPEARANCE:** COLOURLESS, COMPRESSED OR LIQUEFIED GAS , WITH NO ODOUR. **PHYSICAL DANGERS:** The gas is lighter than air. **CHEMICAL DANGERS:** **OCCUPATIONAL EXPOSURE LIMITS (OELs):** TLV: ppm; mg/m^3 simple asphyxiant (ACGIH 1993-1994). MAK not established.	**ROUTES OF EXPOSURE:** The substance can be absorbed into the body by inhalation. **INHALATION RISK:** On loss of containment this gas can cause suffocation by lowering the oxygen content of the air in confined areas. **EFFECTS OF SHORT-TERM EXPOSURE:** Contact with compressed or liquid gas may cause frostbite. **EFFECTS OF LONG-TERM OR REPEATED EXPOSURE:**
PHYSICAL PROPERTIES	Boiling point: -161°C Melting point: -183°C Solubility in water, ml/100 ml at 20°C: 3.3 Relative vapour density (air = 1): 0.6	Flash point: Flammable Gas Auto-ignition temperature: 537°C Explosive limits, vol% in air: 5-15
ENVIRONMENTAL DATA		

NOTES

Density of the liquid at boiling point: 0.42 kg/l. The substance may travel to a source of ignition and flash back. High concentrations in the air cause a deficiency of oxygen with the risk of unconsciousness or death. Check oxygen content before entering area. Turn leaking cylinder with the leak up to prevent escape of gas in liquid state. After use for welding, turn valve off; regularly check tubing, etc., and test for leaks with soap and water. The measures mentioned in section PREVENTION are applicable to production, filling of cylinders, and storage of the gas.

Transport Emergency Card: TEC (R)-622, 20G04
NFPA Code: H 1; F 4; R 0;

ADDITIONAL INFORMATION

ICSC: 0291 **METHANE**

IMPORTANT LEGAL NOTICE:

Neither the CEC or the IPCS nor any person acting on behalf of the CEC or the IPCS is responsible for the use which might be made of this information. This card contains the collective views of the IPCS Peer Review Committee and may not reflect in all cases all the detailed requirements included in national legislation on the subject. The user should verify compliance of the cards with the relevant legislation in the country of use.

Antimony

Material Safety Data Sheet

Antimony

ACC# 01610

Section 1 - Chemical Product and Company Identification

MSDS Name: Antimony
Catalog Numbers: A845-500
Synonyms: Stibium; antimony regulus
Company Identification:
Fisher Scientific
1 Reagent Lane
Fair Lawn, NJ 07410
For information, call: 201-796-7100
Emergency Number: 201-796-7100
For CHEMTREC assistance, call: 800-424-9300
For International CHEMTREC assistance, call: 703-527-3887

Section 2 - Composition, Information on Ingredients

CAS#	Chemical Name	Percent	EINECS/ELINCS
7440-36-0	ANTIMONY	>=99.5	231-146-5

Section 3 - Hazards Identification

EMERGENCY OVERVIEW

Appearance: silver white solid.
Warning! Causes eye, skin, and respiratory tract irritation. Harmful if inhaled or swallowed. Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment. May cause blood abnormalities. May cause cardiac disturbances. Inhalation of fumes may cause metal-fume fever.
Target Organs: Kidneys, liver, cardiovascular system.

Potential Health Effects

Eye: Causes eye irritation. May cause conjunctivitis.
Skin: Causes skin irritation. Chronic exposure may cause dizziness, dry throat, sleepiness, anorexia, and nausea. Chronic inhalation may result in liver, kidney, and cardiac changes.
Ingestion: May cause severe digestive tract irritation with abdominal pain, nausea, vomiting and diarrhea. May cause slow pulse, low blood pressure, shallow breathing, and
Inhalation: Dust is irritating to the respiratory tract. Inhalation of fumes may cause metal fume fever, which is characterized by flu-like symptoms with metallic taste, fever, chills, cough, weakness, chest pain, muscle pain and increased white blood cell count.
Chronic: Prolonged or repeated skin contact may cause dermatitis. Chronic exposure may cause dizziness, dry throat, sleepiness, anorexia, and nausea. Chronic inhalation may result in liver, kidney, and cardiac changes.

Section 4 - First Aid Measures

Eyes: Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical aid.
Skin: Get medical aid. Flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes.
Ingestion: If victim is conscious and alert, give 2-4 cupfuls of milk or water. Never give anything by mouth to an unconscious person. Get medical aid.
Inhalation: Remove from exposure and move to fresh air immediately. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical aid.
Notes to Physician: Treat symptomatically and supportively.
Antidote: The use of Dimercaprol or BAL (British Anti-Lewisite) as a chelating agent should be determined by qualified medical personnel.

Section 5 - Fire Fighting Measures

General Information: As in any fire, wear a self-contained breathing apparatus in pressure-demand, MSHA/NIOSH (approved or equivalent), and full protective gear. Material will burn in a fire. Dust can be an explosion hazard when exposed to heat or flame. Bulk metal is combustible in air at high temperatures.
Extinguishing Media: DO NOT USE WATER, CO2, OR FOAM DIRECTLY ON FIRE ITSELF. Use dry sand, graphite powder, dry sodium chloride-based extinguishers.
Flash Point: Not applicable.
Autoignition Temperature: 330 deg C (626.00 deg F)
Explosion Limits, Lower:0.42 oz/ft3
Upper: Not available.
NFPA Rating: (estimated) Health: 2; Flammability: 1; Instability: 0

Section 6 - Accidental Release Measures

General Information: Use proper personal protective equipment as indicated in Section 8.
Spills/Leaks: Vacuum or sweep up material and place into a suitable disposal container. Avoid generating dusty conditions.

Section 7 - Handling and Storage

Handling: Use with adequate ventilation. Minimize dust generation and accumulation. Avoid contact with eyes. Keep away from heat, sparks and flame. Avoid ingestion and inhalation.
Storage: Keep away from heat and flame. Do not store in direct sunlight. Store in a cool, dry, well-ventilated area away from incompatible substances. Tarnishes in moist air.

Section 8 - Exposure Controls, Personal Protection

Engineering Controls: Use adequate general or local exhaust ventilation to keep airborne concentrations below the permissible exposure limits.
Exposure Limits

Chemical Name	ACGIH	NIOSH	OSHA - Final PELs
ANTIMONY	0.5 mg/m3 TWA	0.5 mg/m3 TWA 50 mg/m3 IDLH	0.5 mg/m3 TWA

OSHA Vacated PELs: ANTIMONY: 0.5 mg/m3 TWA
Personal Protective Equipment
Eyes: Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.
Skin: Wear appropriate gloves to prevent skin exposure.
Clothing: Wear appropriate protective clothing to minimize contact with skin.
Respirators: Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced.

Section 9 - Physical and Chemical Properties

Physical State: Solid
Appearance: silver white
Odor: none reported
pH: Not available.
Vapor Pressure: Negligible.
Vapor Density: Not available.
Evaporation Rate: Negligible.
Viscosity: Not available.
Boiling Point: 1635 deg C
Freezing/Melting Point:630 deg C
Decomposition Temperature: Not available.
Solubility: Insoluble in water.
Specific Gravity/Density: 6.684
Molecular Formula: Sb
Molecular Weight:121.71

Section 10 - Stability and Reactivity

Chemical Stability: Stable at room temperature in closed containers under normal storage and handling conditions.
Conditions to Avoid: Incompatible materials, ignition sources, moisture.
Incompatibilities with Other Materials: Incompatible with ammonium nitrate, bromine, bromine trifluoride, bromoazide, chloric acid, chlorine, chlorine monoxide, chlorine trifluoride, fluorine, iodine, nitric acid, potassium nitrate, potassium permanganate, potassium peroxide, sodium nitrate, and sodium peroxide.
Hazardous Decomposition Products: Stibine fumes.
Hazardous Polymerization: Has not been reported.

Section 11 - Toxicological Information

RTECS#:
CAS# 7440-36-0: CC4025000
LD50/LC50:
CAS# 7440-36-0:
Oral, rat: LD50 = 7 gm/kg;
.

Carcinogenicity:
CAS# 7440-36-0: Not listed by ACGIH, IARC, NTP, or CA Prop 65.

Epidemiology: Present evidence in humans is inconclusive regarding an increased risk of lung cancer and reproductive disorders from antimony exposure.
Teratogenicity: No data available.
Reproductive Effects: No data available.

Mutagenicity: No data available.
Neurotoxicity: No data available.
Other Studies:

Section 12 - Ecological Information

No information available.

Section 13 - Disposal Considerations

Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. US EPA guidelines for the classification determination are listed in 40 CFR Parts 261.3. Additionally, waste generators must consult state and local hazardous waste regulations to ensure complete and accurate classification.
RCRA P-Series: None listed.
RCRA U-Series: None listed.

Section 14 - Transport Information

	US DOT	Canada TDG
Shipping Name:	ANTIMONY POWDER	ANTIMONY POWDER
Hazard Class:	6.1	6.1
UN Number:	UN2871	UN2871
Packing Group:	III	III

Section 15 - Regulatory Information

US FEDERAL

TSCA
CAS# 7440-36-0 is listed on the TSCA inventory.
Health & Safety Reporting List
CAS# 7440-36-0: Effective 10/4/82, Sunset 10/4/92
Chemical Test Rules
None of the chemicals in this product are under a Chemical Test Rule.
Section 12b

None of the chemicals are listed under TSCA Section 12b.

TSCA Significant New Use Rule

None of the chemicals in this material have a SNUR under TSCA.

CERCLA Hazardous Substances and corresponding RQs

CAS# 7440-36-0: 5000 lb final RQ (no reporting of releases of this hazardous substance is requir

SARA Section 302 Extremely Hazardous Substances

None of the chemicals in this product have a TPQ.

SARA Codes

CAS # 7440-36-0: immediate, delayed.

Section 313

This material contains ANTIMONY (CAS# 7440-36-0, >=99.5%),which is subject to the reporting requirements of Section 313 of SARA Title III and 40 CFR Part 373.

Clean Air Act:

This material does not contain any hazardous air pollutants.
This material does not contain any Class 1 Ozone depletors.
This material does not contain any Class 2 Ozone depletors.

Clean Water Act:

None of the chemicals in this product are listed as Hazardous Substances under the CWA. CAS# 7440-36-0 is listed as a Priority Pollutant under the Clean Water Act. CAS# 7440-36-0 is listed as a Toxic Pollutant under the Clean Water Act.

OSHA:

None of the chemicals in this product are considered highly hazardous by OSHA.

STATE

CAS# 7440-36-0 can be found on the following state right to know lists: California, New Jersey, Pennsylvania, Minnesota, Massachusetts.

California Prop 65

California No Significant Risk Level: None of the chemicals in this product are listed.

European/International Regulations

European Labeling in Accordance with EC Directives

Hazard Symbols:

XN N

Risk Phrases:

R 20/22 Harmful by inhalation and if swallowed.
R 51/53 Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment.

Safety Phrases:

S 61 Avoid release to the environment. Refer to special instructions /safety data sheets.

WGK (Water Danger/Protection)

CAS# 7440-36-0: No information available.

Canada - DSL/NDSL

CAS# 7440-36-0 is listed on Canada's DSL List.

Canada - WHMIS

This product has a WHMIS classification of D1B.
This product has been classified in accordance with the hazard criteria of the Controlled Products Regulations and the MSDS contains all of the information required by those

regulations.

Canadian Ingredient Disclosure List

CAS# 7440-36-0 is listed on the Canadian Ingredient Disclosure List.

Section 16 - Additional Information

MSDS Creation Date: 5/26/1998
Revision #6 Date: 2/11/2008

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Antimony Trioxide

International Chemical Safety Cards

ANTIMONY TRIOXIDE

ICSC: 0012

ANTIMONY TRIOXIDE
Antimony sesquioxide
Antimony(III) oxide
Antimony white
Sb_2O_3
Molecular mass: 291.5

CAS # 1309-64-4
RTECS # CC5650000
ICSC # 0012
UN # 1549
EC # 051-005-00-X

TYPES OF HAZARD/ EXPOSURE	ACUTE HAZARDS/ SYMPTOMS	PREVENTION	FIRST AID/ FIRE FIGHTING
FIRE	Not combustible. Gives off irritating or toxic fumes (or gases) in a fire.		In case of fire in the surroundings: all extinguishing agents allowed.
EXPLOSION			
EXPOSURE		PREVENT DISPERSION OF DUST! STRICT HYGIENE! AVOID EXPOSURE OF (PREGNANT) WOMEN!	
• INHALATION	Cough. Headache. Nausea. Sore throat. Vomiting.	Local exhaust or breathing protection.	Fresh air, rest. Refer for medical attention.
• SKIN	Redness. Pain. Blisters.	Protective gloves.	Remove contaminated clothes. Rinse and then wash skin with water and soap.
• EYES	Redness. Pain.	Safety goggles, or eye protection in combination with breathing protection if powder.	First rinse with plenty of water for several minutes (remove contact lenses if easily possible), then take to a doctor.
• INGESTION	Abdominal pain. Diarrhoea. Sore throat. Vomiting. Burning sensation in the stomach (further see Inhalation).	Do not eat, drink, or smoke during work.	Rinse mouth. Refer for medical attention.

SPILLAGE DISPOSAL	STORAGE	PACKAGING &

		LABELLING
Sweep spilled substance into containers. Carefully collect remainder, then remove to safe place. Do NOT let this chemical enter the environment (extra personal protection: P2 filter respirator for harmful particles).	Separated from food and feedstuffs.	Do not transport with food and feedstuffs. Xn symbol R: 40 S: 22-36 UN Hazard Class: 6.1

SEE IMPORTANT INFORMATION ON BACK

ICSC: 0012

International Chemical Safety Cards

ANTIMONY TRIOXIDE

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IMPORTANT DATA	**PHYSICAL STATE; APPEARANCE:** ODOURLESS WHITE CRYSTALLINE POWDER. **PHYSICAL DANGERS:** **CHEMICAL DANGERS:** The substance decomposes on heating producing toxic fumes (antimony). Reacts under certain circumstances with hydrogen, producing a very poisonous gas (stibine). **OCCUPATIONAL EXPOSURE LIMITS (OELs):** TLV (as Sb): ppm; 0.5 mg/m^3 (as TWA) (ACGIH 1991-1992).	**ROUTES OF EXPOSURE:** The substance can be absorbed into the body by inhalation of its aerosol. **INHALATION RISK:** Evaporation at 20°C is negligible; a harmful concentration of airborne particles can, however, be reached quickly on dispersion. **EFFECTS OF SHORT-TERM EXPOSURE:** The substance irritates the eyes, the skin and the respiratory tract. **EFFECTS OF LONG-TERM OR REPEATED EXPOSURE:** Repeated or prolonged contact with skin may cause dermatitis. Lungs may be affected by repeated or prolonged exposure to the dust of this substance. The substance may have effects on the lungs. This substance is possibly carcinogenic to humans. Animal tests show that this substance possibly causes toxic effects upon human reproduction.
PHYSICAL PROPERTIES	Boiling point: (partially sublimes) 1550°C Melting point: 656°C (see Notes)°C Relative density (water = 1): 5.2/5.7 (see Notes)	Solubility in water, g/100 ml at 30°C: none Vapour pressure, Pa at 574°C: 130
ENVIRONMENTAL DATA	This substance may be hazardous to the environment; special attention should be given to fish. In the food chain important to humans, bioaccumulation takes place, specifically in crustacea.	

NOTES

Melting point established under the absence of oxygen. Density differs with crystalline structure. Depending on the degree of exposure, periodic medical examination is indicated. The recommendations on this card do not apply to vapour exposure during the production. Timonox is a trade name.

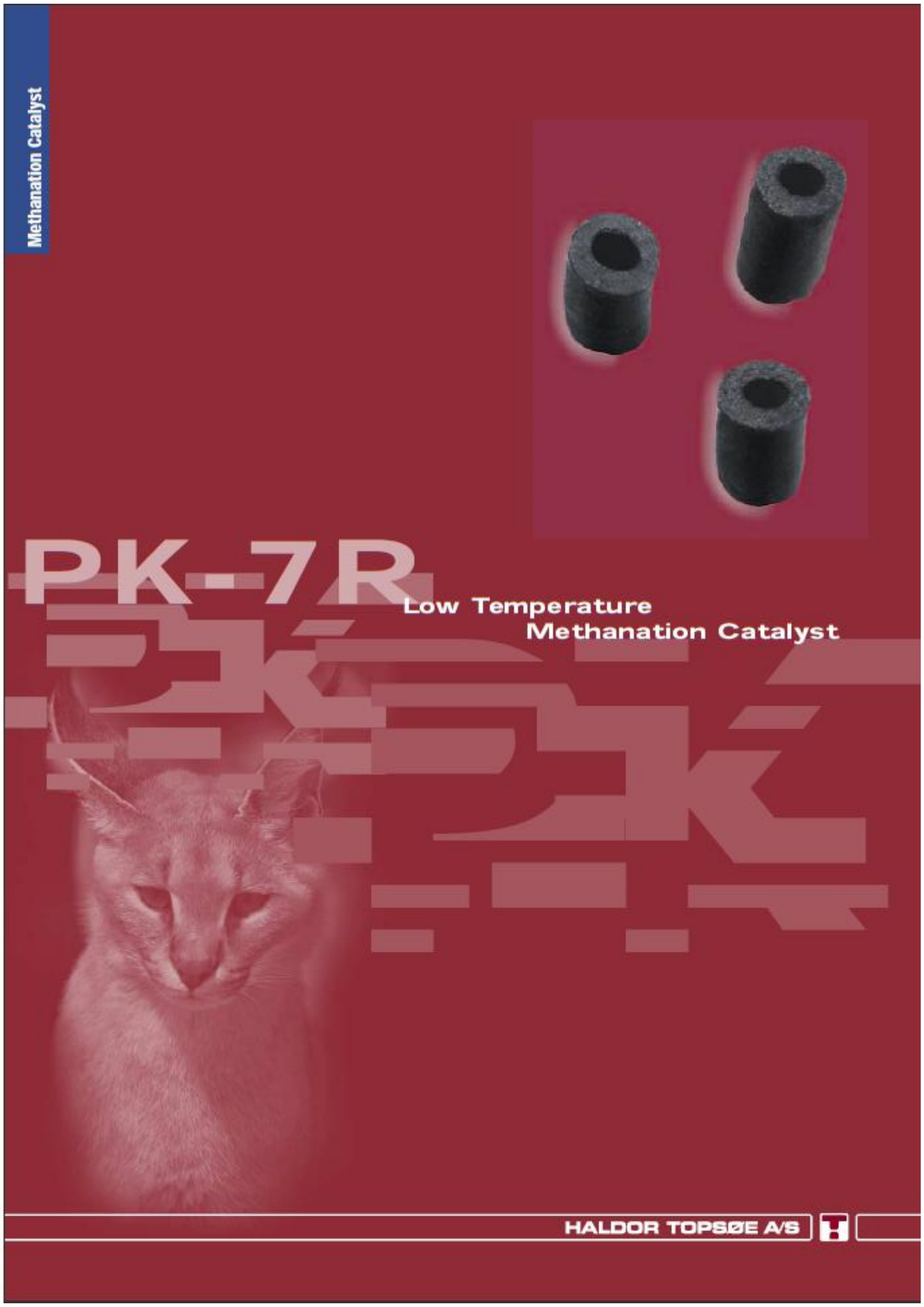
Transport Emergency Card: TEC (R)-61G11

ADDITIONAL INFORMATION

ICSC: 0012 **ANTIMONY TRIOXIDE**

IMPORTANT LEGAL NOTICE:	Neither the CEC or the IPCS nor any person acting on behalf of the CEC or the IPCS is responsible for the use which might be made of this information. This card contains the collective views of the IPCS Peer Review Committee and may not reflect in all cases all the detailed requirements included in national legislation on the subject. The user should verify compliance of the cards with the relevant legislation in the country of use.

Methanation Catalyst Information



Methanation Catalyst

Methanation involves final removal of CO, CO_2 and trace quantities of O_2 from process gas in hydrogen and ammonia plants. For many years nickel catalysts have been giving adequate performance provided that the operating temperature has been sufficiently high. However, the typical operating temperature for methanation catalyst has gradually decreased due to more efficient shift catalysts and improved CO_2 removal systems. At lower operating temperatures, many plants have experienced unacceptable CO and CO_2 leakage from the methanator when using traditional catalysts.

Topsøe's highly active, prereduced methanation catalyst **PK-7R** is a nickel type catalyst based on an alumina carrier. It was developed to operate at inlet temperatures down to 190°C/375°F, a performance which has been proven in the industry since its introduction in 1994.

In plants, where the methanator is operating in low temperature range, PK-7R has provided full conversion of carbon oxides as opposed to traditional methanation catalysts used in the same service.

Advantages of PK-7R

Low Operating Temperature Capability
In most plants, process gas entering the methanator is heated from a relatively low temperature to the required inlet temperature by heat exchange with the methanator effluent gas. With more efficient CO shift and CO_2-removal technology available today, the temperature increase in such methanators will inevitably decrease and lead to a lower methanator inlet temperature. In these cases, use of conventional methanation catalysts may no longer ensure a full CO and CO_2 conversion.

The capability of PK-7R to operate at low temperatures will ensure that CO and CO_2 are fully converted at an operating temperature of 190°C/375°F. Furthermore, the lower level of the operating temperature will often lead to savings in energy consumption.

Prereduced for Higher Activity
The superior activity and capability of PK-7R to operate at low temperatures are a result of Topsøe's optimised catalyst production and prereduction technology. PK-7R is reduced in our catalyst manufacturing plant under carefully controlled conditions, which cannot be reproduced in industrial plants and result in a substantially higher nickel surface area, which is preserved during the entire operating lifetime.

Low Pressure Drop
With the ring-shaped PK-7R catalyst, a 50% reduction in pressure drop is achieved relative to the conventional spherical or cylindrical shaped methanation catalysts. This shape also yields a higher catalyst activity resulting from a higher external surface/volume ratio.

TYPICAL CHEMICAL AND PHYSICAL CHARACTERISTICS FOR PK-7R

	EXTRUDED RING
Ni (WT %)	> 23
SIZE, OD X ID	5 x 2.5 mm 3/16" x 3/32"
OPERATING TEMPERATURE RANGE	190 - 450°C 375 - 840°F

Excellent Resistance towards Poisoning
The controlled prereduction of PK-7R, combined with the high nickel surface area, ensures an excellent resistance towards catalyst poisoning.

High Thermal Resistance
PK-7R has a very high thermal stability and can tolerate temperatures as high as 700°C/1300°F. Consequently, the catalyst can withstand temperature excursions caused by upsets in CO_2 removal systems or other operating problems. The extraordinary thermal stability of PK-7R also minimises catalyst deterioration by ageing, thereby ensuring a long lifetime.

Catalyst Operation

Ease of Handling, Loading and Activation
PK-7R is stable in air at ambient temperatures and, with a few extra precautions, may be handled and loaded in the same manner as conventional methanation catalysts. Because PK-7R is delivered prereduced, no special procedure is required to activate the catalyst. The catalyst is simply exposed to process gas at normal operating conditions and methanation begins immediately.

Normal Operation and Catalyst Lifetime
The high activity of PK-7R allows operation at inlet temperatures as low as 190°C/375°F with fully satisfactory conversion of all carbon oxides and oxygen. Typically, the maximum recommended temperature for continuous operation is 450°C/840°F.

The temperature increase across the methanation catalyst depends on composition of feed gas.
The approximate temperature rise is
- 75°C/135°F per mole% CO
- 60°C/108°F per mole% CO_2
- 165°C/297°F per mole% O_2 converted

Deactivation of methanation catalyst generally results from thermal ageing, poisoning by impurities in the process gas or excessive carry-over of solvent from the CO_2 removal system. PK-7R possesses exceptional resistance towards thermal ageing and poisoning and a charge of PK-7R is expected to provide excellent performance for more than 10 years.

After Sales Service
Topsøe provides assistance and follow-up service during the lifetime of the catalyst charge in form of regular performance evaluations and troubleshooting, if required.

A complete catalyst manual including step-by-step procedures for loading and operation of the PK-7R catalyst, is supplied in connection with catalyst purchase.

Topsøe R & D
Topsøe's worldwide services to the chemical, petrochemical and refining industries are based on a fundamental understanding of heterogeneous catalysis, including development and production of catalysts, process technologies and engineering services.

Quality catalysts
– proven by performance
Topsøe's unique integrated approach has resulted in profitable solutions providing catalysts in the areas of:

· Feed Purification
· Adiabatic Steam Reforming
· Steam Reforming
· CO Shift Conversion
► **Methanation**
· Ammonia Synthesis
· Methanol Synthesis
· Formaldehyde
· Sulphuric Acid
· Refinery Hydroprocessing
· DeNOx and DeSOx
· Combustion of VOC

Based on many years of experience, the development of Topsøe catalysts is dedicated to provide a second-to-none performance. This means that focus always is on key factors such as enhancement of high and stable activity, long operating life, high resistance to poisoning, low pressure drop, energy savings and reduced emissions.

Customised after sales service
Topsøe's after sales service relies upon an on-going exchange of information between the client and us, to provide clients with relevant and most up-to-date information. The four pillars in Topsøe's service programme are:
Frequent Contact and Discussions, On-site Supervision, Evaluation of Plant Performance and Troubleshooting.

Visit www.haldortopsoe.com for more information.

The information and recommendations have been prepared by Topsøe specialists having a thorough knowledge of catalysts. However, any operation instructions should be considered to be of a general nature and we cannot assume any liability for upsets or damage of the customers' plants or personnel. Nothing herein is to be construed as recommending any practice or any product in violation of any patent, law or regulation.

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