4-2016

High-Temperature Nuclear Power Cycle Using Either Helium or s-CO2

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Mink, Sally E.; Gedal, Stephanie E.; Weber, Dillon M.; and Dantuluri, Abhinav, "High-Temperature Nuclear Power Cycle Using Either Helium or s-CO2" (2016). *Senior Design Reports (CBE)*. Paper 84.
http://repository.upenn.edu/cbe_sdr/84

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Abstract

The goal of this process was to model the helium-based modular, nuclear reactor power cycle after the existing MIT Pebble-Bed Nuclear Reactor Power Cycle (Kadak, 2005), and to improve on the design by changing the working fluid to supercritical carbon dioxide (s-CO_2). The power output of the process as specified in the problem statement, provided by Adam Brostow, was 120 MW. S-CO_2 is a much denser fluid, and should theoretically require smaller equipment sizes, making it the more economically viable option for this process. However, it was found that with a return on investment (ROI) of -2.13% and a net present value (NPV) of -$489 million, this process was not economically feasible, due to the high temperatures, pressures, and flow rates required. This process had an electrical output of 118 MW, while the helium met the design condition of 120 MW. The helium process had a ROI of 11% and a NPV of $241 million. For this reason, helium is recommended as the working fluid for a nuclear reactor power cycle of this magnitude.

Disciplines

Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering

University of Pennsylvania

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Philadelphia, PA 19104

April 5th, 2016

Dear Professor Fabiano, Dr. Seider, and Mr. Brostow,

Enclosed are the contents of the written report containing the solution to the design problem recommended by Adam A.Brostow of Air Products and Chemicals. The assignment was in two parts: to model a helium-based modular, nuclear, power plant that would produce 120 MW of electricity, and then to try to improve it by changing the working fluid to supercritical carbon dioxide (s-CO_2). Mr. Brostow provided an existing process flow diagram designed by MIT as a Pebble-Bed Nuclear Reactor Power Cycle.

The electrical output of the helium process meets the 120 MW design condition exactly and the s-CO_2 process supplies 118 MW. Theoretically, the s-CO_2 cycle should be more economically feasible because it is a denser fluid than helium, and should require smaller equipment sizes. After a thorough investigation, it was found that the s-CO_2 cycle was not economically feasible, with a return on investment of -2.13% and a net present value of -$489 million, due to the high temperatures, pressures, and flow rates necessary for the design. The helium, by contrast, has a return on investment of 11% and a net present value of $241 million. For this reason, helium is recommended as the working fluid of choice for such a design.

Both the helium and s-CO_2 processes were modeled on ASPEN Plus V8.8. The cost estimates and profitability analysis were calculated using the ASPEN Process Economic Analyzer, ASPEN Exchanger Design & Rating, the “Profitability Analysis-4.0” Microsoft Excel spreadsheet prepared by Brian Downey, and *Product and Process Design Principles 3rd Edition*, by Seider, Seader, Lewin, & Widagdo.

We would like to thank you and the industrial consultants, Richard Bockrath, Gary Sawyer, and David M. Kolesar, for your assistance throughout this project.

Sincerely,

Abhinav Dantuluri Sally Mink

Dillon Weber Stephanie Gedal

High-Temperature Nuclear Power Cycle Using Either Helium or s-CO_2

Senior Design Project, CBE 459

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Project submitted to:	Professor Leonard A. Fabiano
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April 12, 2016

Table of Contents

1. Abstract

The goal of this process was to model the helium-based modular, nuclear reactor power cycle after the existing MIT Pebble-Bed Nuclear Reactor Power Cycle (Kadak, 2005), and to improve on the design by changing the working fluid to supercritical carbon dioxide (s-CO_2). The power output of the process as specified in the problem statement, provided by Adam Brostow, was 120 MW. S-CO_2 is a much denser fluid, and should theoretically require smaller equipment sizes, making it the more economically viable option for this process. However, it was found that with a return on investment (ROI) of -2.13% and a net present value (NPV) of -$489 million, this process was not economically feasible, due to the high temperatures, pressures, and flow rates required. This process had an electrical output of 118 MW, while the helium met the design condition of 120 MW. The helium process had a ROI of 11% and a NPV of $241 million. For this reason, helium is recommended as the working fluid for a nuclear reactor power cycle of this magnitude.

2. Introduction and Objective-Time Chart

2.1 Introduction

The idea behind using a nuclear reactor to generate electricity is that the entire process runs on clean energy. The nuclear reactor is used to heat the helium to a high temperature. The process of generating electricity using this heat was first published by MIT (Kadak, 2005), and the process diagram is shown below in Figure 2.1. The hot helium stream coming from the reactor is sent through the intermediate heat exchanger and then expanded in a series of turbines, also known as expanders, which power the compressors and generate the electricity for the process. The compressors, in conjunction with the intercoolers, provide the cooled and compressed fluid that absorbs heat in the recuperator heat exchanger. This cycle is known as the Brayton Power Cycle.

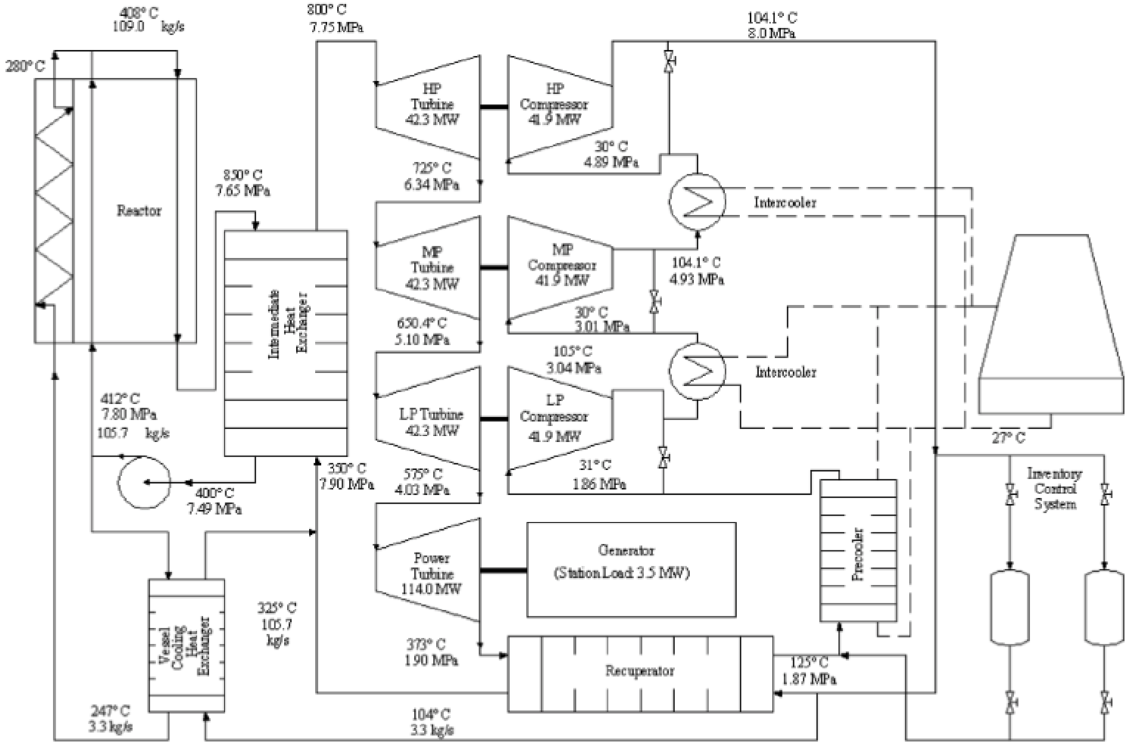


Figure 2.1. MIT Pebble-Bed Nuclear Reactor Power Cycle (Kadak, 2005).

For the purposes of this project, the details concerning the nuclear reactor were considered out-of-scope. As specified by Kadak in his paper, the reactor would be a pebble-bed type. These types of reactors are inherently safer than other options because they prevent the possibility of a meltdown or fuel damage and support online refueling. The fundamental concept of the reactor is that it takes advantage of the high temperature properties of helium, permitting thermal efficiencies upwards of 50%.

This helium-based cycle was to be modeled first, and then compared to a similar process using supercritical carbon dioxide (s-CO_2) as the working fluid. There was also discussion of the possibility of a combined cycle, using both helium and s-CO_2 as the working fluids in conjunction with each other, but this was concluded as out-of-scope for this project. The idea behind using s-CO_2 instead of helium is that, as a supercritical fluid, the s-CO_2 is much more dense than helium, reducing the compression and capital costs of operation, which is important in developing a modular design. The helium-based nuclear power cycle process, as shown in Figure 2.1, was likely to be changed when s-CO_2 became the working fluid. The assignment was to make this process economically more feasible than the helium-based process, because CO_2 is much more readily available than helium.

2.2 Objective-Time Chart

Project Name: High-Temperature Nuclear Power Cycle Using Either Helium or s-CO2

Project Leaders: Sally Mink, Steph Gedal, Dillon Weber, Abhinav Dantuluri

Specific Goals: Model two high-temperature nuclear reactor power cycles after the MIT design using the ASPEN Plus process simulator: one with helium as the working fluid and one with supercritical carbon dioxide as the working fluid.

Project Scope:

In-Scope

- Power cycles generating 120 MW for both the helium-based and s-CO_2-based processes.
- A profitable cycle for both, with the s-CO_2 cycle potentially more economical due to s-CO_2 being more dense

Out-of-Scope

- A similar power cycle design, except with concentrated solar power as the source of energy
- Nuclear reactor details and design
- Combined cycle (both helium and s-CO_2 as the working fluids)

Deliverables:

- Business Opportunity Assessment
    - Will the s-CO_2 cycle end up being more profitable than the helium cycle as expected?
    - Will either cycle be profitable?
- Technical Feasibility Assessment
    - Will the designs be technically feasible?
- Manufacturing Capability Assessment
    - Can the design be manufactured without significant capital investment?
- Timeline Assessment
    - Will the processes achieve a reasonable investor rate of return?

Timeline: Complete design and economic analysis by April 12, 2015.

3. Market and Competitive Analyses

The helium process will produce 120 MW of electricity for sale in the PJM Interconnection wholesale market, which is North America's largest wholesale electricity market and serves Pennsylvania and many of the surrounding states. According to analysis of data from the Energy Information Administration (EIA) – a branch of the United States Department of Energy responsible for providing energy data and forecasts for prices – on wholesale prices, electricity sold for an average of $54/MWh over the last 5 years in this market. However, a recommended price of $70/MWh was used after consultation with technical advisors (Seider, et al., 2016). In addition, the EIA predicts that United States electricity prices to rise at an annual rate of 0.6% to 2040, so this forecast was used to model changes in the price of the product over the lifetime of the process.

The current peak electricity demand in the PJM market is approximately 183 GW (188,000 MW). Moody's Analytics has predicted this demand will grow at an average rate of 0.9% over the next 15 years ("PJM Load," 2015), meaning additional generation capacity will be needed as older power plants retire. By 2020, at least 2,653 MW of capacity is set to retire in the PJM market and this process aims to be the replacement of choice for investors for several key reasons ("Future Deactivations," 2016).

First, this process produces electricity without generation of carbon dioxide or other harmful emissions into the environment. The implementation of the Clean Power Plan in the PJM market will ensure strong demand for carbon-free power, and the growing possibility of further economic or regulatory restrictions on greenhouse-gas emitting power sources, such as a Carbon Tax or Cap and Trade Scheme, means the product will be increasingly attractive to investors worried about the regulatory risk of CO_2. Regardless of political concerns regarding climate change, it is clear that there is a sustained market for carbon-free power in the United States generally and in PJM specifically.

Second, this process is a reliable source of baseload power, meaning a reliable electricity generation source that can generate at all hours of the day and night. The process avoids the inherent, intangible risks of intermittency that are associated with renewable power while remaining carbon-free. Much of the retiring electricity capacity in this market is from thermal coal plants, which were originally sources of baseload power—consistently available for generation of electricity at any time. Wind and photovoltaic solar generated power thus cannot perfectly replace these lost baseload coal plants because of their intermittent nature, while this process has no concern about intermittency. This makes it a logical and safe choice for replacing retiring coal plants without the need for expensive solutions like utility-scale battery storage.

This provides a strong opportunity for the helium loop to be implemented at various nuclear power plants throughout the PJM market. There are currently 33 operating nuclear units in PJM, if the process was implemented on all stations it could result in an additional power capacity of 3,960 MW.

As of 2013, nearly 4,500 MW of combined-cycle gas plants had committed to construction and operation (Spees & Pfeifenberger, 2013). This will be the main competitor in the market. An analysis of the competitiveness of this project and a combined-cycle gas turbine, as well as that of other electricity generation technologies is best pursued using the concept of a levelized cost of electricity. This cost is defined by the EIA as “the per-kilowatt-hour cost (in real dollars) of building and operating a generating plant over an assumed financial life and duty cycle” (“Levelized Cost,” 2015). Because our process and those we will be comparing it with are on a utility-scale, the levelized cost was adjusted here to a per-megawatt-hour cost in calculations.

Based on this metric, our helium process easily outcompetes coal-fired generation as well as wind and hydroelectric, according to average EIA numbers provided in the Annual Energy Outlook 2015 report (“Levelized Cost,” 2015). It is important to note that specific levelized costs will vary with each individual project and are not set for a given source of generation, and that for fuel-based generation such as natural gas combined-cycle turbines, the levelized cost is highly sensitive to the price of fuel. Consistently lower natural gas prices since the EIA Report data was gathered, and the natural gas glut in the Northeastern region due to hydraulic fracturing of shale in Pennsylvania leads to the belief that combined cycle gas levelized costs are likely much more competitive with this process than the EIA report suggests. Additionally, the EIA assumes an additional discount rate in its calculations for all CO_2 emitting power sources under the assumption a stricter regulatory framework will eventually be put in place—a further case for reducing the reported cost of natural gas generation in this comparison.

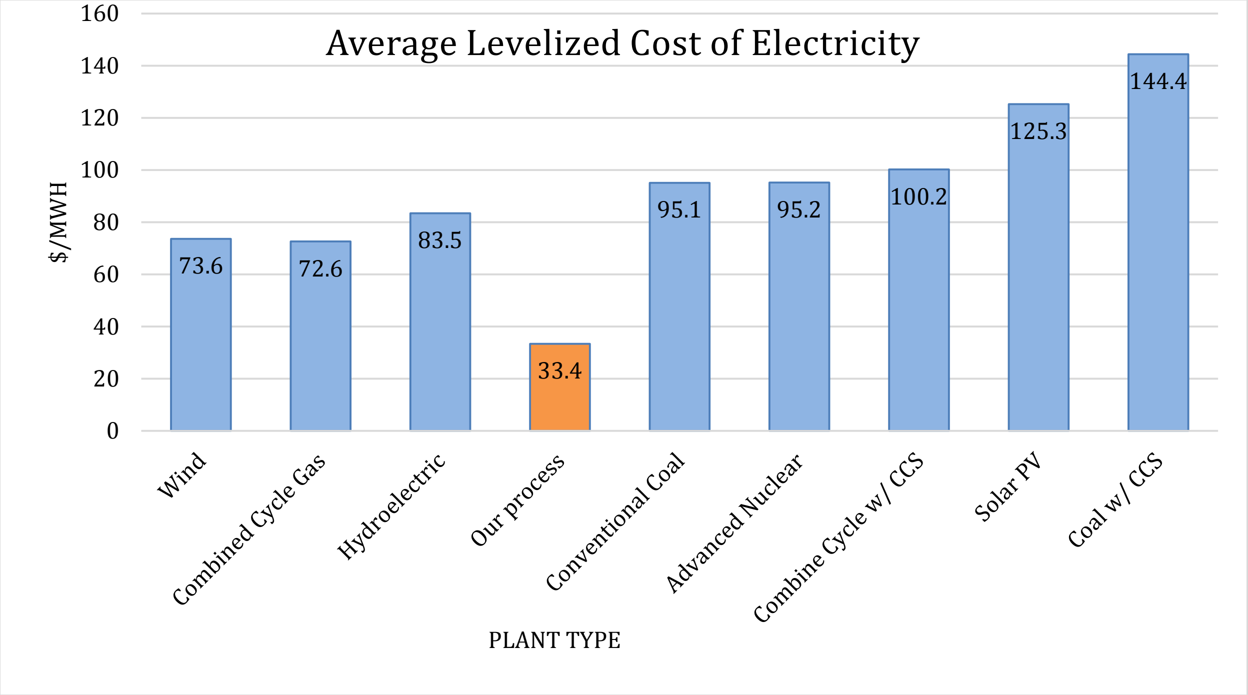


Figure 7.1: Per Megawatt-Hour Cost of Electricity for Various Generating Plants. Values presented are averages compiled throughout the United States and do not indicate the economics of any specific power plant (Conti et al., 2015).

4. Preliminary Process Synthesis

The goal of this project is to design a modular addition to a power plant that generates 120 MW of electricity in the most economically efficient way. There were two working fluids that were examined that are well suited for high temperature processes. The first of these is helium, which is a small molecule that leaks out of the system and typically requires special equipment. The limitations of using helium motivate us to replace the secondary circuit with supercritical carbon dioxide (s-CO_2). Figure 4.1 outlines the decision making process that was taken in order to determine the best possible process using the most effective working fluid. All of the alternatives are discussed in the sections below.

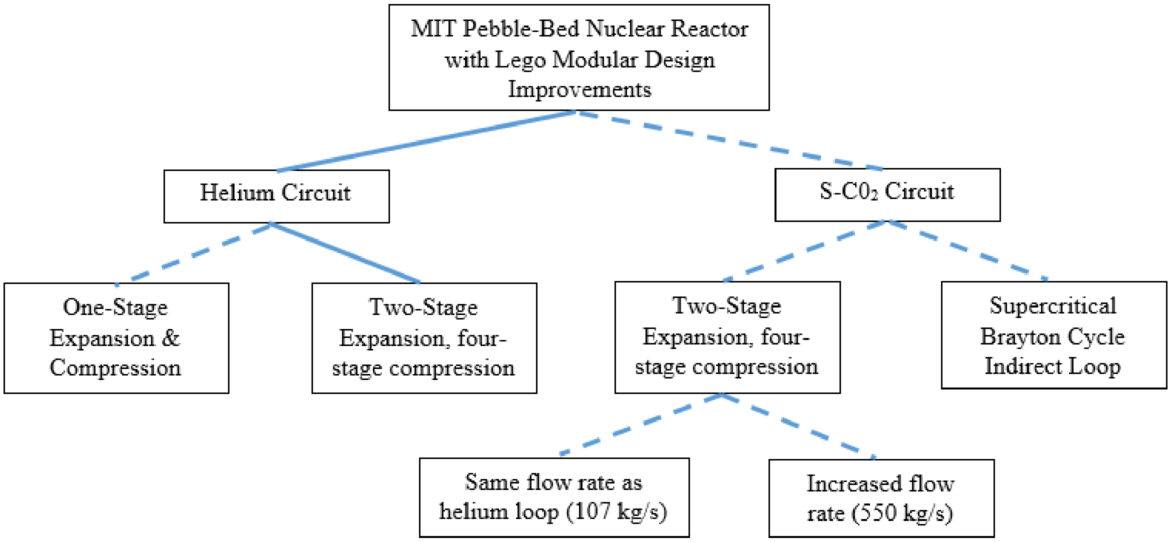


Figure 4.1. Preliminary Process Synthesis. The decision making map that was used to document all of the alternative process designs that were considered while solving the design problem.

4.1 Helium Circuit with Single Turbine-Compressor Stage

The first iteration of the power plant using helium as the working fluid followed a simplified version of the MIT Pebble-Bed Nuclear Reactor Power Cycle. The recommended 850,000 lb/hr flow rate is used in this flow diagram. However, only 26.7 MW of power is generated, which falls short of the 120 MW goal. The result is expected, because the original Pebble-Bed Power Cycle was simplified for the purpose of studying the contribution and specifications of each piece of equipment. Figure 4.2, below, shows the first step of the process design, which uses one turbine-compressor stage and follows the flow and pressure specifications of the original Pebble-Bed Power Cycle design.

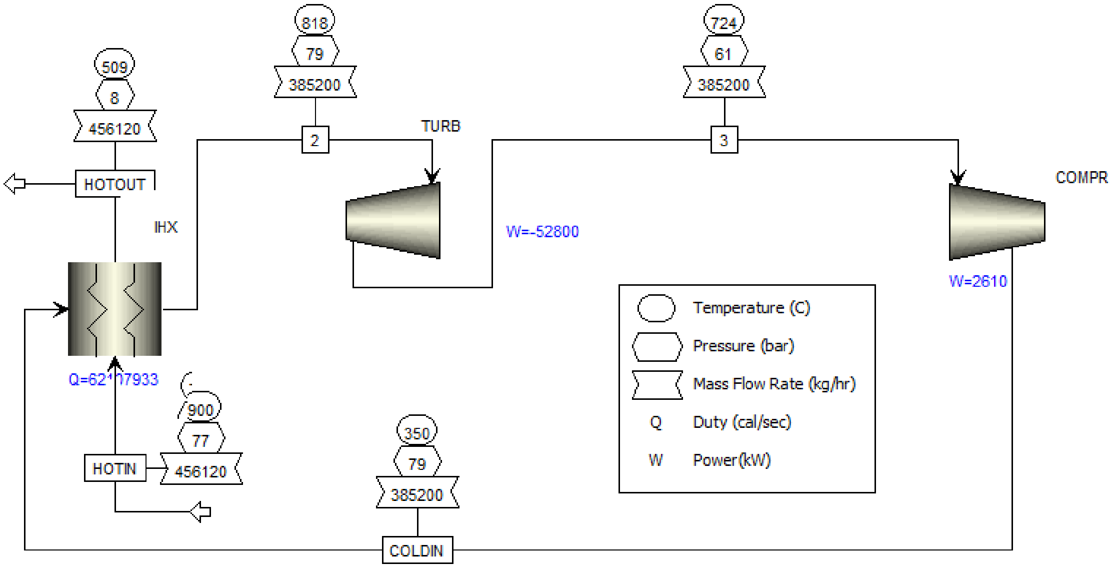


Figure 4.2. Simplified Pebble-Bed Power Cycle. This process uses helium in a single turbine-compressor stage.

4.2 Helium Circuit with Three Turbines, Four Compressors

The previous process design, Figure 4.2, was used as a starting point for the next attempt. Two more turbines and three more compressors were added in Figure 4.3, which is the helium circuit design that generates the required amount of power, 120 MW. In this design, the helium flows through three turbines, which power four compressors and generate a net of 120 MW of power. In the original Pebble-Bed Power Cycle design, each of the first two turbines powered two combined shaft compressor pairs and the last turbine acted as a generator, producing 120 MW of power. However, it was more efficient to have free-standing compressors due to their low pressure ratios and the high cost of such large combined shaft compressors. This helium circuit competes with the best iteration of the s-CO_2 circuit. Refer to the Profitability Analysis in section 15 for more information on how it was selected to be the best overall design.

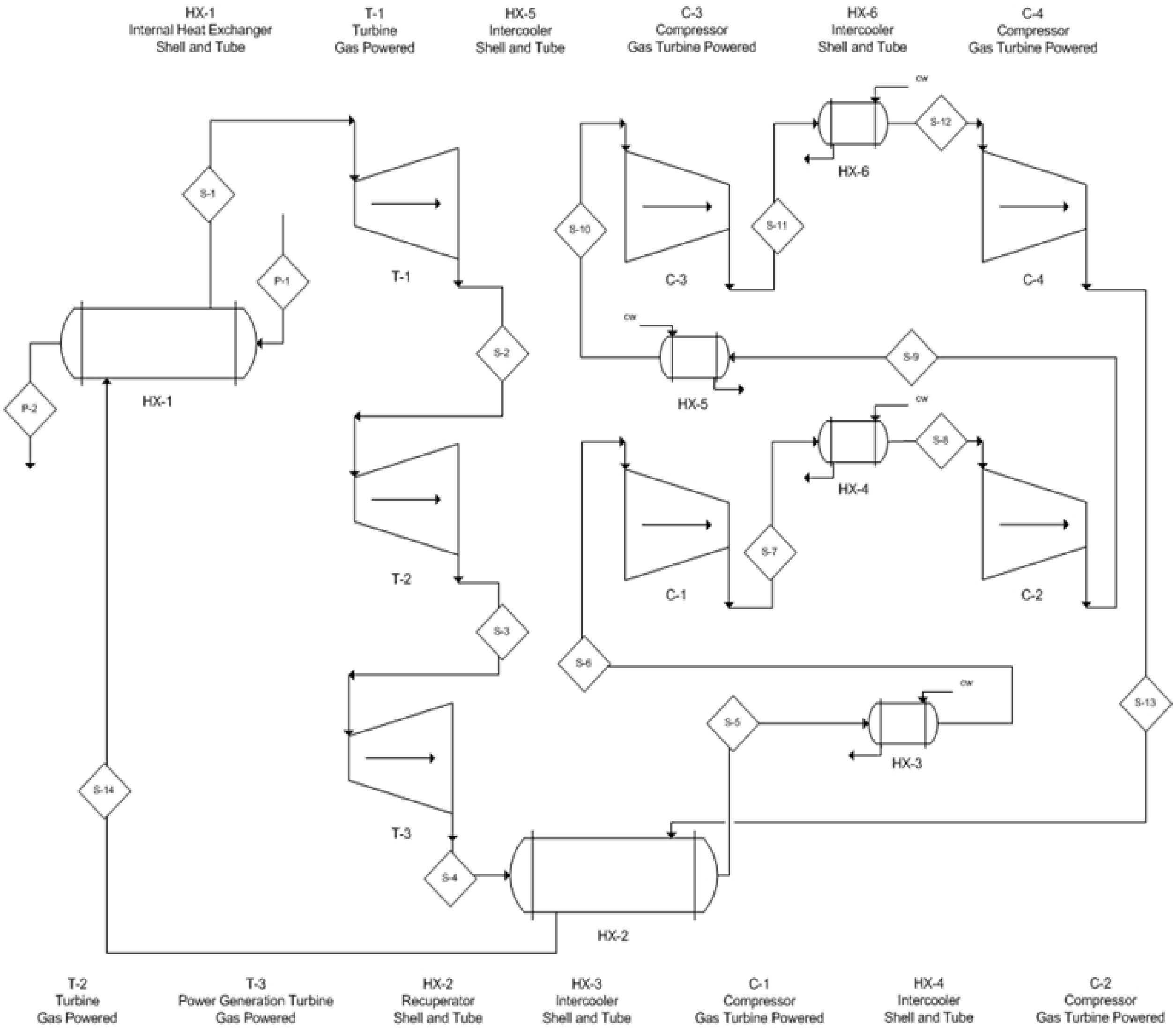


Figure 4.3. Final Process Design. Produces 120 MW of electricity. Details on profitability, especially as compared to the best design using s-CO_2 are discussed in later sections.

4.3 S-CO_2 Circuit using 850,000 lb/hr Flow Rate

This process flow diagram takes the same equipment from the Pebble-Bed Power Cycle and the flow rate used for the helium process, shown in Figure 4.3, and changes the working fluid to s-CO_2. Several key pressure and temperature changes were also necessary since the properties of the working fluid are now changed. This design does not produce nearly as much power as the helium did. This process design, shown in Figure 4.4, will act as a starting point for the iterations using s-CO_2 as the working fluid in the secondary circuit. Note that the working fluid in the primary loop, “HOT1”, is still helium.

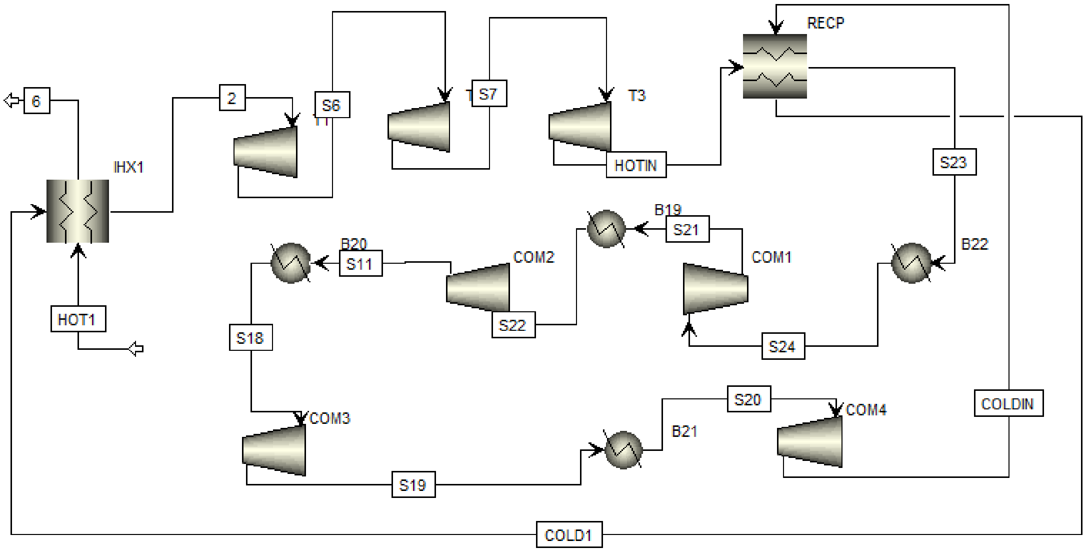


Figure 4.4. S-CO_2. Process Design using Three Turbines, Four Compressors. This process generates net power in the generator (third turbine, T3). The flow rate used for this iteration was 850,000 lb/hr.

4.4 S-CO_2 Circuit 4.4 million lb/hr Flow Rate

Since the design discussed above did not generate nearly enough power, the flow rate of the working fluid was increased about five times. Although at a flow rate of 4.4 million lb/hr slightly more power was produced, it still did not reach the 120 MW goal, so this entire design was abandoned.

4.5 S-CO_2 Supercritical Brayton Cycle

Finally, the s-CO_2. circuit was built using a modified Brayton Power Cycle for supercritical CO_2.. The Brayton cycle, as developed by the Sandia National Laboratories did not produce enough power, so the primary loop was traced through two more heat exchangers, using more residual heat to heat up two more streams before they entered turbines (Wright et al., 2010). This modification, shown in Figure 4.5, was able to generate enough power, making this process design a viable competitor to the helium process shown in Figure 4.3. The flow rate of this process, however, is 9.5 million lb/hr, which is about 10 times the flow rate in the best helium cycle. This seems unintuitive, since the reason for switching to the s-CO_2 process is so that a more dense fluid could be used to minimize the equipment size necessary, prevent leaks in the system, and avoid the high costs of helium. However, the more dense and high pressure a fluid is, the harder it is to expand it through a turbine, thereby producing less power. Since s-CO_2 did not produce enough power through the turbines at 850,000 lb/hr, it was necessary to increase the flow rate. Unfortunately, higher flowrates end up offsetting the extra power produced because the equipment sizes get extremely large. Therefore, even though s-$CO_{2.}$ is more dense than helium, the large flow rate required to get the same power output is too large to justify the high capital expenditure, making this option not economically viable. Refer to the Profitability Analysis in Section 15.1.2 for a detailed economic justification of the final process design, where the economic pitfalls of the s-CO_2 Supercritical Brayton Cycle will also be more evident.

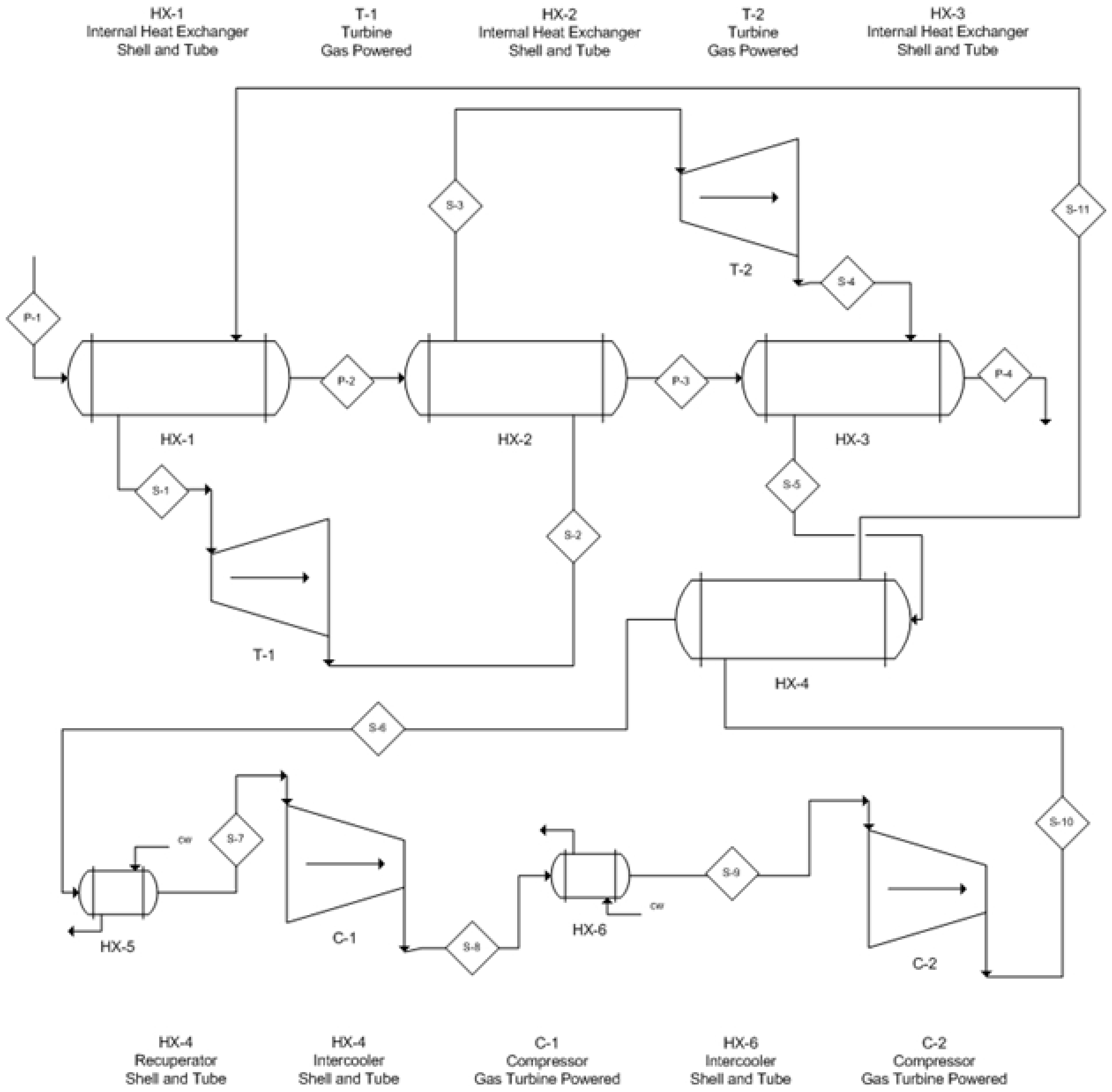


Figure 4.5. S-CO_2 Circuit Based on Supercritical Brayton Cycle. The Brayton cycle here has been slightly modified. Also, helium is still being used in the primary loop.

5. Assembly of Database

5.1 Property Methods

In this project, the Peng-Robinson (PR) property method was used during the helium process, while the Lee-Kesler Plöcker (LK PLOCK) property method was used for the supercritical carbon dioxide process in Aspen 8.8. The Peng-Robinson property method was selected for the helium process because of its ability to accurately represent a large range of gases including helium, and it was also the recommended property method by multiple industrial consultants. The Lee-Kesler Plöcker property method was selected for the s-CO_2 process because of its accuracy in representing non-polar substances, especially in the supercritical region, and it is often used in simulations for s-CO_2 Brayton cycles ("Development of a Supercritical," 2004).

5.2 Toxicity

Helium is a nontoxic asphixiant, while sCO_2 is a toxic asphixiant that must be monitored very closely (Appendix C.2). The Occupational Safety and Health Administration (OSHA) recommends a CO_2 concentration limit of 0.5% by volume for an 8-hour workday. All toxicity levels are stated on a by volume basis in this report. The American Conference of Governmental Industrial Hygienists (ACGIH) also recommends an additional ceiling exposure limit of 3%, and an immediately dangerous to life and health limit of 4%. A concentration of 9% CO_2 over a period of 5 minutes can prove to be fatal ("Appendix C," 2006). The safety protocol and alarm techniques used to ensure low levels of helium and CO_2 in the work area is covered in the Safety and Health Concerns in section 14.1.

5.3 Materials Pricing

The pricing of the materials is one of the main factors inspiring the attempted switch from using helium as the working fluid in the process to using supercritical carbon dioxide.

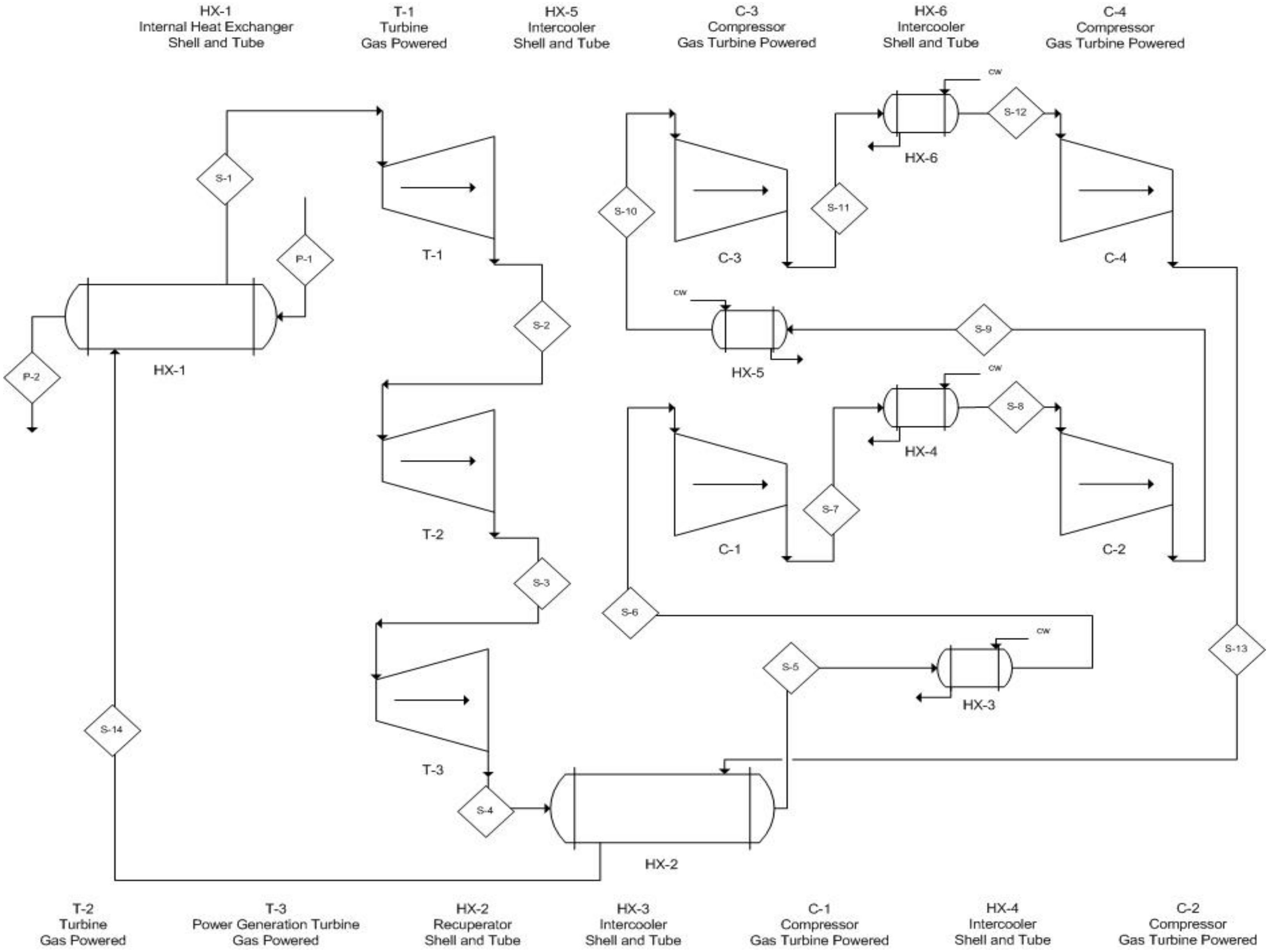
Helium is a relatively rare element on Earth, and is only found naturally in dilute quantities, at a maximum purity of about 7% (Tilghman, 2011). Carbon dioxide, however, is a waste product in most power generation facilities, and can be found in concentrations above 99% by weight in separated combustion flue gas streams (Last & Schmick, 2011). Thus, helium is relatively difficult to obtain and expensive, while carbon dioxide is quite cheap and abundant.

Helium costs around $200 per thousand cubic feet at our operating temperature and pressure (Hamak, 2016), and with an operating volume in the helium system of about 11.1 million cubic feet, that gives us a helium cost of around $2.2 million. Prices for bulk carbon dioxide are incredibly difficult to find, since although there is a lot of it available, hardly anyone is interested in buying it. However, in *small* bulk quantities the cost is around three cents per cubic foot ("Price List," 2013), which when combined with the s-CO_2 process operating volume of 626 thousand cubic feet yields a carbon dioxide cost of only $18.8 thousand. We also need to factor in about another 10% volume for small system losses throughout the operating year, as recommended by the consultants.

Both of these costs can be regarded as negligible given the costs of our processes. Also, since our s-CO_2 process is already financially infeasible, the exact price of the carbon dioxide is not important.

6. Process Flow Diagram and Material Balances

6.1 Helium Process Flow Diagram

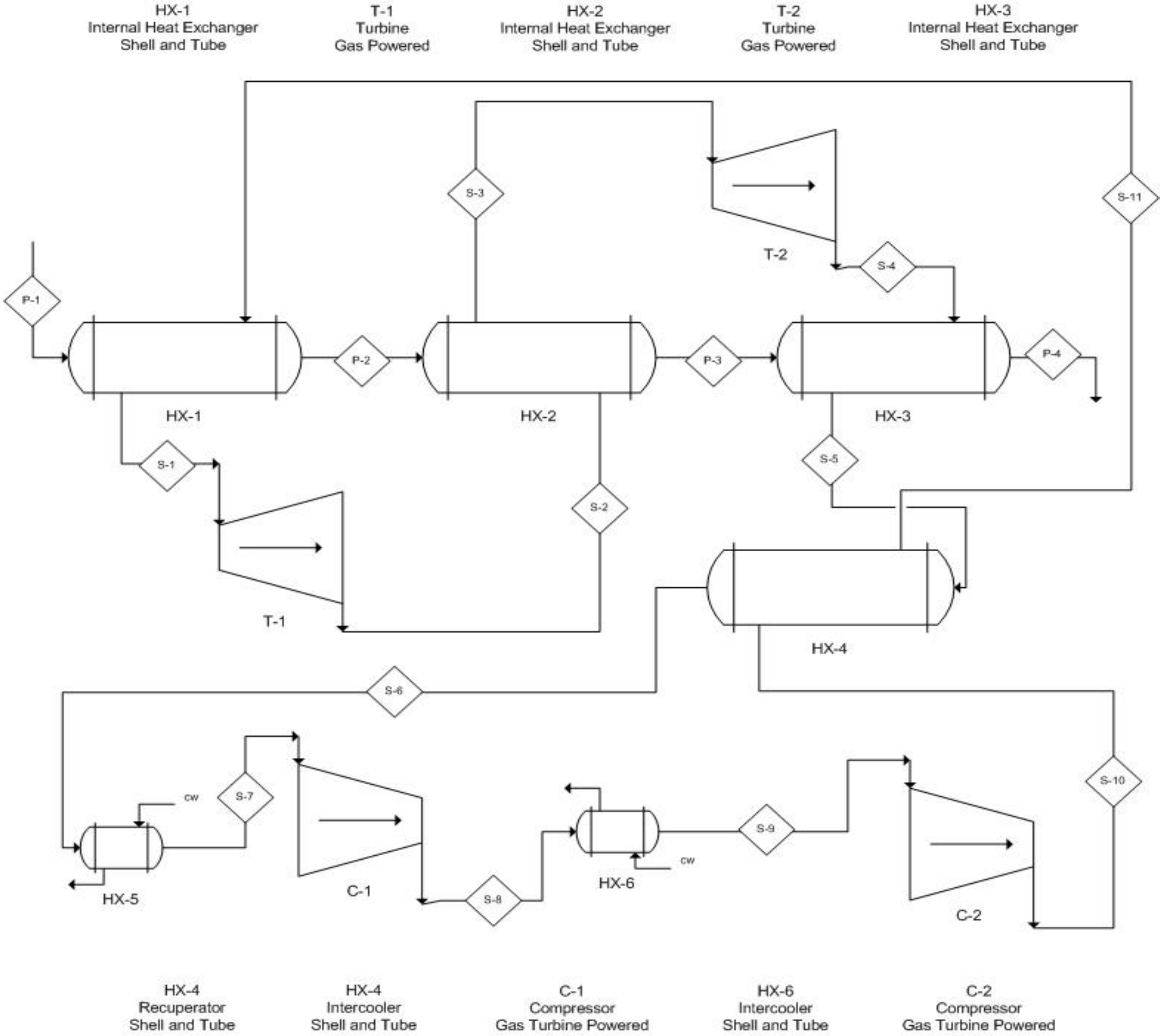


6.2 Helium Material Balance

Stream Number	**P-1**	**P-2**	**S-1**	**S-2**	**S-3**	**S-4**	**S-5**	**S-6**
Temperature (°F)	1652.0	948.6	1503.8	1334.8	1165.5	770.0	361.2	86.0
Pressure (psi)	1121.1	110.1	1145.8	890.9	675.3	306.8	306.8	393.1
Mass Flow (lb/s)	279.3	279.3	235.9	235.9	235.9	235.9	235.9	235.9
Volume Flow (ft^3/s)	1425.7	9593.9	1096.6	1286.5	1534.7	2546.8	1703.9	889.5
Density (lb/ft^3)	0.196	0.029	0.215	0.183	0.154	0.093	0.138	0.265

Stream Number	**S-7**	**S-8**	**S-9**	**S-10**	**S-11**	**S-12**	**S-13**	**S-14**
Temperature (°F)	169.7	122.0	205.5	157.5	240.7	157.5	253.7	662.0
Pressure (psi)	506.7	514.9	653.4	677.3	847.6	886.2	114.8	1145.8
Mass Flow (lb/s)	235.9	235.9	235.9	235.9	235.9	235.9	235.9	235.9
Volume Flow (ft^3/s)	797.3	726.1	655.7	588.0	534.6	452.3	405.8	631.6
Density (lb/ft^3)	0.296	0.325	0.360	0.401	0.441	0.522	0.581	0.374

6.3 S-CO_2 Process Flow Diagram



6.4 S-CO_2 Material Balance

Stream Number	P-1	P-2	P-3	P-4	S-1	S-2	S-3	S-4
Temperature (°F)	1652.0	1338.6	1293.5	1139.0	1310.0	1197.1	1220.0	1133.5
Pressure (psi)	1121.1	1121.1	1121.1	1121.1	1160.3	797.7	797.7	592.0
Mass Flow (lb/s)	1322.8	1322.8	1322.8	1322.8	2645.6	2645.6	2645.6	2645.6
Volume Flow (ft^3/s)	621.0	528.2	514.7	468.4	1005.0	1357.8	1376.9	1751.9
Density (lb/ft^3)	2.13	2.50	2.57	2.82	2.63	1.95	1.92	1.51

Stream Number	S-5	S-6	S-7	S-8	S-9	S-10	S-11
Temperature (°F)	1211.8	191.2	82.4	139.4	131.4	176.3	1148.7
Pressure (psi)	592.0	592.0	592.0	870.2	870.2	1160.3	1160.3
Mass Flow (lb/s)	2645.6	2645.6	2645.6	2645.6	2645.6	2645.6	2645.6
Volume Flow (ft^3/s)	1839.3	631.4	449.7	337.4	325.9	264.2	911.5
Density (lb/ft^3)	1.44	4.19	5.88	7.84	8.12	10.01	2.90

7. Process Description

7.1 Helium Process

The helium process produces 120 MW of electricity by taking residual heat from a primary helium stream in a nuclear reactor and transferring it to a secondary expansion and compression loop also composed of helium. This initial heat transfer between the primary loop P-1 and the secondary loop S-1 occurs at HX-1 in Figure 4.3 on page 15. The reader will find reference to this flowsheet helpful throughout the description of this process. P-1 comes out of HX-1 (page 53) as P-2 and is recycled through the reactor, though the process by which the primary loop is heated and cool in the nuclear reactor core is outside the scope of this project.

The prime area of concern for this process is the secondary helium loop and its expansion and compression. Stream S-1 has a mass flow rate of 850,000 lb/hr helium and receives approximately 2.6×10^9 Joules of residual heat from P-1. Exiting HX-1, S-1 is at a temperature of 1504 °F and pressure of 1146 psi. It then enters turbine T-1 (page 63) for the first stage expansion. T-1 expands the helium, with an accompanying pressure drop to 885 psi and a temperature drop to 1335 °F. This first-stage expansion produces 52.8 MW of power.

After exiting T-1, S-2 enters the second turbine, T-2 (page 64). T-2 also produces 52.8 MW of power and the helium exits this process unit at 682 psi and 1166 °F. T-1 and T-2 generate specified amounts of power which correspond with the power inputs required for the compressors to be discussed momentarily. Finally, the helium stream enters T-3 (page 65) and is once again expanded to produce 123 MW of power. The stream then exits this turbine at a temperature of 770 °F and a pressure of 305 psi. Each of the turbines in the expansion step was assumed to have an efficiency of 90%, as suggested by industrial consultants.

S-4 then enters HX-2 (page 54), the recuperator. The recuperator is composed of five identical shell-and-tube heat exchangers in parallel. The details of these exchangers can be found in the Equipment List and Unit Descriptions in section 9.

Stream S-4 transfers 2.71×10^9 joules to the cold stream and exits HX-2 as S-5, with a temperature of 361 °F and a pressure of 305 psi.

The stream S-5 then enters HX-3 (page 55), which is a further shell-and-tube heat exchanger with utility cooling water flowing through it. The helium stream exits this heat exchanger at 86 °F. This additional cooling was included to reduce the power requirements of the coming compression to reasonable amounts.

Now the helium enters compressor C-1 (page 59), before interacting with the intercooler HX-4 (page 56) and passing through compressor C-2 (page 60). This compressions results in a pressure increase to 653 psi, while the temperature is increased to 205 °F before being cooled again at HX-5 (page 57) to 158 °F. C-1 and C-2 each require 26.1 MW of power to achieve the desired compression.

The helium stream then enters C-3 (page 61) for another compression stage, is cooled at HX-6 (page 58) and enters the final compressor C-4 (page 63). C-3 requires an additional 26.1 MW of power to achieve its compression while C-4 requires 30 MW of power. Having reached a temperature of 253 °F and a pressure of 1146 psi, stream S-13 re-enters HX-2 as a cold stream to be heated by S-4. The helium stream S-14 exits HX-2 at a temperature of 662 °F and a pressure of 1146 psi, which is a sufficient condition to close the loop and send it back to HX-1 for heat transfer from the primary loop P-1. This loop, having achieved the 120 MW target, continues to cycle through for continuous operation and production of electricity.

The selection of a three turbine, four compressor model with intercoolers was based on the MIT design given in the original problem statement (Kadak, 2005). Earlier designs included fewer compressors which, due to the inability to cool the process streams between compressions and the need to achieve greater compression ratios, produced less net power generation and was thus less profitable. All intercoolers throughout this process use simple cooling water.

7.2 S-CO_2 Process

The s-CO_2 process will produce 118.7 MW of net power from the residual heat of the nuclear reactor. As with the helium process, consideration of the primary helium loop is beyond the scope of this project though in this design residual heat is extracted in three stages from this primary stream before it loops back to the nuclear reactor. The process flowsheet can be viewed in Figure 4.5 on page 22 and will be helpful in reading this process description.

The s-CO_2 stream S-1, which has a mass flow rate of 9.5 million lb/hr CO_2, exits HX-1 (page 66) at a temperature of 1310 °F and a pressure of 1160 psi. It then enters T-1 (page 74) where it is expanded to produce 91.4 MW of power. This expansion brings the s-CO_2 down to a temperature of 1197 °F and 798 psi as S-2. S-2 then enters HX-2 (page 67), which is a second shell-and-tube heat exchanger and receives a further heat transfer from the primary helium loop stream (now at 1339 °F and 1117 psi). The s-CO_2 stream leaves HX-2 as S-3 at a temperature of 1220 °F and 798 psi and then enters T-2 (page 75). T-2 expands the s-CO_2 to generate an additional 69 MW of power, bringing the secondary loop conditions to 1134 °F and 595 psi.

After leaving T-2, the stream S-4 enters HX-3 (page 68) to receive the final heat transfer from the primary helium loop and reaches a temperature of 1211 °F and pressure of 595 psi. The stream then enters HX-4 (page 69), a recuperator shell-and-tube heat exchanger network of five-by-five heat exchangers in series and parallel. The necessity of this heat exchanger network significantly increases the overall cost of the project as discussed in the Profitability Analysis section.

The stream exits the recuperator as stream S-6 and enters HX-5 (page 70) for further cooling before compression. Again, this cooling is done to reduce the overall duty required in compression, just as in the helium process.

HX-5 cools S-6 and the stream exits as S-7 at 82 °F and 595 psi before entering C-1 (page 72). C-1 increases the pressure to 870 psi while also raising the temperature to 140 °F. This compression requires 23.3 MW of power.

Leaving the compressor and intercooler, the s-CO_2 stream S-8 enters an intercooler HX-6 (page 71) where it is cooled to 131 °F before again being compressed in C-2 (page 73) to a pressure of 1160 psi and temperature of 176 °F. This compression requires 18.4 MW of power. The stream exits the compressor then enters the recuperator as the cold stream S-10 and is heated by the previously mentioned stream S-4 to a temperature of 1148 °F. This stream S-11 is then recycled back to HX-1 to be heated by the primary helium loop.

As noted earlier, the primary loop interacts with the secondary loop on three occasions in this process, at HX-1, HX-2, and HX-3. This was found to be the most efficient way to extract the residual heat from the stream for s-CO_2, whose heat transfer properties are far less favorable than those of helium. The choice to use a three-stage heating by the primary loop was motivated because of the size constraints on what would have needed to be an impossibly large heat exchanger for a single-stage heating of the secondary loop such as the one performed in the helium process described above.

8. Energy Balance and Utility Requirements

8.1 Helium Process

The energy balances of the helium and the s-CO_2 process start with free residual heat from the nuclear reactor in stream P-1 in the helium and s-CO_2 processes, respectively. From here, both processes heat a secondary circuit that runs through a series of compressors, turbines and intercoolers to generate 120 MW power.

In the helium loop, the biggest utility requirement is that of the four intercoolers. These coolers are placed between each compressor to reduce the power consumed by the compressors. The intercoolers use cooling water that is recycled throughout the plant and comes into the process at 80.6 °F. The cooling water is cooled in a cooling tower that is already attached and used by the nuclear reactor. This cooling water costs .01 cents/gallon and about 11.9 million lb/hr of water is used for each intercooler (Seider et al., 2009). This is true for the s-CO_2 process as well. The overall energy use and utility costs of the intercoolers are summarized in Table 8.1. The energy balances for the heat exchangers in the process are also found there in the first two lines of the table.

Table 8.1. Heat Exchanger Energy Balance and Utility Requirements for the Helium Process.

Demand	Satisfaction	Energy Transferred (MWh)	Cost/MWh ($)
Stream S-14 is heated from 662 °F to 1504 °F	Stream P-1 is cooled from 1652 °F to 948 °F	260.033	--
Stream S-4 is cooled from 770 °F to 361 °F	Stream S-13 is heated from 253 °F to 662 °F	126.225	--
Stream S-5 is cooled from 361 °F to 86 °F	Cooling water is heated from 81 °F to 86 °F	84.856	$19.32
Stream S-7 is cooled from 1211 °F to 190 °F	Cooling water is heated from 81 °F to 104 °F	14.7296	$19.32
Stream S-9 is cooled from 205 °F to 158 °F	Cooling water is heated from 81 °F to 86 °F	14.808	$19.32
Stream S-11 is cooled from 241 °F to 158 °F	Cooling water is heated from 81 °F to 88 °F	25.669	$19.32

The turbine, compressor, and generator energy balances are summarized in Table 8.2. The first two turbines, T-1 and T-2 generate enough energy to power the four compressors, which each take 26.1 MW. The last turbine, which is effectively a generator, generates an excess of 120 MW of energy, which is the ultimate goal of our process design. This excess energy, which is noted at the bottom of Table 8.2 as the total power generated, is what is being sold at the end of the day.

Note that the pressures between each stage of compression vary by about 15 to 30 psi because the stream is slightly expanded through each intercooler before it enters the compressor.

Table 8.1. Turbine and Compressor Power Requirements for the Helium Process.

Demand	**Satisfaction**	**Power Generated/ Consumed (MW)**
Turbine T-1 generates power	Stream S-1 is expanded from 1146 psi to 885 psi	52.8
Turbine T-2 generates power	Stream S-2 is expanded from 885 psi to 682 psi	52.8
Turbine T-3 generates power	Stream S-3 is expanded from 682 psi to 305 psi	123
Stream S-6 is compressed from 392 psi to 508 psi	Compressor C-1 consumes power	-26.1
Stream S-8 is compressed from 522 psi to 653 psi	Compressor C-2 consumes power	-26.1
Stream S-10 is compressed from 682 psi to 841 psi	Compressor C-3 consumes power	-26.1
Stream S-12 is compressed from 885 psi to 1146 psi	Compressor C-4 consumes power	-30.3
TOTAL Power Generated		**120**

8.2 S-CO_2 process

The s-CO_2 process is similar to the helium one in terms of utility requirements. However, this process only uses two intercoolers during the compression stages. Both coolers use 11.9 million lb/hr of water, just as in the helium process. On the other hand, the s-CO_2 process uses four heat exchangers. In this process, heat is transferred from the primary to the secondary loop in steps, between each expansion, requiring two extra heat exchangers. The heat exchanger energy balances as well as the overall cost and energy requirements of the utilities are shown in Table 8.3.

Table 8.2. Heat Exchanger Energy Balance and Utility Requirements for the s-CO_2 Process.

Demand	Satisfaction	Energy Transferred (MWh)	Cost/MWh ($)
Stream S-11 is heated from 1148 °F to 1310 °F	Stream P-1 is cooled from 1652 °F to 1339 °F	132.419	--
Stream S-2 is heated from 1197 °F to 1220 °F	Stream P-2 is cooled from 1339 °F to 1294 °F	18.6816	--
Stream S-4 is heated from 1134 °F to 1211 °F	Stream P-3 is cooled from 1294 °F to 1139 °F	63.2895	--
Stream S-5 is cooled from 1211 °F to 190 °F	Stream S-10 is heated from 176 °F to 1148 °F	768.994	--
Stream S-8 is cooled from 140 °F to 131 °F	Process is heated from 81 °F to 82 °F	7.93241	$19.32
Stream S-6 is cooled from 190 °F to 82 °F	Cooling water is heated from 81 °F to 100 °F	87.8065	$19.32

The power consumption and generation from the turbines and compressors is summarized in Table 8.4. The first turbine, T-1, is responsible for powering both compressors as well as generating about 50 MW. The second turbine is effectively a generator and harvests 69 MW, bringing the power generated in the whole cycle to about 118.6 MW. Although the turbine-compressor system is different than in the helium process, the energy balance works out to be essentially the same.

Table 8.3. Turbine and Compressor Power Requirements for the s-CO_2 Process.

Demand	**Satisfaction**	**Power Generated/ Consumed (MW)**
Turbine T-1 generates power	Stream S-1 is expanded from 1160 psi to 798 psi	91.363
Turbine T-2 generates power	Stream S-3 is expanded from 798 psi to 595 psi	69.050
Stream S-9 is compressed from 870 psi to 1160 psi	Compressor C-1 consumes power	-18.398
Stream S-7 is compressed from 595 psi to 870 psi	Compressor C-2 consumes power	-23.364
TOTAL Power Generated		**118.651**

9. Equipment List and Unit Descriptions

9.1 Heat Exchangers

The heat exchangers were all designed as shell-and-tube units with the ASPEN Exchanger Design & Rating program, using data from the ASPEN simulations of the processes. Both the helium and carbon dioxide cycles have extremely high flow rates and temperature and pressure conditions, making the design of these exchangers especially difficult. Constraints were made on the program to limit the number of units in series, as this would complicate the design and increase the price. However, due to the aforementioned high flow rates, temperatures, and pressures, each of the exchanger designs needed to have multiple units in parallel. The exchangers had extremely large areas and high prices, compared to average heat exchangers for such processes, to accommodate for the design conditions. The descriptions of each heat exchanger for each process are detailed in the following pages.

9.2 Compressors

The compressors are all centrifugal-style, with carbon steel as the material of construction. The temperatures and pressures were low enough that carbon steel can be used. Carbon steel is ideal because it is the cheapest available material that can be used with these design conditions. All of the compressors have an electricity utility requirement, which is satisfied by two of the turbines, T-1 and T-2. The design data shown in the following tables is taken from the ASPEN simulation output of the process with helium as the working fluid. The efficiency of all the compressors was set to be 70%. The unit descriptions of the compressors for both processes are detailed in the following pages.

9.3 Turbines

The turbines generate electricity, with T-1 and T-2 being the two turbines that directly drive compressors, called companders. T-1 directly drives C-1 and C-2, while T-2 directly drives C-3 and C-4. T-3 is the generator-loaded turbine that produces the electrical power output for the cycle. Each of the turbines in this process uses the material Stainless Steel 310S. SS 310S is used because it is the cheapest known type of stainless steel that will withstand the high temperatures and pressures in this design. All the turbines were designed with an efficiency of 90%. The data in the following tables was taken from the ASPEN simulation output of the cycle, except the total purchase cost. The total purchase cost was calculated using the equations in the textbook, and a sample calculation is shown in Appendix B.4.

9.4 Helium Process

9.4.1 Heat Exchangers

Since bare module factor is based on the type of equipment, the bare module factor for all of the heat exchangers is 3.17 (Seider, et al., 2009). The overall summary as given by ASPEN is in Appendix B.5 of this report.

HX-1

HX-1 is also known as the internal heat exchanger for the helium process. It cools the hot stream coming from the reactor from 1652 °F to 949 °F in order to provide heat for the feed to the power generating loop, increasing the temperature of this stream from 662 °F to 1472 °F. The flow rates of helium on the tube side (hot side) and shell side (cold side) are 1 million lb/h and 850,000 lb/h, respectively. The exchanger was designed as a shell and tube with those inputs in the ASPEN Exchanger Design and Rating Program. Stainless Steel 310S was the chosen material of construction because it is the cheapest material programmed into ASPEN that can handle these high temperatures. The results of the program showed that this exchanger would have 1 unit in series and 4 in parallel. The total surface area would be 38,920 ft^2, with a heat transfer coefficient of 110 BTU/h-ft^2-°F, and a heat duty of $8.709x10^8$ BTU/h. The purchase cost, given in the ASPEN output, was $4,296,000. The total installed cost was calculated to be $13,620,000 (Seider, et al., 2009).

Initially, this exchanger was modeled using Hastelloy C, an expensive metal, making its cost in the hundred million dollar range. After consulting with engineers in the field who expertise in modeling heat exchangers at these temperatures, it was concluded that Stainless Steel 310S could be used, reducing the price significantly. The number of units in series was limited to 1 using a design constraint, which simplified the design and reduced the price even more. Another decision that was made was dealing with the TEMA (Tubular Exchanger Manufacturer's Association) type. The BEM type was chosen due to its low cost per square foot of heat transfer area and because it provides the maximum amount of surface area for a given shell tube diameter and length. After trying other types, this one seemed to be the best option, as expected.

HX-2

The second heat exchanger is known in the helium process as a recuperator. It cools the stream coming from the generator-loaded turbine from 410 °F to 183 °F to reheat the stream that is sent back to HX-1 from 123 °F to 350 °F. The flow rate on both the tube and shell side is 849,200 lb/h. These were the inputs on the exchanger design program. HX-2 was also a shell and tube exchanger, as well as the same TEMA type. With the lower temperatures, a cheaper material of construction, Stainless Steel 304, could be used. The number of units in series was 1 and the number of units in parallel was 5. The total surface area was calculated to be 147,400 ft^2, the heat transfer coefficient was 30.54 BTU/h-ft^2-°F, and the heat duty was 2.406x10^8 BTU/h. The purchase cost was $4,112,000, and the installed cost was found to be $13,030,000.

HX-3

HX-3 is the shell and tube intercooler that cools the stream from the recuperator going into the first compressor, C-1, with cooling water. The stream from the recuperator, S-5, has a flow rate of 849,200 lb/h through the tube side (hot side), and it is cooled from 183 °F to 30 °F. The cooling water has a flow rate of 6,455,000 lb/h through the shell side (cold side), and the temperature increases from 68 °F to 113 °F. This shell and tube intercooler also has a BEM TEMA type. Carbon steel was used as the material of construction because it was the cheapest material of construction for heat exchangers; the temperatures here were low enough that carbon steel could be used. The number of units in series was 1 and there were 5 units in parallel. The total surface area is 18,020 ft^2, the heat transfer coefficient was 262.3 BTU/h-ft^2-°F, and the heat duty was 2.895x10^8 BTU/h. The purchase cost was found to be $518,700, and the installed cost was calculated to be $1,644,000.

HX-4

HX-4 is another shell and tube intercooler that cools the stream from the first compressor, C-1, going into the second compressor, C-2, with cooling water. The tube side flow is the helium, which cools from 76 °F to 50 °F, and has a flow rate of 849,200 lb/h. The shell side flow is the cooling water, with a flow rate of 5,599,000 lb/h, and the temperature increases from 68 °F to 77 °F. This intercooler also has the BEM model, with 1 unit in series and 9 units in parallel. The material of construction was selected to be carbon steel, for the same reasons listed for HX-3. The total surface area was 6575 ft^2, the heat transfer coefficient was 262.3 BTU/h-ft^2-°F, and the heat duty was 5.026x10^8 BTU/h. The purchase cost was $323,700, and the installed cost was $1,644,000.

HX-5

The fifth heat exchanger cools the stream from the second compressor, C-2, going into the third compressor, C-3, also with cooling water. This stream flows through the tube side at 849,200 lb/h, and is cooled from 204.8 °F to 158 °F. The cooling water flows through the shell side with a flow rate of 5,629,000 lb/h, and is heated from 68 °F to 77 °F. This is a shell and tube intercooler with the BEM type and is to be constructed with carbon steel. It has 1 unit in series and 10 units in parallel. The total surface area is 5502 ft^2, the heat transfer coefficient is 286.8 BTU/h-ft^2-°F, and a heat duty of 5.019x10^7 BTU/h. The purchase cost was $312,100, and the installed cost was $989,200.

HX-6

The sixth heat exchanger cools the stream from the third compressor, C-3, going into the fourth compressor, C-4. The tube side flow consists of helium, has a flow rate of 849,200 lb/h, and is cooled from 240.8 °F to 158 °F. The shell side flow is cooling water at a rate of 4,880,000 lb/h that is heated from 68 °F to 86 °F. HX-6 is a shell and tube intercooler with 1 unit in series and 8 in parallel. The total surface area is 73,850 ft^2, with a heat transfer coefficient of 55.65 BTU/h-ft^2-°F and a heat duty of 8.786x10^7 BTU/h. The material of construction was carbon steel. The purchase cost was $1,634,000, and the installed cost was calculated to be $5,181,000.

9.4.2 Compressors

C-1

The function of the first compressor was to increase the pressure of stream S-6 to yield stream S-7 going into the second compressor. C-1 was designed as a centrifugal compressor with an electric motor and carbon steel as the material of construction. Carbon steel was used because it was the cheapest available material for such a process, and since helium is the working fluid, there is no possibility of rusting occurring. The pressure increased from 393 psi to 515 psi, and the temperature increased from 86 °F to 179 °F. The flow rate through this compressor was 849,200 lb/h, and the driver power was 35,000 hp. The utility requirement is 26.1 MW, and the total installed cost was found to be $16,890,000. The cost numbers were retrieved from the ASPEN simulation using the ASPEN Process Economic Analyzer (APEA).

C-2

The function of the second compressor was to increase the pressure of stream S-8 to yield stream S-9 going into the second compressor. C-2 was designed as a centrifugal compressor with an electric motor and carbon steel as the material of construction. Carbon steel was used because it was the cheapest available material for such a process, and since helium is the working fluid, there is no possibility of rusting occurring. The pressure increased from 515 psi to 654 psi, and the temperature increased from 122 °F to 206 °F. The flow rate through this compressor was 849,200 lb/h, and the driver power was 35,000 hp. The utility requirement is 26.1 MW, and the total installed cost was found to be $14,570,000. The cost numbers were retrieved from the ASPEN simulation using the APEA.

C-3

The function of the third compressor was to increase the pressure of stream S-10 to yield stream S-11 going into the fourth compressor. C-3 was designed as a centrifugal compressor with an electric motor and carbon steel as the material of construction. Carbon steel was used because it was the cheapest available material for such a process, and since helium is the working fluid, there is no possibility of rusting occurring. The pressure increased from 677 psi to

847 psi, and the temperature increased from 157 °F to 241 °F. The flow rate through this compressor was 849,200 lb/h, and the driver power was 35,000 hp. The utility requirement is 26.1 MW, and the total installed cost was found to be $11,340,000. The cost numbers were retrieved from the ASPEN simulation using the APEA.

C-4

The function of the fourth compressor was to increase the pressure of stream S-12 to yield stream S-13 going into the recuperator, HX-2. C-4 was designed as a centrifugal compressor with an electric motor and carbon steel as the material of construction. Carbon steel was used because it was the cheapest available material for such a process, and since helium is the working fluid, there is no possibility of rusting occurring. The pressure increased from 886 psi to 1146 psi, and the temperature increased from 157 °F to 254 °F. The flow rate through this compressor was 850,000 lb/h, and the driver power was 35,000 hp. The utility requirement is 26.1 MW, and the total installed cost was found to be $11,100,000. The cost numbers were retrieved from the ASPEN simulation using the APEA.

9.4.3 Turbines

The Sample Calculations for the design and costing of the turbines are shown in Appendix B.4.

T-1

The function of this turbine is to generate electricity for compressors C-1 and C-2. The material used was Stainless Steel 310S, for the same reasons some heat exchangers were designed using this material. SS 310S is the cheapest material that can withstand these temperatures and pressures. The helium flowed through at a rate of 849,200 lb/h. The stream expands from 1146 psi to 890 psi, and the temperature correspondingly cools from 1504 °F to

1335 °F. The driver power was 70,810 hp. The total cost was calculated to be $19,320,000 (Seider, et al., 2009).

T-2

The function of this turbine is to generate electricity for compressors C-3 and C-4. The material used was Stainless Steel 310S, for the same reasons some heat exchangers were designed using this material. SS 310S is the cheapest material that can withstand these temperatures and pressures. The helium flowed through at a rate of 849,200 lb/h. The stream expands from 890 psi to 676 psi, and the temperature correspondingly cools from 1335 °F to 1166 °F. The driver power was 70,810 hp. The total cost was calculated to be $19,320,000.

T-3

T-3 generates electricity as the power output for the process. The material used was Stainless Steel 310S, for the same reasons some heat exchangers were designed using this material. SS 310S is the cheapest material that can withstand these temperatures and pressures. The helium flowed through at a rate of 849,200 lb/h. The stream expands from 676 psi to 307 psi, and the temperature correspondingly cools from 1166 °F to 770 °F. The driver power was 164,900 hp. The total cost was calculated to be $38,330,000.

9.5.4 Equipment Summary

Unit Name	Unit Type	Material of Construction	Size	Total Installed Cost
HX-1	Shell-and-Tube Heat Exchanger	SS 310S	38,920 ft^2	$ 13,620,000
HX-2	Shell-and-Tube Heat Exchanger	SS 304	147,400 ft^2	$ 13,030,000
HX-3	Shell-and-Tube Intercooler	Carbon Steel	18,020 ft^2	$ 1,644,000
HX-4	Shell-and-Tube Intercooler	Carbon Steel	6,575 ft^2	$ 1,026,000
HX-5	Shell-and-Tube Intercooler	Carbon Steel	5,502 ft^2	$ 989,200
HX-6	Shell-and-Tube Intercooler	Carbon Steel	73,850 ft^2	$ 5,180,000
C-1	Centrifugal Compressor	Carbon Steel	35,000 hp	$ 16,890,000
C-2	Centrifugal Compressor	Carbon Steel	35,000 hp	$ 14,570,000
C-3	Centrifugal Compressor	Carbon Steel	35,000 hp	$ 11,340,000
C-4	Centrifugal Compressor	Carbon Steel	35,000 hp	$ 11,100,000
T-1	Isentropic Turbine	SS 310S	70,810 hp	$ 19,320,000
T-2	Isentropic Turbine	SS 310S	70,810 hp	$ 19,320,000
T-3	Isentropic Turbine	SS 310S	164,900 hp	$ 38,330,000

9.5 S-CO_2 Process

9.5.1 Heat Exchangers

Since bare module factor is based on the type of equipment, the bare module factor for all of the heat exchangers is 3.17 (Seider, et al., 2009). The overall summary as given by ASPEN is in Appendix B.5 of this report. Because of the extremely high flow rates, the solutions for the heat exchangers on the ASPEN Exchanger Design & Rating Program weren't converging.

Therefore, the flow rates were cut tenfold when designing the heat exchangers, and the values given in the output from ASPEN were scaled up accordingly.

HX-1

HX-1 cools the feed of supercritical CO_2, P-1, using a different stream of CO_2, S-11, coming from the fourth heat exchanger, HX-4. The exchanger was designed with a shell and tube BEM type, as are all the exchangers in this process, with Stainless Steel 310S as the material of construction. The flow rate on the tube side (hot side) was 4,762,000 lb/h and the stream was cooled from 1652 °F to 1339 °F. The flow rate on the shell side (cold side) was 9,524,000 lb/h, and the stream was heated from 1148 °F to 1310 °F. The number of units in series was 1 and the number of units in parallel was 3. The total surface area given by ASPEN was 13,200 ft^2, with a heat transfer coefficient of 163.9 BTU/h-ft^2-°F and a heat duty of 4.550×10^8 BTU/h. The purchase cost was given to be $3,916,000, and the installed cost was calculated to be $12,410,000.

HX-2

This heat exchanger cools the stream coming from HX-1, P-2, with the stream, S-2, coming from the first turbine, T-1. HX-2 is a shell and tube exchanger with the BEM type. The tube side flow rate was 4,762,000 lb/h and the stream was cooled from 1339 °F to 1294 °F. The shell side flow rate was 9,524,000 lb/h, and the stream was heated from 1197 °F to 1220 °F. The working fluid was supercritical CO_2, and Stainless Steel 304L was used as the material of construction. The number of units in series was 1 and the number of units in parallel was 3. The total surface area was 6,986 ft^2, with a heat transfer coefficient of 133.5 BTU/h-ft^2-°F and a heat duty of 6.521×10^7 BTU/h. The purchase cost was given to be $5,044,000, and the installed cost was calculated to be $15,990,000.

HX-3

This heat exchanger cools the stream coming from HX-2, P-3, with the stream, S-4, coming from the second turbine, T-2. HX-3 is a shell and tube exchanger with the BEM type. The tube side flow rate was 4,762,000 lb/h and the stream was cooled from 1294 °F to 1139 °F. The shell side flow rate was 9,524,000 lb/h, and the stream was heated from 1134 °F to 1211 °F. The working fluid was supercritical CO_2, and Stainless Steel 304 was used as the material of construction. The number of units in series was 2 and the number of units in parallel was 4. Unlike the previously described heat exchangers, it was not possible to design HX-3 with only one unit in series. This does complicate the design, but after multiple attempts at varying the design constraints, this design proved to be the cheapest. The total surface area was 116,700 ft^2, with a heat transfer coefficient of 133.5 BTU/h-ft^2-°F and a heat duty of $2.181x10^8$ BTU/h. The purchase cost was given to be $33,030,000, and the installed cost was calculated to be $104,700,000.

HX-4

This heat exchanger cools the stream, S-5, with the stream, S-10, coming from the second compressor, C-2. HX-4 is a shell and tube exchanger with the BEM type. The tube side flow rate was 9,524,000 lb/h and the stream was cooled from 1212 °F to 191.2 °F. The shell side flow rate was 9,5424,000 lb/h, and the stream was heated from 176.3 °F to 1149 °F. The working fluid was supercritical CO_2, and Stainless Steel 304 was used as the material of construction. The number of units in series was 5 and the number of units in parallel was 5. Unlike the previously described heat exchangers, it was not possible to design HX-4 with only one unit in series. This does complicate the design, but after multiple attempts at varying the design constraints, this design proved to be the least expensive. However, the price ended up being extremely high. The total surface area was 201,600 ft^2, with a heat transfer coefficient of 29.35 BTU/h-ft^2-°F and a heat duty of 2.650x10^8 BTU/h. The purchase cost was given to be \$250,200,000, and the installed cost was calculated to be \$793,100,000. This extremely high cost can be attributed to the design conditions.

HX-5

This heat exchanger cools the stream S-6 using cooling water. HX-5 is a shell and tube exchanger with the BEM type. The tube side (CO_2) flow rate was 9,524,000 lb/h and the stream was cooled from 183.2 °F to 82.4 °F. The shell side (cooling water) flow rate was 1,190,000 lb/h, and the stream was heated from 80.6 °F to 98.6 °F. Carbon steel was used as the material of construction. The number of units in series was 2 and the number of units in parallel was 1. The total surface area was 64,960 ft^2, with a heat transfer coefficient of 172 BTU/h-ft^2-°F and a heat duty of 2.377x10^7 BTU/h. The purchase cost was given to be \$1,889,000, and the installed cost was calculated to be \$5,987,000.

HX-6

This heat exchanger cools the stream S-6 using cooling water. HX-5 is a shell and tube exchanger with the BEM type. The tube side (CO_2) flow rate was 9,524,000 lb/h and the stream was cooled from 140 °F to 131 °F. The shell side (cooling water) flow rate was 1,190,000 lb/h, and the stream was heated from 80.6 °F to 82.4 °F. Carbon steel was used as the material of construction. The number of units in series was 1 and the number of units in parallel was 1. The total surface area was 3,063 ft^2, with a heat transfer coefficient of 387.3 BTU/h-ft^2-°F and a heat duty of 2.355x10^7 BTU/h. The purchase cost was given to be \$474,800, and the installed cost was calculated to be \$1,505,000.

9.5.2 Compressors

C-1

The function of the first compressor was to increase the pressure of stream S-7 to yield stream S-8 going into the sixth heat exchanger. C-1 was designed as a centrifugal compressor with an electric motor and carbon steel as the material of construction. Carbon steel was used because it was the cheapest available material for such a process, and since helium is the working fluid, there is no possibility of rusting occurring. The pressure increased from 592 psi to 870 psi, and the temperature increased from 82.4 °F to 139 °F. The flow rate through this compressor was 216,400 lb/h, and the driver power was 31,330 hp. The utility requirement is 23.4 MW, and the total installed cost was found to be $7,451,000. The cost numbers were retrieved from the ASPEN simulation using the APEA.

C-2

The function of the second compressor was to increase the pressure of stream S-9 to yield stream S-10 going into the fourth heat exchanger. C-2 was designed as a centrifugal compressor with an electric motor and carbon steel as the material of construction. Carbon steel was used because it was the cheapest available material for such a process, and since helium is the working fluid, there is no possibility of rusting occurring. The pressure increased from 870 psi to 1160 psi, and the temperature increased from 131 °F to 176 °F. The flow rate through this compressor was 216,400 lb/h, and the driver power was 24,670 hp. The utility requirement is 18.4 MW, and the total installed cost was found to be $7,578,000. The cost numbers were retrieved from the ASPEN simulation using the APEA.

9.5.3 Turbines

The Sample Calculations for the design and costing of the turbines are shown in Appendix B.4.

T-1

The first turbine works with the second to generate electricity as the power output of the process and to provide electricity to the compressors. The material used was Stainless Steel 310S, for the same reasons some heat exchangers were designed using this material. SS 310S is the cheapest material that can withstand these temperatures and pressures. The helium flowed through at a rate of 216,400 lb/h. The stream expands from 1160 psi to 798 psi, and the temperature correspondingly cools from 1310 °F to 1197 °F. The driver power was 122,500 hp. The total cost was calculated to be $30,120,000.

T-2

The second turbine works with the first to generate electricity as the power output of the process and to provide electricity to the compressors. The material used was Stainless Steel 310S, for the same reasons some heat exchangers were designed using this material. SS 310S is the cheapest material that can withstand these temperatures and pressures. The helium flowed through at a rate of 216,400 lb/h. The stream expands from 798 psi to 592 psi, and the temperature correspondingly cools from 1220 °F to 1133 °F. The driver power was 92,600 hp. The total cost was calculated to be $24,010,000.

9.5.4 Equipment Summary

Unit Name	Unit Type	Material of Construction	Size	Total Installed Cost
HX-1	Shell-and-Tube Heat Exchanger	SS 310S	13,200 ft^2	$ 12,410,000
HX-2	Shell-and-Tube Heat Exchanger	SS 304L	6,986 ft^2	$ 15,990,000
HX-3	Shell-and-Tube Intercooler	SS 304	116,700 ft^2	$ 33,030,000
HX-4	Shell-and-Tube Intercooler	Carbon Steel	201,600 ft^2	$ 793,200,000
HX-5	Shell-and-Tube Intercooler	Carbon Steel	64,960 ft^2	$ 5,987,000
HX-6	Shell-and-Tube Intercooler	Carbon Steel	3,063 ft^2	$ 1,505,000
C-1	Centrifugal Compressor	Carbon Steel	31,330 hp	$ 7,451,000
C-2	Centrifugal Compressor	Carbon Steel	24,670 hp	$ 7,578,000
T-1	Isentropic Turbine	SS 310S	122,500 hp	$ 30,120,000
T-2	Isentropic Turbine	SS 310S	92,600 hp	$ 24,010,000

10. Specification Sheets

10.1 Helium Process

10.1.1 Heat Exchangers

HEAT EXCHANGER (Helium Process)		
Identification:	HX-1	
Function:	Cools stream from reactor to heat the feed to the power cycle	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Working Fluid:	Helium	
Stream ID	**Tube Side**	**Shell Side**
Inlet	P-1	S-14
Outlet	P-2	S-1
Flow Rate (lb/h)	1,006,000	849,200
Temperature In (°F)	1652	662
Temperature Out (°F)	949	1472
Design Data:	Surface Area (ft^2)	38,920
	LMTD (°F)	229.3
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	110
	Heat Duty (BTU/h)	8.709×10^8
	Material of Construction	Stainless Steel 310S
	Number of Units in Series	1
	Number of Units in Parallel	4
Purchase Cost	$4,296,000	
Installed Cost	$13,620,000	

HEAT EXCHANGER (Helium Process)		
Identification:	HX-2	
Function:	Cool the expanded stream from the generator-loaded turbine, and reheat the working fluid that is sent back to HX-1	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Working Fluid:	Helium	
Stream ID	**Tube Side**	**Shell Side**
Inlet	S-13	S-4
Outlet	S-14	S-5
Flow Rate (lb/h)	849,200	849,200
Temperature In (°F)	410	123
Temperature Out (°F)	183	350
Design Data:	Surface Area (ft^2)	147,400
	LMTD (°F)	60
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	30.54
	Heat Duty (BTU/h)	2.406×10^8
	Material of Construction	Stainless Steel 304
	Number of Units in Series	1
	Number of Units in Parallel	5
Purchase Cost	$4,112,00	
Installed Cost	$13,030,000	

HEAT EXCHANGER (Helium Process)		
Identification:	HX-3	
Function:	Cools stream from the recuperator going into the first compressor	
Operation:	Continuous	
Exchanger Type:	Shell and Tube Intercooler	
TEMA Type:	BEM	
Working Fluid:	Helium	
Stream ID	**Tube Side**	**Shell Side**
Inlet	S-5	CW
Outlet	S-6	CW
Flow Rate (lb/h)	849,200	6,455,000
Temperature In (°F)	183	68
Temperature Out (°F)	30	113
Design Data:	Surface Area (ft^2)	18,020
	LMTD (°F)	87.95
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	262.3
	Heat Duty (BTU/h)	2.895×10^8
	Material of Construction	Carbon Steel
	Number of Units in Series	1
	Number of Units in Parallel	5
Purchase Cost	$518,700	
Installed Cost	$1,644,000	

<table>
<tr><th colspan="3">HEAT EXCHANGER (Helium Process)</th></tr>
<tr><td>Identification:</td><td colspan="2">HX-4</td></tr>
<tr><td>Function:</td><td colspan="2">Cools stream from the first compressor, C-1, going into the second compressor, C-2</td></tr>
<tr><td>Operation:</td><td colspan="2">Continuous</td></tr>
<tr><td>Exchanger Type:</td><td colspan="2">Shell and Tube Intercooler</td></tr>
<tr><td>TEMA Type:</td><td colspan="2">BEM</td></tr>
<tr><td>Working Fluid:</td><td colspan="2">Helium and Cooling Water</td></tr>
<tr><td>Stream ID</td><td>Tube Side</td><td>Shell Side</td></tr>
<tr><td>Inlet</td><td>S-7</td><td>CW</td></tr>
<tr><td>Outlet</td><td>S-8</td><td>CW</td></tr>
<tr><td>Flow Rate (lb/h)</td><td>849,200</td><td>5,599,000</td></tr>
<tr><td>Temperature In (°F)</td><td>76</td><td>68</td></tr>
<tr><td>Temperature Out (°F)</td><td>50</td><td>77</td></tr>
<tr><td rowspan="7">Design Data:</td><td>Surface Area (ft^2)</td><td>6575</td></tr>
<tr><td>LMTD (°F)</td><td>229.2</td></tr>
<tr><td>Heat Transfer Coefficient (BTU/h-ft^2-°F)</td><td>262.3</td></tr>
<tr><td>Heat Duty (BTU/h)</td><td>5.026x10^8</td></tr>
<tr><td>Material of Construction</td><td>Carbon Steel</td></tr>
<tr><td>Number of Units in Series</td><td>1</td></tr>
<tr><td>Number of Units in Parallel</td><td>9</td></tr>
<tr><td>Purchase Cost</td><td colspan="2">$323,700</td></tr>
<tr><td>Installed Cost</td><td colspan="2">$ 1,026,000</td></tr>
</table>

HEAT EXCHANGER (Helium Process)		
Identification:	HX-5	
Function:	Cools stream from the second compressor, C-2, going into the third compressor, C-3	
Operation:	Continuous	
Exchanger Type:	Shell and Tube Intercooler	
TEMA Type:	BEM	
Working Fluid	Helium and Cooling Water	
Stream ID	**Tube Side**	**Shell Side**
Inlet	S-9	CW
Outlet	S-10	CW
Flow Rate (lb/h)	849,200	5,629,000
Temperature In (°F)	204.8	68
Temperature Out (°F)	158	77
Design Data:	Surface Area (ft^2)	5502
	LMTD (°F)	107.8
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	286.8
	Heat Duty (BTU/h)	$5.019\text{x}10^7$
	Material of Construction	Carbon Steel
	Number of Units in Series	1
	Number of Units in Parallel	10
Purchase Cost	$312,100	
Installed Cost	$989,200	

HEAT EXCHANGER (Helium Process)		
Identification:	HX-6	
Function:	Cools stream from the third compressor, C-3, going into the fourth compressor, C-4	
Operation:	Continuous	
Exchanger Type:	Shell and Tube Intercooler	
TEMA Type:	BEM	
Working Fluid:	Helium and Cooling Water	
Stream ID	**Tube Side**	**Shell Side**
Inlet	S-11	CW
Outlet	S-12	CW
Flow Rate (lb/h)	849,200	4,880,000
Temperature In (°F)	240.8	68
Temperature Out (°F)	158	86
Design Data:	Surface Area (ft^2)	73,850
	LMTD (°F)	119.5
	Heat Transfer Coefficient ($BTU/h\text{-}ft^2\text{-}°F$)	55.65
	Heat Duty (BTU/h)	8.786×10^7
	Material of Construction	Carbon Steel
	Number of Units in Series	1
	Number of Units in Parallel	8
Purchase Cost	$1,634,000	
Installed Cost	$5,181,000	

10.1.2 Compressors

COMPRESSOR (Helium Process)		
Identification:	C-1	
Function:	To increase the pressure of stream S-6 to yield stream S-7 going into the second compressor	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Centrifugal
	Driver Type:	Electric Motor
	Material:	Carbon Steel
	Pressure Inlet: (psi)	392
	Pressure Outlet: (psi)	515
	Temperature Inlet (°F)	86
	Temperature Outlet (°F)	170
	Flow Rate (lb/h)	849,200
	Driver Power (hp)	35,000
	Efficiency	70%
Utility Requirement: (MW)	26.1	
Total Purchase Cost:	$15,870,000	
Total Installed Cost:	$16,890,000	

COMPRESSOR (Helium Process)		
Identification:	C-2	
Function:	To increase the pressure of stream S-8 to yield stream S-9 going into the third compressor	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Centrifugal
	Driver Type:	Electric Motor
	Material:	Carbon Steel
	Pressure Inlet: (psi)	515
	Pressure Outlet: (psi)	654
	Temperature Inlet (°F)	122
	Temperature Outlet (°F)	206
	Flow Rate (lb/h)	849,220
	Driver Power (hp)	35,000
	Efficiency	70%
Utility Requirement: (MW)	26.1	
Total Purchase Cost:	$13,490,000	
Total Installed Cost:	$14,570,000	

COMPRESSOR (Helium Process)		
Identification:	C-3	
Function:	To increase the pressure of stream S-10 to yield stream S-11 going into the fourth compressor	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Centrifugal
	Driver Type:	Electric Motor
	Material:	Carbon Steel
	Pressure Inlet: (psi)	677
	Pressure Outlet: (psi)	847
	Temperature Inlet (°F)	157
	Temperature Outlet (°F)	241
	Flow Rate (lb/h)	849,200
	Driver Power (hp)	35,000
	Efficiency	70%
Utility Requirement: (MW)	26.1	
Total Purchase Cost:	$10,120,000	
Total Installed Cost:	$11,340,000	

COMPRESSOR (Helium Process)		
Identification:	C-4	
Function:	To increase the pressure of stream S-12 to yield stream S-13 going into the recuperator, HX-2	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Centrifugal
	Driver Type:	Electric Motor
	Material:	Carbon Steel
	Pressure Inlet: (psi)	886
	Pressure Outlet: (psi)	1146
	Temperature Inlet (°F)	157
	Temperature Outlet (°F)	254
	Flow Rate (lb/h)	849,200
	Driver Power (hp)	35,000
	Efficiency	70%
Utility Requirement: (MW)	26.1	
Total Purchase Cost:	$9,724,000	
Total Installed Cost:	$11,104,100	

10.1.3 Turbines

TURBINE (Helium Process)		
Identification:	T-1	
Function:	To generate electricity for compressors C-1 and C-2	
Operation:	Continuous	
Design Data:	Type:	Electrical
	Material:	Stainless Steel 310S
	Pressure Inlet: (psi)	1146
	Pressure Outlet: (psi)	890
	Temperature Inlet (°F)	1504
	Temperature Outlet (°F)	1335
	Flow Rate (lb/h)	849,220
	Driver Power (hp)	70,810
	Efficiency	90%
Total Purchase Cost:	$8,987,000	
Total Installed Cost:	$19,320,000	

TURBINE (Helium Process)		
Identification:	T-2	
Function:	To generate electricity for compressors C-3 and C-4	
Operation:	Continuous	
Design Data:	Type:	Electrical
	Material:	Stainless Steel 310S
	Pressure Inlet: (psi)	890
	Pressure Outlet: (psi)	676
	Temperature Inlet (°F)	1335
	Temperature Outlet (°F)	1166
	Flow Rate (lb/h)	849,200
	Driver Power (hp)	70,810
	Efficiency	90%
Total Purchase Cost:	$8,987,000	
Total Installed Cost:	$19,320,000	

TURBINE (Helium Process)		
Identification:	T-3	
Function:	To generate electricity as the power output of the process	
Operation:	Continuous	
Design Data:	Type:	Electrical
	Material:	Stainless Steel 310S
	Pressure Inlet: (psi)	676
	Pressure Outlet: (psi)	307
	Temperature Inlet (°F)	1166
	Temperature Outlet (°F)	770
	Flow Rate (lb/h)	849,200
	Driver Power (hp)	164,900
	Efficiency	90%
Total Purchase Cost:	$17,830,000	
Total Installed Cost:	$38,330,000	

10.2 S-CO_2 Process

10.2.1 Heat Exchangers

HEAT EXCHANGER (CO_2 Process)		
Identification:	HX-1	
Function:	Cools feed, P-1, using stream S-11 coming from the fourth exchanger, HX-4	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Stream ID	**Tube Side**	**Shell Side**
Inlet	P-1	S-11
Outlet	P-2	S-1
Flow Rate (lb/h)	4,762,000	9,524,000
Temperature In (°F)	1652	1148
Temperature Out (°F)	1339	1310
Design Data:	Surface Area (ft^2)	13,200
	LMTD (°F)	220.8
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	163.9
	Heat Duty (BTU/h)	$4.550x10^8$
	Material of Construction	Stainless Steel 310S
	Number of Units in Series	1
	Number of Units in Parallel	3
Purchase Cost	$3,916,000	
Installed Cost	$12,410,000	

HEAT EXCHANGER (CO_2 Process)		
Identification:	HX-2	
Function:	Cools stream P-2 using stream S-2 coming from the first turbine, T-1	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Stream ID	**Tube Side**	**Shell Side**
Inlet	P-2	S-2
Outlet	P-3	S-3
Flow Rate (lb/h)	4,762,000	9,524,000
Temperature In (°F)	1339	1197
Temperature Out (°F)	1294	1220
Design Data:	Surface Area (ft^2)	6,986
	LMTD (°F)	108
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	133.5
	Heat Duty (BTU/h)	6.521×10^7
	Material of Construction	Stainless Steel 304L
	Number of Units in Series	1
	Number of Units in Parallel	3
Purchase Cost	$5,044,000	
Installed Cost	$15,990,000	

HEAT EXCHANGER (CO_2 Process)		
Identification:	HX-3	
Function:	Cools stream P-3 using stream S-4 coming from the second turbine, T-2	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Stream ID	**Tube Side**	**Shell Side**
Inlet	P-3	S-4
Outlet	P-4	S-5
Flow Rate (lb/h)	4,762,000	9,524,000
Temperature In (°F)	1294	1134
Temperature Out (°F)	1139	1211
Design Data:	Surface Area (ft^2)	116,700
	LMTD (°F)	28.51
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	133.5
	Heat Duty (BTU/h)	2.181×10^8
	Material of Construction	Stainless Steel 304
	Number of Units in Series	2
	Number of Units in Parallel	4
Purchase Cost	\$33,030,000	
Installed Cost	\$104,700,000	

HEAT EXCHANGER (CO_2 Process)		
Identification:	HX-4	
Function:	Cools stream S-5 using stream S-10 coming from the second compressor, C-2	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Stream ID	**Tube Side**	**Shell Side**
Inlet	S-5	S-10
Outlet	S-6	S-11
Flow Rate (lb/h)	9,524,000	9,524,000
Temperature In (°F)	1212	176.3
Temperature Out (°F)	191.2	1149
Design Data:	Surface Area (ft^2)	201,600
	LMTD (°F)	45.44
	Heat Transfer Coefficient ($BTU/h\text{-}ft^2\text{-}°F$)	29.35
	Heat Duty (BTU/h)	2.650×10^8
	Material of Construction	Stainless Steel 304
	Number of Units in Series	5
	Number of Units in Parallel	5
Purchase Cost	$250,200,000	
Installed Cost	$793,100,000	

HEAT EXCHANGER (CO_2 Process)		
Identification:	HX-5	
Function:	Cools stream S-6 using cooling water	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Stream ID	**Tube Side**	**Shell Side**
Inlet	S-6	CW
Outlet	S-7	CW
Flow Rate (lb/h)	9,524,000	1,190,000
Temperature In (°F)	183.2	80.6
Temperature Out (°F)	82.4	98.6
Design Data:	Surface Area (ft^2)	64,960
	LMTD (°F)	21.77
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	172
	Heat Duty (BTU/h)	2.377×10^7
	Material of Construction	Carbon Steel
	Number of Units in Series	2
	Number of Units in Parallel	1
Purchase Cost	$1,889,000	
Installed Cost	$5,987,000	

HEAT EXCHANGER (CO_2 Process)		
Identification:	HX-6	
Function:	Cools stream S-8 using cooling water	
Operation:	Continuous	
Exchanger Type:	Shell and Tube	
TEMA Type:	BEM	
Stream ID	**Tube Side**	**Shell Side**
Inlet	S-8	CW
Outlet	S-9	CW
Flow Rate (lb/h)	9,524,000	1,190,000
Temperature In (°F)	140	80.6
Temperature Out (°F)	131	82.4
Design Data:	Surface Area (ft^2)	3063
	LMTD (°F)	53.91
	Heat Transfer Coefficient (BTU/h-ft^2-°F)	387.3
	Heat Duty (BTU/h)	2.355×10^7
	Material of Construction	Carbon Steel
	Number of Units in Series	1
	Number of Units in Parallel	1
Purchase Cost	$474,800	
Installed Cost	$1,505,000	

10.2.2 Compressors

COMPRESSOR (CO_2 Process)		
Identification:	C-1	
Function:	To increase the pressure of stream S-7 to yield stream S-8 going into the sixth heat exchanger, HX-6	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Centrifugal
	Driver Type:	Electric Motor
	Material:	Carbon Steel
	Pressure Inlet: (psi)	592
	Pressure Outlet: (psi)	870
	Temperature Inlet (°F)	82.4
	Temperature Outlet (°F)	139
	Flow Rate (lb/h)	216,400
	Driver Power (hp)	31,330
	Efficiency	70%
Utility Requirement: (MW)	23.4	
Total Purchase Cost:	$ 5,490,000	
Total Installed Cost:	$7,451,000	

COMPRESSOR (CO_2 Process)		
Identification:	C-2	
Function:	To increase the pressure of stream S-9 to yield stream S-10 going into the fourth heat exchanger, HX-4	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Centrifugal
	Driver Type:	Electric Motor
	Material:	Carbon Steel
	Pressure Inlet: (psi)	870
	Pressure Outlet: (psi)	1160
	Temperature Inlet (°F)	131
	Temperature Outlet (°F)	176
	Flow Rate (lb/h)	216,400
	Driver Power (hp)	24,670
	Efficiency	70%
Utility Requirement: (MW)	18.4	
Total Purchase Cost:	$5,388,000	
Total Installed Cost:	$7,578,000	

10.2.3 Turbines

TURBINE (CO_2 Process)		
Identification:	T-1	
Function:	To generate electricity as the power output of the process and to provide electricity to the compressors	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Electrical
	Material:	Stainless Steel 310S
	Pressure Inlet: (psi)	1160
	Pressure Outlet: (psi)	798
	Temperature Inlet (°F)	1310
	Temperature Outlet (°F)	1197
	Flow Rate (lb/h)	216,400
	Driver Power (hp)	122,500
	Efficiency	90%
Total Purchase Cost:	$14,010,000	
Total Installed Cost:	$30,120,000	

TURBINE (CO_2 Process)		
Identification:	T-2	
Function:	To generate electricity as the power output of the process and to provide electricity to the compressors	
Operation:	Continuous	
Working Fluid:	Helium	
Design Data:	Type:	Electrical
	Material:	Stainless Steel 310S
	Pressure Inlet: (psi)	798
	Pressure Outlet: (psi)	592
	Temperature Inlet (°F)	1220
	Temperature Outlet (°F)	1133
	Flow Rate (lb/h)	216,400
	Driver Power (hp)	92,600
	Efficiency	90%
Total Purchase Cost:	$11,170,000	
Total Installed Cost:	$24,010,000	

12. Equipment Cost and Fixed-Capital Investment Summaries

12.1 Helium Process

A summary of capital investment costs and purchase costs for all process units in the helium process is available in Table 12.1. The total permanent investment for the process is approximately $218 million, with equipment costs and installation accounting for $166 million of this total. Contingency and contractor fees were assumed to be 5% of direct permanent investment, which is consistent with estimates for new electricity plant costs as calculated by the Energy Information Administration (EIA) ("Levelized Cost," 2015). Site preparation and service facilities were estimated at 1% of bare module cost each. This is a lower estimate than that provided by Downey in the Profitability Analysis Spreadsheet (2008). The choice was made to lower this cost, as well as the cost of land (1% of total depreciable capital) due to the nature of this process: it will add on to an existing plant facility rather than break ground as a new plant and thus, the existence of developed infrastructure and available land is assumed to represent an opportunity for cost savings.

The cost of start-up for this process is estimated at 10% of total depreciable capital as recommended by Downey. A site factor of 1.1 was used to account for creating this process in a Northeastern U.S. location. A detailed breakdown of these costs is available in the Profitability Analysis section.

Table 12.1. Equipment Cost and Capital Investment Summary for Helium Design. Costs for compressors were calculated using the Process Economic Analyzer (*Aspen Process*, 2015). Costs for turbines, as well as bare module factors, were calculated using the textbook (Seider, et al., 2009), and heat exchanger costs were calculated using the Exchanger Design and Rating program (*Aspen Exchanger*, 2015).

Unit Name	**Unit Description**	**Estimated Purchase Cost**	**Bare Module Factor**	**Estimated Capital Investment**
T1	High Temperature Turbine	$8,986,000	2.15	$19,320,000
T2	High Temperature Turbine	$8,986,000	2.15	$19,320,000
T3	High Temperature Turbine	$17,827,000	2.15	$38,330,000
C1	High Pressure Compressor	$15,874,000	1.06	$16,830,000
C2	High Pressure Compressor	$13,488,000	1.08	$14,570,000
C3	High Pressure Compressor	$10,123,000	1.12	$11,340,000
C4	High Pressure Compressor	$9,724,000	1.14	$11,090,000
HX-1	Internal Heat Exchanger (Shell-and-Tube)	$4,296,000	3.17	$13,620,000
HX-2	Recuperator Heat Exchanger (Shell-and-Tube)	$4,112,000	3.17	$13,040,000
HX-3	Intercooler Heat Exchanger (Shell-and-Tube)	$519,000	3.17	$1,645,000
HX-4	Intercooler Heat Exchanger (Shell-and-Tube)	$324,000	3.17	$1,027,000
HX-5	Intercooler Heat Exchanger (Shell-and-Tube)	$312,000	3.17	$989,000
HX-6	Intercooler Heat Exchanger (Shell-and-Tube)	$1,634,000	3.17	$5,180,000
Total		$96,205,000		$166,301,000
Cost per MWh per year		$101		$175

12.2 S-CO$_2$ Process

A summary of capital investment costs and purchase costs for all process units in the s-CO$_2$ process is available in Table 12.2. The total permanent investment for the process is approximately $1.26 billion, with equipment costs and installation accounting for $1 billion of this total. Contingency and contractor fees were assumed to be 5% of direct permanent investment, which is consistent with estimates for new electricity plant costs as calculated by the EIA (“Levelized Cost,” 2015). Site preparation and service facilities were estimated at 1% of bare module cost each. This is a lower estimate than that provided by Downey in the profitability analysis spreadsheet. The choice was made to lower this cost, as well as the cost of land (1% of total depreciable capital) due to the nature of this process: it will add on to an existing plant facility rather than break ground as a new plant and thus, the existence of developed infrastructure and available land is assumed to represent an opportunity for cost savings.

The cost of start-up for this process is estimated at 10% of total depreciable capital as recommended by Downey. A site factor of 1.1 was used to account for creating this process in a Northeastern U.S. location. A detailed breakdown of these costs is available in the profitability analysis section.

Table 12.2. Equipment Cost and Capital Investment Summary for s-CO_2 design. Costs for compressors were calculated using the Process Economic Analyzer (*Aspen Process*, 2015). Costs for turbines, as well as bare module factors, were calculated using the textbook (Seider, et al., 2009), and heat exchanger costs were calculated using the Exchanger Design and Rating program (*Aspen Exchanger*, 2015).

Unit Name	**Unit Description**	**Estimated Purchase Cost**	**Bare Module Factor**	**Estimated Capital Investment**
T-1	Turbine - Gas Powered	$14,000,000	2.15	$30,100,000
T-2	Turbine - Gas Powered	$11,200,000	2.15	$2,408,000
C-1	Compressor - Gas Turbine Powered	$7,451,000	1.36	$10,130,000
C-2	Compressor - Gas Turbine Powered	$7,578,000	1.41	$10,680,000
HX-1	Internal Heat Exchanger - Shell and Tube	$3,916,000	3.17	$12,410,000
HX-2	Internal Heat Exchanger – Shell-and-Tube	$5,044,000	3.17	$15,990,000
HX-3	Internal Heat Exchanger – Shell-and-Tube	$33,000,000	3.17	$104,610,000
HX-4	Recuperator Heat Exchanger – Shell-and-Tube	$250,000,000	3.17	$792,500,000
HX-5	Intercooler Heat Exchanger – Shell-and-Tube	$1,889,000	3.17	$5,988,000
HX-6	Intercooler Heat Exchanger – Shell-and-Tube	$475,000	3.17	$1,506,000
Total		$334,553,000		$986,322,000
Cost per MWh per year		$358		$1,056

13. Operating Cost – Cost of Manufacture

13.1 Helium Process

Fixed costs for this process are estimated at $5.2 million per year. The variable costs are estimated at $5.1 million per year. This gives a total cost of manufacture of $10.3 million per year, or $10.89/MWh produced. A short discussion of these costs is provided below, and a detailed table is available in the profitability analysis section.

13.1.1 Utilities

The utilities are estimated at a yearly cost of $2.3 million. This comes from an estimation of the need for cooling water at 0.01 cents/gallon of cooling water (Seider, et al., 2009). The cost per MWh of electricity produced comes to $2.41. Cooling water to cool hot streams is the only needed utility for this process, as all electricity needed to power compressors and other plant machinery is provided by the process and heating is provided to the process from the primary nuclear reactor loop.

13.1.2 Operations

Operations costs were calculated assuming the need for a single operator to oversee the process and five shifts for continuous operation of the plant. Our operators will have Direct wages and benefits costs of $40/operator hour, with salaries and benefits costs set to zero as we do not anticipate needing to hire additional management or operation support staff to supervise the operators. Operating supplies and services is estimated at 6% of direct wages and benefits for the operators.

13.1.3 Maintenance

Maintenance costs for yearly operation of the plant are assumed to be $1 million. Wages and benefits for maintenance came to $445,000 with an equivalent amount allocated for materials and services. Maintenance overhead was estimated at $22,000 per year and salaries and benefits for management of the maintenance team was estimated at $111,000 per year. These costs are significant reductions from the estimates (Seider, et al., 2009). Due to the limited number of process units in this process and the likelihood of a maintenance team already existing at the plant at which this process would be installed, cost of maintenance is expected to be minimal.

13.1.4 Operating Overhead

Operating overhead for this process is estimated at $195,000 per year, with $146,000 allocated for general plant overhead and $48,000 for mechanical department services. These cost estimates are again reductions from that suggested by Downey (2008), as need for additional operations costs will be limited due to the existence of an already built an operating plant.

13.1.5 Property taxes and insurance

Property taxes and Insurance are expected to cost $3,563,000 per year, or 2% of Total Depreciable Capital (Seider, et al., 2009).

13.2 S-CO_2 Process

Fixed costs for this process are estimated at $3.2 million per year. The variable costs are estimated at $5 million per year. This gives a total cost of manufacture of $7.2 million per year, or $8.79/MWh produced. A short discussion of these costs is provided below, and a detailed table is available in the profitability analysis section.

13.2.1 Utilities

The utilities are estimated at a yearly cost of $2.3 million. This comes from an estimation of the need for cooling water at .01 cents/gallon of cooling water (Seider, et al., 2009). The cost per MWh of electricity produced comes to $2.41. Cooling water to cool hot streams is the only needed utility for this process, as all electricity needed to power compressors and other plant machinery is provided by the process and heating is provided to the process from the primary nuclear reactor loop.

13.2.2 Operations

Operations costs were calculated assuming the need for a single operator to oversee the process and five shifts for continuous operation of the plant. Our operators will have direct wages and benefits costs of $40/operator hour, with salaries and benefits costs set to zero as we do not anticipate needing to hire additional management or operation support staff to expand the plant. Operating supplies and services is estimated at 6% of direct wages and benefits for the operators.

13.2.3 Maintenance

Maintenance costs for yearly operation of the plant are assumed to be $1 million. Wages and benefits for maintenance came to $445,000 with an equivalent amount allocated for materials and services. Maintenance overhead was estimated at $22,000 per year and salaries and benefits for management of the maintenance team was estimated at $111,000 per year. These costs are significant reductions from the estimates provided by Seider et al. Due to the limited number of process units in this process and the likelihood of a maintenance team already existing at the plant at which this process would be installed, cost of maintenance is expected to be minimal.

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13.2.5 Property taxes and insurance

Property taxes and Insurance are expected to cost $3,563,000 per year.

14. Other Important Considerations

Many considerations that would be important in designing a plant like this were out of the scope of our project. Primarily, these include environmental concerns, since our project depends on the use of a nuclear power plant. One of the main reasons that nuclear power is not more widespread is because of public concern over a nuclear disaster. However, since our project assumes that we are merely using the waste heat stream from a nuclear plant, the environmental and other concerns relating to the nuclear power itself were considered outside the scope of the project and not explored further. Plant startup and shutdown costs are also important considerations, but these analyses were also considered outside the scope of our process, and the default percentages were used in calculating these costs. Two other important concerns, Safety and Health and Plant Location, are explored further below.

14.1 Safety and Health Concerns

Two of the largest safety concerns in engineering industries are fires and explosions, and toxic releases and dispersion. Since the power generation cycle in this project is at very high temperatures and pressures, both of these safety concerns are incredibly important in this process. Thus, the flammability and toxicity of the fluids used in the power generation cycle must be examined. All concentration levels noted here are on a per volume basis.

14.1.1 Helium

Helium is a relatively safe gas when looking at these two safety concerns, as it is both non-flammable and non-toxic. Although this seems to remove the two largest safety concerns identified above, helium is an asphixiant, so although inhaling it is not a toxicity issue, a leak is still dangerous as it could cause suffocation (Appendix C.1).

The most important methods to combat the risk of suffocation from a helium release are installation of an industrial exhaust system to eliminate the risk of fluid buildup in the plant area, and an easy and well-marked evacuation route in case a large leak or blowout were to occur. Industrial exhaust systems consist of large fans to increase ventilation, an air filtration unit to clean the air, and an exhaust pipe to release the cleaned air outside or recycle it back into the work area. Of course, there is a possibility that the ventilation system could be compromised, or a leak could go undetected and be too large for the leaking fluid to be removed through the industrial ventilation. As a secondary protection, the containment building of the power generation equipment must be fitted with oxygen-depletion alarm systems, and site workers are also required to carry portable oxygen monitors, which can be carried in a pocket and provide continuous oxygen monitoring. A secondary emergency ventilation system is also necessary that immediately vents all of the work area gaseous contents into the outside air.

In addition to the oxygen depletion alarm system, emergency-breathing apparatuses, a form of self-contained breathing apparatuses that are easy to don and so are used in emergency evacuation situations, are placed at strategic places throughout the facilities ("Respiratory Protection," 2011). They are placed in such a way that a worker standing in any area of the plant is no more than 400 feet away from an emergency breathing apparatus or a doorway (Appendix B.2). This is done because of the large size of the plant, which makes it probable that not all workers will be able to hold their breath for a long enough time to exit the facilities.

OSHA identifies the minimum acceptable oxygen level as 19.5%, so the first alarm threshold is placed at this concentration. At this alarm, all personnel are required to immediately evacuate the enclosed area of the process. A secondary alarm threshold is placed at 14%, when oxygen depletion begins to impair worker judgment, and this is when the emergency ventilation system is triggered. A final emergency alarm is placed at 8% oxygen, the level at which a 10-minute exposure can prove fatal (“Overview of OSHA Standards”).

14.1.2 Carbon Dioxide

The above safety measures are used in both the scenario of helium as the working fluid and CO_2 as the working fluid. However, CO_2 has a couple additional safety concerns. First, whereas helium is nontoxic, CO_2 is a toxic asphixiant, so CO_2 levels are also measured when this is the working fluid of the plant (Appendix C.2). Similar alarm systems as the oxygen monitors are placed around the plant in this process, with different CO_2 alarm limits. The first limit is placed at 0.5%, which is the maximum allowable concentration for an 8-hour workday as recommended by OSHA. A second alarm threshold is placed at 3%, marking the ceiling exposure limit recommended by the American Conference of Governmental Industrial Hygienists (ACGIH). A third and final alarm threshold is placed at 4%, as this is the concentration identified by the ACGIH as being immediately dangerous to workers’ life and health. The fatal concentration of CO_2 is about 9% over a 5-minute period (“Appendix C,” 2006).

The second additional safety concern when working with CO_2 is that the fluid is incompatible with many common metals, including chromium, above 550 °C, and uranium above 750 °C (Appendix C.2). The piping of the process as well as the equipment units are made out of varying grades of stainless steel, which contain chromium and other non-compatible metals. Fortunately, as scale develops inside the piping and equipment units from the interaction of the CO_2 with the metals, the scale itself acts as a barrier to continued degradation of the metal. Degradation of the metal is shown to be a mere decrease in thickness of about 1mm per year at the most, with no added frailty with the scale formation (“Development of a Supercritical,” 2004). Thus, piping is checked for leaks or excessive buildup during scheduled maintenance every year, but it is unlikely to need replacements any more often than in the helium process.

14.1.3 Overall Plant

Both high temperatures and high pressures are present throughout the helium and the CO_2 processes. These extreme conditions led to the careful selection of piping and equipment materials, and higher grades of stainless steel are used where necessary to prevent leaks, explosions, or meltdowns. Extensive temperature monitoring is put in place in the system, with alarms set to sound if the temperature exceeds 90% of the meltdown temperature of the material, and emergency cooling systems surrounding the compressors. Guardrails are also placed around all major equipment to keep employees at a safe distance in case of hot piping and equipment, and warning labels are placed on all pipes and equipment warning of the high temperatures and pressures. As a secondary protection, in case operators accidentally brush against a piece of equipment, all operators are required to wear boiler suits, which consist of a full suit of clothing made to withstand extremely high temperatures (Meher). Reinforced containment walls are also built around the process, to contain any contaminants in the case of a blowout.

14.2 Plant Location

The only location restriction of our process is that it needs to be located in very close proximity to a nuclear facility. With nearly a hundred operating nuclear facilities in the United States, there are numerous potential locations for our process. We chose to locate our process close to Philadelphia, since we are most familiar with the energy markets and nuclear facilities of the surrounding area. The Philadelphia area also has four nuclear power generation units within about fifty miles of the city and many more close by (“Operating Nuclear Power Reactors,” 2015), making it a promising location for a pilot nuclear power generation process. The location was important for the Economic Analysis, as it affected both the site factor, which is 1.1 for the Northeast region, and the local price of electricity in the PJM Interconnection service area.

15. Profitability Analysis – Business Case

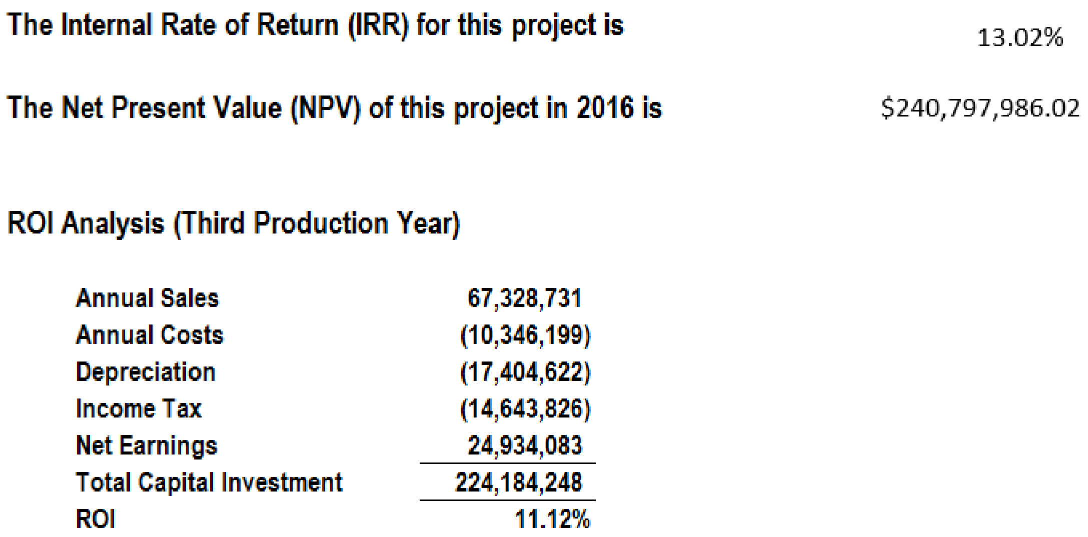
The Profitability Analysis-4.0.xls spreadsheet by Brian K. Downey (2008) was used in order to make a business case for the best helium and s-CO_2 processes. The profitability analysis worksheets will be compared for both working fluids and a final recommendation will be made after a thorough economic analysis of each competing process.

15.1 Profitability Measures

15.1.1 Helium Process

For the profitability analysis, it is assumed that the effective tax rate is 37% for both competing processes. For the helium process, the cash flow analysis determined that the project would have an 11% return on investment (ROI), a net present value (NPV) of $241 million, and a 13% internal rate of return (IRR). The cash flow in each year is summarized in Table 24.1 and shows that the helium process will break even after the ninth year of the project's life using a discount rate of 6.1%. This is the typical discount rate used for power plant projects by the EIA ('Levelized Costs', 2015).

Note that normally cash flow sheets are only projected for the first 20 years. However, a nuclear plant license lasts for 40 years, so all profitability analyses are performed with a 40 year project lifetime for completeness. Due to the limitations of the Profitability Analysis spreadsheet, the cash flow of the last 19 years of the project were determined independently. All years of the cash flow were aggregated in Table 15.1 to reflect the 40-year lifetime of the project.



The Internal Rate of Return (IRR) for this project is 13.02%

The Net Present Value (NPV) of this project in 2016 is $240,797,986.02

ROI Analysis (Third Production Year)

Annual Sales	67,328,731
Annual Costs	(10,346,199)
Depreciation	(17,404,622)
Income Tax	(14,643,826)
Net Earnings	24,934,083
Total Capital Investment	224,184,248
ROI	11.12%

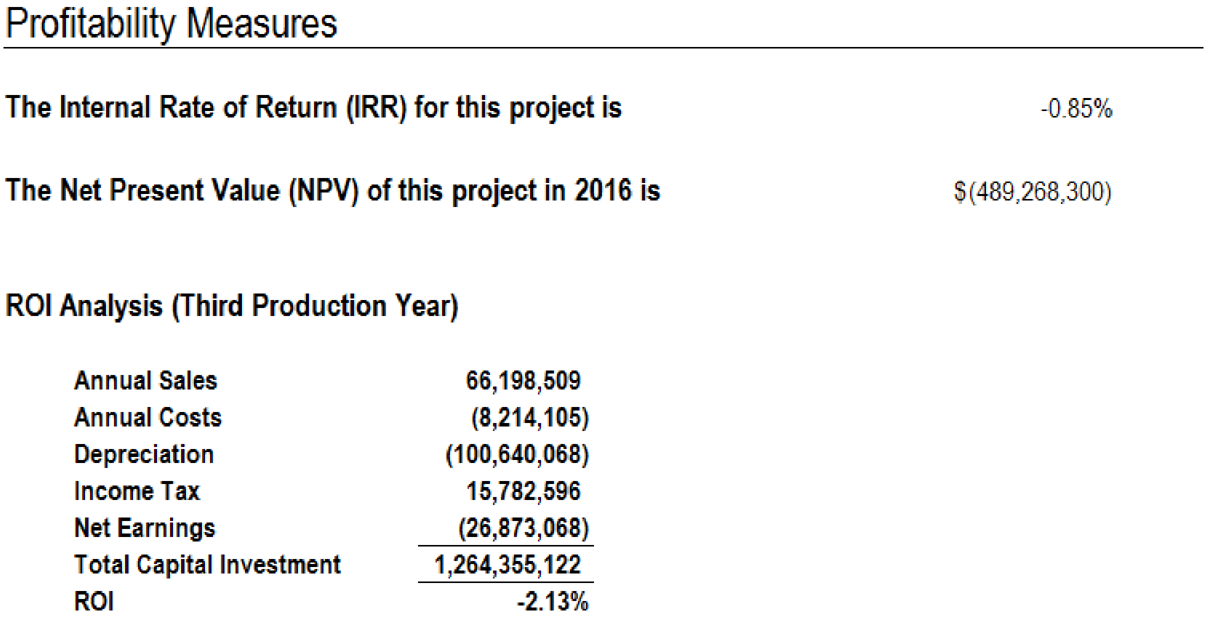
Table 15.1 End of the Year Cash Flows. Here, the helium process is presented with the corresponding cumulative NPV at a 6.1% discount rate for a 40 year project.

Year	Cash Flow	Cumulative NPV at 6.1%
2017	$ (220,871,000.00)	$ (208,172,478.79)
2018	$ 12,630,800.00	$ (196,952,291.91)
2019	$ 22,927,100.00	$ (177,756,635.24)
2020	$ 31,414,300.00	$ (152,967,244.61)
2021	$ 31,108,400.00	$ (129,830,579.78)
2022	$ 30,856,800.00	$ (108,200,477.05)
2023	$ 30,652,900.00	$ (87,948,665.33)
2024	$ 30,694,500.00	$ (68,835,285.42)
2025	$ 30,955,100.00	$ (50,667,844.52)
2026	$ 31,224,000.00	$ (33,396,159.90)
2027	$ 31,481,200.00	$ (16,983,383.40)
2028	$ 31,753,200.00	$ (1,380,570.81)
2029	$ 32,013,500.00	$ 13,445,742.28
2030	$ 32,288,700.00	$ 27,539,772.08
2031	$ 32,552,300.00	$ 40,931,941.06
2032	$ 32,830,700.00	$ 53,662,105.11
2033	$ 31,152,700.00	$ 65,047,134.78

2034	$ 29,483,000.00	$ 75,202,481.65
2035	$ 29,759,700.00	$ 84,863,796.93
2036	$ 30,038,100.00	$ 94,054,839.57
2037	$ 30,318,200.00	$ 102,798,239.65
2038	$ 31,226,400.00	$ 111,285,811.68
2039	$ 40,721,289.40	$ 121,717,814.39
2040	$ 41,004,725.77	$ 131,618,486.97
2041	$ 41,289,862.76	$ 141,014,829.54
2042	$ 41,576,710.57	$ 149,932,473.82
2043	$ 41,865,279.47	$ 158,395,752.26
2044	$ 42,155,579.79	$ 166,427,763.69
2045	$ 42,447,621.90	$ 174,050,435.66
2046	$ 42,741,416.27	$ 181,284,583.70
2047	$ 43,036,973.40	$ 188,149,967.50
2048	$ 43,334,303.88	$ 194,665,344.33
2049	$ 43,633,418.34	$ 200,848,519.77
2050	$ 43,934,327.48	$ 206,716,395.81
2051	$ 44,237,042.09	$ 212,285,016.58
2052	$ 44,541,572.97	$ 217,569,611.83
2053	$ 44,847,931.05	$ 222,584,638.05
2054	$ 45,156,127.27	$ 227,343,817.72
2055	$ 45,466,172.67	$ 231,860,176.39
2056	$ 45,778,078.34	$ 236,146,078.05
2057	$ 52,718,355.45	$ 240,797,986.02

15.1.2 S-CO_2 Process

For the s-CO_2 process, the cash flow analysis determined that the project would have a -2.13% return on investment (ROI) after the third year of production, a net present value (NPV) of -$489 million, and a -0.85% internal rate of return (IRR). The cash flow in each year is summarized in Table 15.2 and shows that the s-CO_2 process will not break even throughout the projected lifespan of the project. Because the unprofitable nature of this project was clear, the lifetime cash flows were not calculated passed the 21 years allowed by the Downey spreadsheet. As discussed in Section 4.5, this project seems like it should generate more power at a lower flowrate than the helium process, but the s-CO_2 is too dense and does not expand through the turbines as well as helium. Therefore, higher flowrates are needed, leading to a higher cost of instillation, which accounts for the main pitfall of this design.



Profitability Measures

The Internal Rate of Return (IRR) for this project is	-0.85%
The Net Present Value (NPV) of this project in 2016 is	$(489,268,300)

ROI Analysis (Third Production Year)

Annual Sales	66,198,509
Annual Costs	(8,214,105)
Depreciation	(100,640,068)
Income Tax	15,782,596
Net Earnings	(26,873,068)
Total Capital Investment	1,264,355,122
ROI	-2.13%

Table 15.2 End of the Year Cash Flows. Here, the s-CO_2 process is shown with the corresponding cumulative NPV at a 6.1% discount rate for a 40 year project.

Year	Cash Flow ($)	Cumulative NPV at 6.1% ($)
2017	(1,261,178,000)	(1,188,669,200)
2018	92,015,100	(1,106,930,400)
2019	147,662,000	(983,300,800)
2020	110,054,100	(896,455,800)
2021	80,894,800	(836,290,800)
2022	81,146,500	(779,408,400)
2023	59,342,600	(740,201,900)
2024	37,540,100	(716,825,800)
2025	37,796,400	(694,643,200)
2026	38,054,300	(673,593,300)
2027	38,313,600	(653,618,400)
2028	38,574,600	(634,663,700)
2029	38,837,100	(616,677,200)
2030	39,101,100	(599,609,600)
2031	39,366,800	(583,413,900)
2032	39,634,000	(568,045,700)
2033	39,902,900	(553,462,900)
2034	40,173,400	(539,625,200)
2035	40,445,400	(526,494,900)
2036	40,719,200	(514,035,600)
2037	40,994,500	(502,213,300)
2038	47,625,800	(489,268,300)

15.2 Cost Summary

15.2.1 Helium Process

A summary of the breakdown of the total capital investment as generated by the Profitability Spreadsheet is included in the tables below. The total capital investment for the best helium process is about $224 million. Of that, variable costs make up about $5 million and fixed costs make up about $5 million. The primary cost for this project is the permanent investment, totaling about $217 million.

The cash flow analysis used a 15-year depreciation schedule following the modified accelerated cost recovery system (MACRS) as determined by the IRS.

Finally, the last table shows a sensitivity analysis on the price of electricity. The price of electricity used in this analysis is $70/MWh (Seider, et al., 2009) and increases accordance with EIA projections (“Wholesale Electricity,” 2016). However, electricity prices have historically wavered and if they drop below $28/MWh, the projected IRR will suffer and possibly produce an economically unsuccessful project.

General Information

Process Title: **Nuclear Reactor**
Product: **Electricity**
Plant Site Location: **PJM Interconnection**
Site Factor: **1.10**
Operating Hours per Year: **7919**
Operating Days Per Year: **330**
Operating Factor: **0.9040**

Product Information

This Process will Yield

120 MWh of Electricity per hour
2,880 MWh of Electricity per day
950,400 MWh of Electricity per year

Price **$70.00 /MWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 15 year MACRS	Product Price
2016	Design		0.0%		
2017	Construction	100%	0.0%		
2018	Production	0%	50.0%	5.00%	$70.00
2019	Production	0%	75.0%	9.50%	$70.42
2020	Production	0%	100.0%	8.55%	$70.84
2021	Production		100.0%	7.70%	$71.27
2022	Production		100.0%	6.93%	$71.70
2023	Production		100.0%	6.23%	$72.13
2024	Production		100.0%	5.90%	$72.56
2025	Production		100.0%	5.90%	$72.99
2026	Production		100.0%	5.91%	$73.43
2027	Production		100.0%	5.90%	$73.87
2028	Production		100.0%	5.91%	$74.32
2029	Production		100.0%	5.90%	$74.76
2030	Production		100.0%	5.91%	$75.21
2031	Production		100.0%	5.90%	$75.66
2032	Production		100.0%	5.91%	$76.11
2033	Production		100.0%	2.95%	$76.57
2034	Production		100.0%		$77.03
2035	Production		100.0%		$77.49
2036	Production		100.0%		$77.96
2037	Production		100.0%		$78.43
2038	Production		100.0%		$78.90

Variable Cost Summary

Variable Costs at 100% Capacity:

General Expenses

Selling / Transfer Expenses:		$	665,280
Direct Research:		$	-
Allocated Research:		$	-
Administrative Expense:		$	1,330,560
Management Incentive Compensation:		$	831,600
Total General Expenses		$	2,827,440
Raw Materials	$0.000000 per MWh of Electricity		$0
Byproducts	$0.000000 per MWh of Electricity		$0
Utilities	$2.414880 per MWh of Electricity		$2,295,102
Total Variable Costs		**$**	**5,122,542**

Fixed Cost Summary

Operations		
Direct Wages and Benefits	$	416,000
Direct Salaries and Benefits	$	-
Operating Supplies and Services	$	24,960
Technical Assistance to Manufacturing	$	-
Control Laboratory	$	-
Total Operations	**$**	**440,960**
Maintenance		
Wages and Benefits	$	445,450
Salaries and Benefits	$	111,362
Materials and Services	$	445,450
Maintenance Overhead	$	22,272
Total Maintenance	**$**	**1,024,535**
Operating Overhead		
General Plant Overhead:	$	145,922
Mechanical Department Services:	$	48,641
Employee Relations Department:	$	-
Business Services:	$	-
Total Operating Overhead	**$**	**194,562**
Property Taxes and Insurance		
Property Taxes and Insurance:	$	3,563,600
Other Annual Expenses		
Rental Fees (Office and Laboratory Space):	$	-
Licensing Fees:	$	-
Miscellaneous:	$	-
Total Other Annual Expenses	**$**	**-**
Total Fixed Costs	**$**	**5,223,657**

Investment Summary

Total Bare Module Costs:		
Fabricated Equipment	$ 35,494,075	
Process Machinery	$ 130,873,804	
Spares	$ -	
Storage	$ -	
Other Equipment	$ -	
Catalysts	$ -	
Computers, Software, Etc.	$ -	
Total Bare Module Costs:		$ 166,367,879
Direct Permanent Investment		
Cost of Site Preparations:	$ 1,663,679	
Cost of Service Facilities:	$ 1,663,679	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		$ 169,695,236
Total Depreciable Capital		
Cost of Contingencies & Contractor Fees	$ 8,484,762	
Total Depreciable Capital		$ 178,179,998
Total Permanent Investment		
Cost of Land:	$ 1,781,800	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 17,818,000	
Total Permanent Investment - Unadjusted		$ 197,779,798
Site Factor		1.10
Total Permanent Investment		$ 217,557,778

Working Capital

	2017	2018	2019
Accounts Receivable	$ 2,734,027	$ 1,367,014	$ 1,367,014
Cash Reserves	$ 969,225	$ 484,612	$ 484,612
Accounts Payable	$ (754,554)	$ (377,277)	$ (377,277)
Electricity Inventory	$ 364,537	$ 182,268	$ 182,268
Raw Materials	$ -	$ -	$ -
Total	**$ 3,313,235**	**$ 1,656,618**	**$ 1,656,618**
Present Value at 6.1%	*$ 3,122,748*	*$ 1,471,606*	*$ 1,386,999*

Total Capital Investment	**$ 223,539,130**

	Variable Costs										
Product Price	$1,280,635	$2,049,017	$2,817,398	$3,585,779	$4,354,161	***$5,122,542***	$5,890,923	$6,659,305	$7,427,686	$8,196,067	$8,964,448
$17.50	-0.48%	-0.92%	-1.38%	-1.85%	-2.35%	-2.87%	-3.42%	-3.99%	-4.61%	-5.27%	-5.98%
$28.00	4.42%	4.11%	3.80%	3.48%	3.15%	2.82%	2.49%	2.14%	1.79%	1.42%	1.05%
$38.50	8.15%	7.90%	7.64%	7.38%	7.12%	6.86%	6.59%	6.32%	6.04%	5.76%	5.48%
$49.00	11.33%	11.11%	10.88%	10.65%	10.42%	10.19%	9.96%	9.72%	9.49%	9.25%	9.01%
$59.50	14.18%	13.97%	13.76%	13.55%	13.35%	13.14%	12.92%	12.71%	12.50%	12.28%	12.07%
$70.00	16.80%	16.61%	16.41%	16.22%	16.02%	15.83%	15.63%	15.43%	15.23%	15.03%	14.83%
$80.50	19.27%	19.09%	18.90%	18.72%	18.53%	18.34%	18.16%	17.97%	17.78%	17.59%	17.40%
$91.00	21.62%	21.44%	21.26%	21.09%	20.91%	20.73%	20.55%	20.37%	20.19%	20.01%	19.83%
$101.50	23.87%	23.70%	23.53%	23.36%	23.19%	23.01%	22.84%	22.67%	22.49%	22.32%	22.14%
$112.00	26.05%	25.88%	25.72%	25.55%	25.38%	25.21%	25.05%	24.88%	24.71%	24.54%	24.37%
$122.50	28.16%	28.00%	27.84%	27.68%	27.51%	27.35%	27.18%	27.02%	26.86%	26.69%	26.53%

15.2.2 S-CO_2 Process

A summary of the breakdown of the total capital investment as generated by the Profitability Spreadsheet is included in the tables below. The total capital investment for the best S-CO_2 process is about $1.26 billion. Of that, variable costs make up about $5 million and fixed costs make up about $3 million. The primary cost for this project is the permanent investment, totaling about $1.26 billion.

The cash flow analysis used a 5-year depreciation schedule following the modified accelerated cost recovery system (MACRS). The s-CO_2 process uses a 5-year depreciation schedule as opposed to a 15-year schedule because it is considered a new carbon free technology and is promoted by the government to run on a 5-year schedule ("Incentives Available," 2016).

A sensitivity analysis is not presented for this process because it is not relevant in the scope of this vastly unsuccessful project.

General Information

Process Title: **Nuclear Reactor**
Product: **Electricity**
Plant Site Location: **PJM Interconnection**
Site Factor: **1.10**
Operating Hours per Year: **7919**
Operating Days Per Year: **330**
Operating Factor: **0.9040**

Product Information

This Process will Yield

118 MWh of Electricity per hour
2,832 MWh of Electricity per day
934,446 MWh of Electricity per year

Price **$70.00 /MWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2016	Design		0.0%		
2017	Construction	100%	0.0%		
2018	Production	0%	50.0%	20.00%	$70.00
2019	Production	0%	75.0%	32.00%	$70.42
2020	Production	0%	100.0%	19.20%	$70.84
2021	Production		100.0%	11.52%	$71.27
2022	Production		100.0%	11.52%	$71.70
2023	Production		100.0%	5.76%	$72.13
2024	Production		100.0%		$72.56
2025	Production		100.0%		$72.99
2026	Production		100.0%		$73.43
2027	Production		100.0%		$73.87
2028	Production		100.0%		$74.32
2029	Production		100.0%		$74.76
2030	Production		100.0%		$75.21
2031	Production		100.0%		$75.66
2032	Production		100.0%		$76.11
2033	Production		100.0%		$76.57
2034	Production		100.0%		$77.03
2035	Production		100.0%		$77.49
2036	Production		100.0%		$77.96
2037	Production		100.0%		$78.43
2038	Production		100.0%		$78.90

Variable Cost Summary

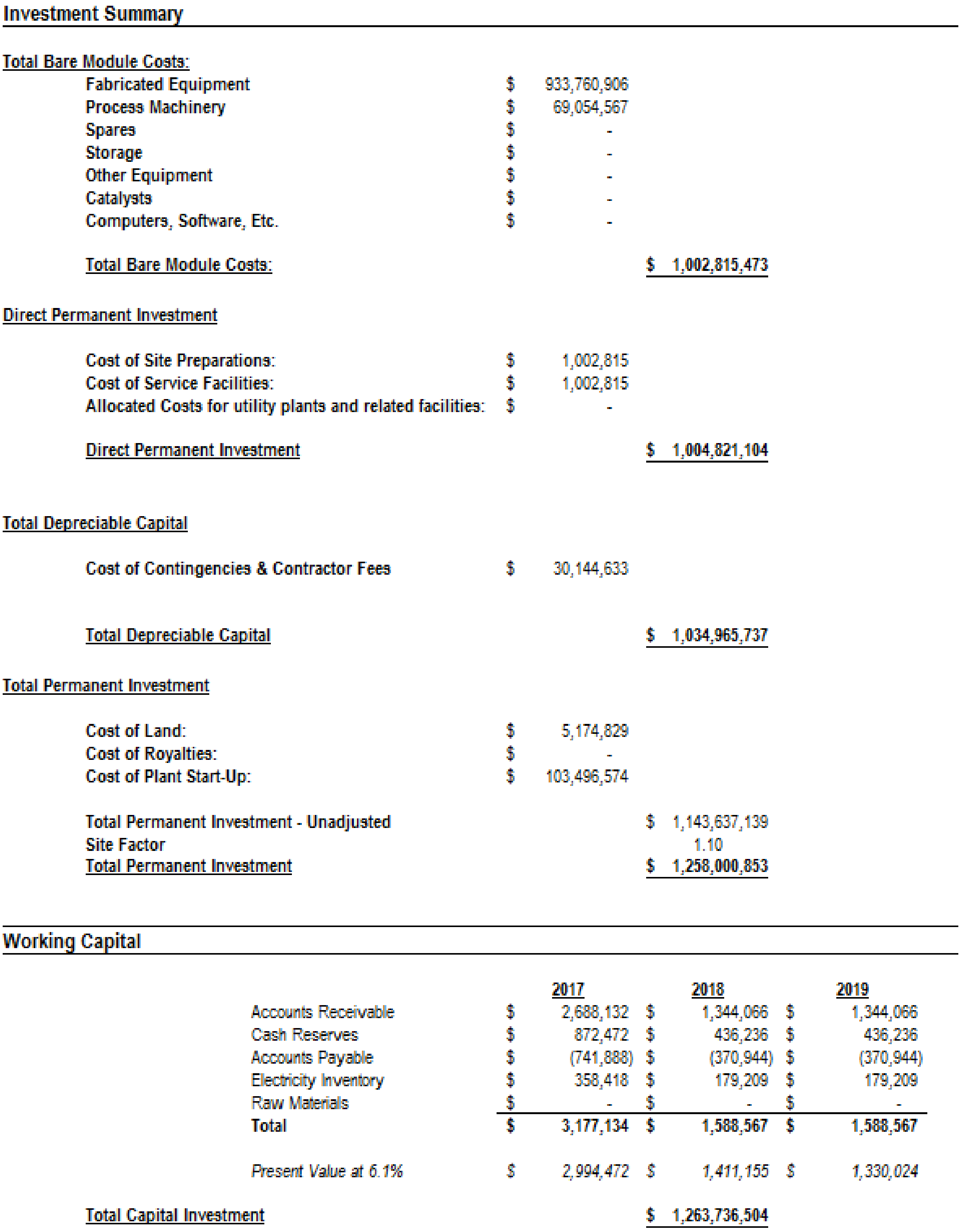
Variable Costs at 100% Capacity:

General Expenses

Selling / Transfer Expenses:		$	654,112
Direct Research:		$	-
Allocated Research:		$	-
Administrative Expense:		$	1,308,224
Management Incentive Compensation:		$	817,640
Total General Expenses		$	2,779,977
Raw Materials	$0.000000 per MWh of Electricity		$0
Byproducts	$0.000000 per MWh of Electricity		$0
Utilities	$2.414880 per MWh of Electricity		$2,256,575
Total Variable Costs		**$**	**5,036,552**

Fixed Cost Summary

Operations			
	Direct Wages and Benefits	$	416,000
	Direct Salaries and Benefits	$	-
	Operating Supplies and Services	$	24,960
	Technical Assistance to Manufacturing	$	-
	Control Laboratory	$	-
	Total Operations	**$**	**440,960**
Maintenance			
	Wages and Benefits	$	25,874
	Salaries and Benefits	$	6,469
	Materials and Services	$	25,874
	Maintenance Overhead	$	1,294
	Total Maintenance	**$**	**59,511**
Operating Overhead			
	General Plant Overhead:	$	67,251
	Mechanical Department Services:	$	22,417
	Employee Relations Department:	$	-
	Business Services:	$	-
	Total Operating Overhead	**$**	**89,669**
Property Taxes and Insurance			
	Property Taxes and Insurance:	$	2,587,414
Other Annual Expenses			
	Rental Fees (Office and Laboratory Space):	$	-
	Licensing Fees:	$	-
	Miscellaneous:	$	-
	Total Other Annual Expenses	**$**	**-**
Total Fixed Costs		**$**	**3,177,553**



Investment Summary

Total Bare Module Costs:		
Fabricated Equipment	$ 933,760,906	
Process Machinery	$ 69,054,567	
Spares	$ -	
Storage	$ -	
Other Equipment	$ -	
Catalysts	$ -	
Computers, Software, Etc.	$ -	
Total Bare Module Costs:		**$ 1,002,815,473**
Direct Permanent Investment		
Cost of Site Preparations:	$ 1,002,815	
Cost of Service Facilities:	$ 1,002,815	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		**$ 1,004,821,104**
Total Depreciable Capital		
Cost of Contingencies & Contractor Fees	$ 30,144,633	
Total Depreciable Capital		**$ 1,034,965,737**
Total Permanent Investment		
Cost of Land:	$ 5,174,829	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 103,496,574	
Total Permanent Investment - Unadjusted		$ 1,143,637,139
Site Factor		1.10
Total Permanent Investment		**$ 1,258,000,853**

Working Capital

	2017	2018	2019
Accounts Receivable	$ 2,688,132	$ 1,344,066	$ 1,344,066
Cash Reserves	$ 872,472	$ 436,236	$ 436,236
Accounts Payable	$ (741,888)	$ (370,944)	$ (370,944)
Electricity Inventory	$ 358,418	$ 179,209	$ 179,209
Raw Materials	$ -	$ -	$ -
Total	**$ 3,177,134**	**$ 1,588,567**	**$ 1,588,567**
Present Value at 6.1%	*$ 2,994,472*	*$ 1,411,155*	*$ 1,330,024*

Total Capital Investment	**$ 1,263,736,504**

16. Conclusions and Recommendations

The two processes that were analyzed each produce about 120 MW of electricity taken from residual heat from a nuclear reactor. Both processes use helium as the working fluid in the primary loop, which is the stream in contact with the nuclear reactor. As for the secondary loop, designs were made using both helium and s-CO_2. Since helium is a small atom that is prone to leak out of the system and is costly to purchase, s-CO_2 was explored. However, after a complete analysis of both competing processes, it is obvious to say that the helium process is the winning process. With an ROI of 11% and a NPV of $241 million, using helium as the working fluid gives the only economically successful process design. It is recommended that the helium process be pursued in further research in attempt to reduce equipment sizes. At the present 11% ROI, the project has economic potential and has value for being carbon free and beating out coal power plants when comparing costs per MWh.

Fortunately, the s-CO_2 process also has promise and is recommended for further research. There is a possibility that using a turbocharger would reduce the number of equipment pieces needed in the whole process, thereby reducing the capital investment. This alternative is looked at by the design team and several insights are discussed in Appendix A.

17. Acknowledgments

We would like to thank our advisor Dr. Warren Seider and our professor Mr. Leonard Fabiano for the countless hours they have spent helping us research and implement the many different aspects of our project. Their industry knowledge and creativity were invaluable throughout the design process. We would also like to thank our industrial consultant Mr. Adam Brostow for writing our problem statement and guiding us through the preliminary planning stages of the project. His experience with our specific equipment pieces was incredibly helpful, and we appreciate his patience in explaining the complexities of a high-capacity Brayton cycle.

In addition, we would like to thank the other industrial consultants who provided their insight and expertise during the semester. We would like to thank Mr. Gary Sawyer for his help in calculating a system volume for both of our processes, Mr. David Kolesar for his help in the design of high-temperature heat exchangers, and Dr. Richard Bockrath for sharing his expertise in safety regulations for high temperature systems. We could not have prepared this report without the constant attention and time given by all of these people.

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Appendix A – Insights into Turbocharger Process Design

A turbocharger is essentially a generator that is driven by an engine. It typically contains an inlet, an outlet, a compressor, a combustion chamber, and a turbine that drives the compressor ("Turbojet," 2016). For our purposes, we could use a modified turbocharger that does not have a combustion chamber since our energy is derived from a hot stream of residual nuclear heat. Therefore, a hot inlet of helium or s-CO_2 would enter the inlet and be passed through turbines that would generate electricity and then compressed in 2 to 3 stages of compression chambers. Figure A.1 shows a graphic of a typical, unmodified turbocharger.

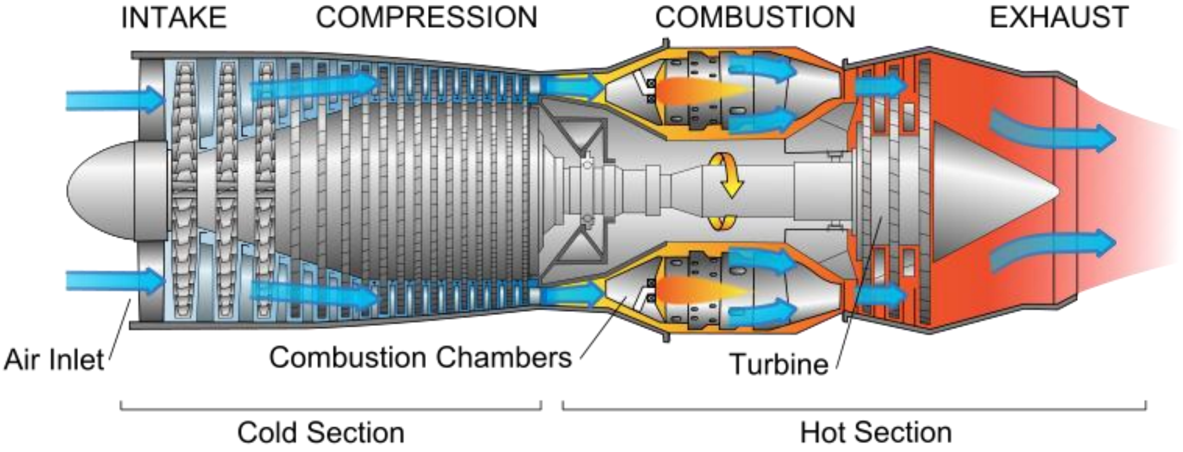


Figure A.1. Model of a typical turbocharger with all units – no modification ("Turbojet," 2016).

Figure A.2 shows a preliminary process design using the turbocharger. The primary loop from the nuclear reactor remains unchanged and has the capacity to deliver the same amount of energy to the secondary loop. This loop works with both the helium and s-CO_2 working fluids, but an economic analysis has not been performed to determine which working fluid is preferred as this is beyond the scope of the design. It is recommended that this design be looked into further and costed in hopes of reducing the cost of capital and increasing the economic viability of the s-CO_2 project.

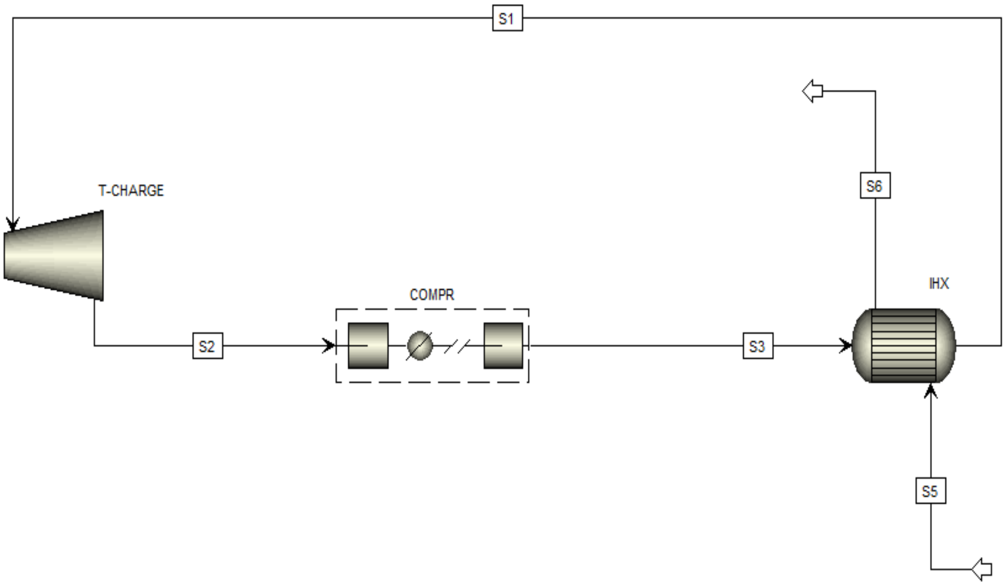


Figure A.2. Preliminary Process design using turbocharger and a 3-stage compressor-intercooler unit.

Appendix B – Sample Calculations

B.1 Intermediate Pressure between Compressors

Most of the temperatures and pressures in the helium process are given to us in the problem statement, but compressors C-1 and C-2, and C-3 and C-4 are treated as pairs in the process and the intermediate pressures between them are not specified. In order to be able to input all of the pressure specifications for the system compressors into the Aspen simulation, it is necessary to find these intermediate pressures. These calculations are shown below, where P_2 is the intermediate pressure, P_1 is the inlet pressure to the first compressor, and P_3 is the outlet pressure from the second compressor.

$$\frac{P_3}{P_1} = \frac{P_2}{P_3} = \sqrt{\frac{P_2}{P_1}}$$

$$P_3 = P_1 * \sqrt{\frac{P_2}{P_1}}$$

B.2 Distance between Emergency Breathing Apparatuses

A couple assumptions are made to find a safe distance at which emergency breathing apparatuses can be placed in the plant. First, it is assumed that although most humans can hold their breath for about two minutes in a normal situation, during an emergency situation this time period is reduced to only about thirty seconds. Second, it is assumed that the average running speed of an adult is around 10 to 15 mph. Taking the slower end of the range to be safe, the following calculations are performed.

$$\text{Running Speed (ft/s)} = 10\ \text{mph} * \frac{1.467\ \text{ft/s}}{1\ \text{mph}} = 14.67\ \text{ft/s}$$

$$\text{Distance} = 14.67\ \text{ft/s} * 30\ \text{s} = 440\ \text{ft}$$

As a safety precaution, this distance was reduced to 400 ft between each emergency breathing apparatus or exit doorway to ambient air.

B.3 System Volume Estimation

The total volumes contained inside piping and equipment for both the helium and the s-CO_2 processes are calculated using a few assumptions about the different piping and pieces of equipment. Here we will show only the calculations for the s-CO_2 system, as the calculations for the helium system follow the same process.

B.3.1 Piping

First, the volume of the piping is calculated. For this, it is a general assumption that water flowing through a piping system can move at a linear velocity of around 15 ft/s before the pressure drop causes problems. Since we have a gas and a supercritical fluid instead of water, this linear velocity is converted to a new linear velocity for the other fluids. It is also assumed here that there are approximately 50 ft of piping between each piece of equipment.

$$\rho_{s-CO_2} * v_{s-CO_s}^2 = \rho_{H_2O} * v_{H_2O}^2$$

$$v_{s-CO_2} = \sqrt{\frac{\rho_{H_2O} * v_{H_2O}^2}{\rho_{s-CO_2}}} = \sqrt{\frac{1\ \mathrm{g/cm^3} * (15\ \mathrm{ft/s})^2}{0.023\ \mathrm{g/cm^3}}} = 98.8\ \mathrm{ft/s}$$

$$\text{Cross} - \text{sectional Area} = \frac{\text{volumetric flowrate}}{\text{linear velocity}} = \frac{1839.29\ \mathrm{ft^3/s}}{98.8\ \mathrm{ft/s}} = 18.6\ \mathrm{ft^2}$$

$$\text{Volume Piping} = 18.6\ \mathrm{ft^2} * 50\ \mathrm{ft} * 10\ \text{Equipment Pieces} = 9300\ \mathrm{ft^3}$$

B.3.2 Turbines and Compressors

For both the turbines and the compressors, the standard assumption of a residence time in each piece of equipment of 5 seconds (based on a linear velocity of 15 ft/s) is used. This has to be adjusted for the new linear velocity, and the following calculations are performed.

Calculations for T-1 are shown, and the process is the same for the other turbine and compressors.

$$\text{Residence Time} = t_{s-CO_2} = \frac{v_{H_2O} * t_{H_2O}}{v_{s-CO_2}} = \frac{15\ \text{ft/s} * 5\ \text{s}}{98.8\ \text{ft/s}} = 0.759\ \text{s}$$

$$\text{Volume Turbine} = \text{volumetric flowrate} * t_{s-CO_2} = 1181.4 \frac{\text{ft}^3}{\text{s}} * 0.759\ \text{s} = 897\ \text{ft}^3$$

B.3.3 Heat Exchangers

The volume of the heat exchangers is calculated without any assumptions, since the heat exchanger designs supply us with all the required information to find the tube-side volume. The calculations are as follows for HX-1.

$$\text{Tube Cross} - \text{sectional Area} = \text{A} = \left(\frac{\pi * d_{in}}{2}\right)^2 = \left(\frac{\pi * 1.67\ \text{ft}}{2}\right)^2 = 6.847\ \text{ft}^2$$

$$\text{Volume Heat Exchanger} = \text{A} * \#\ \text{of tubes} * \text{tube length} = 6.847\ \text{ft}^2 * 226\ \text{tubes} * 12\ \text{ft} = 5917\ \text{ft}^3$$

Once all of the volumes of the pieces of equipment are found, they are summed together to get the total volume of the system.

B.4 Turbine Purchase Cost

The costs of the turbines were calculated using the equations from the textbook (Table 22.32). A sample calculation is shown below for T-1 from the helium process, where α is a factor that accounts for the material. It is 1 for carbon steel, and 2 for stainless steel.

$$C_p = \alpha * 530 * P^{0.81} = 2 * 530 * (70{,}806\ hp)^{0.81} = \$\ 8{,}986575$$

B.5 Levelized Cost of Electricity

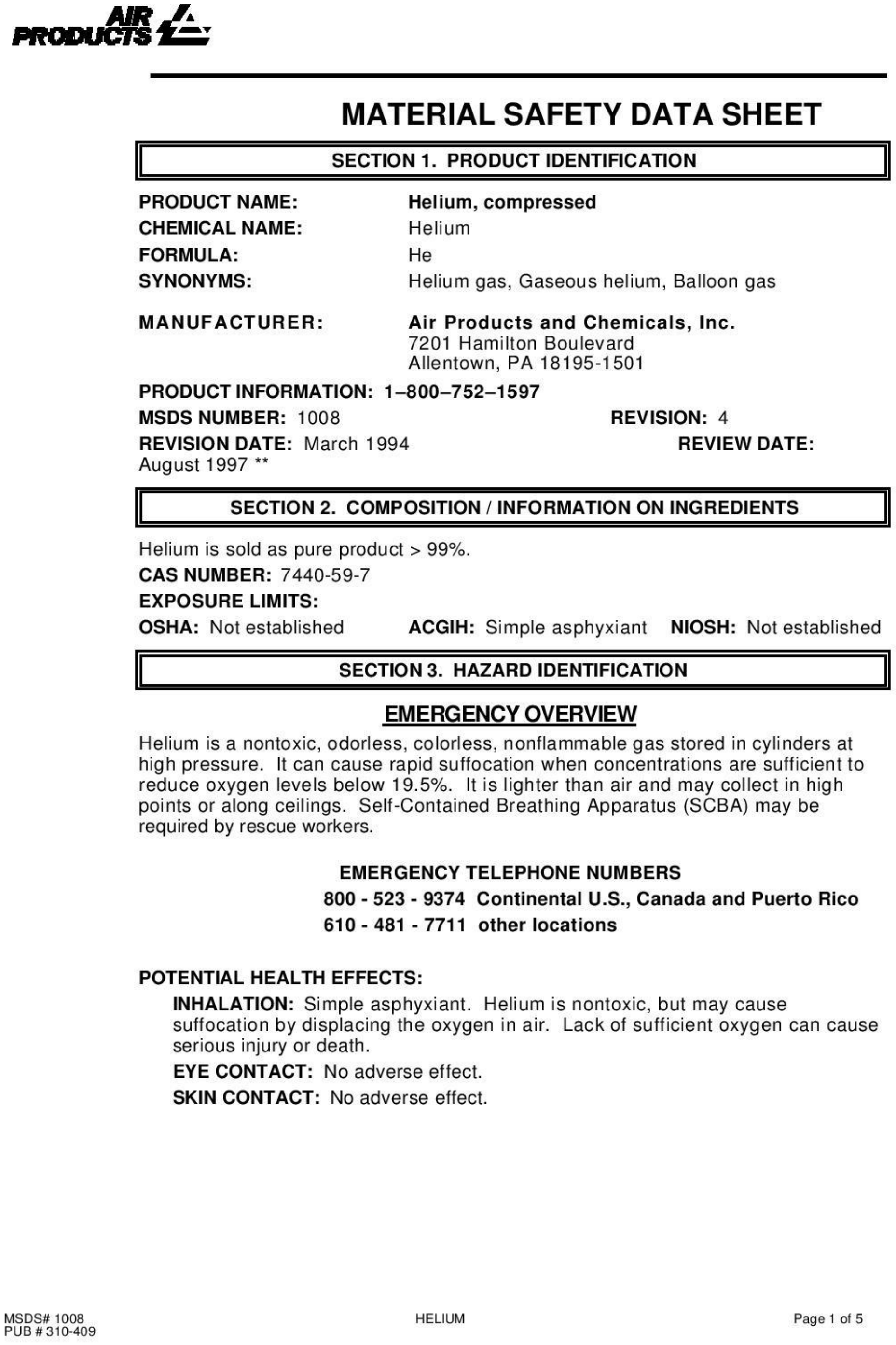
The levelized cost of electricity was calculated using the EIA definition in the Levelized Cost source.

$$LCOE = \frac{C}{G * Y} + \frac{Fc}{G} + \frac{Vc}{G} = 33.4$$

C = Total Permanent Investment: \$217,000,000
F_c = Total Fixed Costs = \$5,200,000
V_c = Total Variable Costs = \$21,000,000
G = Net generation (per year) = 950,400 MWh
Y = Years of operation = 40

Appendix C. Material Safety and Data Sheets

C.1 Helium



AIR PRODUCTS

MATERIAL SAFETY DATA SHEET

SECTION 1. PRODUCT IDENTIFICATION

PRODUCT NAME:	**Helium, compressed**
CHEMICAL NAME:	Helium
FORMULA:	He
SYNONYMS:	Helium gas, Gaseous helium, Balloon gas
MANUFACTURER:	**Air Products and Chemicals, Inc.** 7201 Hamilton Boulevard Allentown, PA 18195-1501

PRODUCT INFORMATION: 1–800–752–1597

MSDS NUMBER: 1008 **REVISION:** 4

REVISION DATE: March 1994 **REVIEW DATE:** August 1997 **

SECTION 2. COMPOSITION / INFORMATION ON INGREDIENTS

Helium is sold as pure product > 99%.

CAS NUMBER: 7440-59-7

EXPOSURE LIMITS:

OSHA: Not established **ACGIH:** Simple asphyxiant **NIOSH:** Not established

SECTION 3. HAZARD IDENTIFICATION

EMERGENCY OVERVIEW

Helium is a nontoxic, odorless, colorless, nonflammable gas stored in cylinders at high pressure. It can cause rapid suffocation when concentrations are sufficient to reduce oxygen levels below 19.5%. It is lighter than air and may collect in high points or along ceilings. Self-Contained Breathing Apparatus (SCBA) may be required by rescue workers.

EMERGENCY TELEPHONE NUMBERS

800 - 523 - 9374 Continental U.S., Canada and Puerto Rico

610 - 481 - 7711 other locations

POTENTIAL HEALTH EFFECTS:

INHALATION: Simple asphyxiant. Helium is nontoxic, but may cause suffocation by displacing the oxygen in air. Lack of sufficient oxygen can cause serious injury or death.

EYE CONTACT: No adverse effect.

SKIN CONTACT: No adverse effect.

MSDS# 1008
PUB # 310-409

HELIUM

Page 1 of 5

EXPOSURE INFORMATION:

ROUTE OF ENTRY: Inhalation

TARGET ORGANS: None

EFFECT: Asphyxiation (suffocation)

SYMPTOMS: Exposure to an oxygen deficient atmosphere (less than 19.5%) may cause dizziness, drowsiness, nausea, vomiting, excess salivation, diminished mental alertness, loss of consciousness and death. Exposure to atmospheres containing 8-10% or less oxygen will bring about unconsciousness without warning and so quickly that the individuals cannot help or protect themselves.

MEDICAL CONDITIONS AGGRAVATED BY OVEREXPOSURE: None

CARCINOGENIC POTENTIAL: Helium is not listed as a carcinogen or potential carcinogen by NTP, IARC, or OSHA Subpart Z.

WARNING

The practice of intentionally inhaling helium for a voice altering effect is extremely dangerous and may result in serious injury or death!

SECTION 4. FIRST AID

INHALATION: Persons suffering from lack of oxygen should be moved to fresh air. If victim is not breathing, administer artificial respiration. If breathing is difficult, administer oxygen. Obtain prompt medical attention.

EYE / SKIN CONTACT: Not applicable

SECTION 5. FIRE AND EXPLOSION

FLASH POINT:	AUTOIGNITION:	FLAMMABLE LIMITS:
Not applicable	Nonflammable	Nonflammable

EXTINGUISHING MEDIA: Helium is nonflammable and does not support combustion. Use extinguishing media appropriate for the surrounding fire.

HAZARDOUS COMBUSTION PRODUCTS: None

SPECIAL FIRE FIGHTING INSTRUCTIONS: Helium is a simple asphyxiant. If possible, remove helium cylinders from fire area or cool with water. Self contained breathing apparatus may be required for rescue workers.

UNUSUAL FIRE AND EXPLOSION HAZARDS: Upon exposure to intense heat or flame cylinder will vent rapidly and or rupture violently. Most cylinders are designed to vent contents when exposed to elevated temperatures. Pressure in a container can build up due to heat and it may rupture if pressure relief devices should fail to function.

SECTION 6. ACCIDENTAL RELEASE MEASURES

Evacuate all personnel from affected area. Increase ventilation to release area and monitor oxygen level. Use appropriate protective equipment (SCBA). If leak is from container or it's valve, call the Air Products' emergency telephone number. If leak is in user's system close cylinder valve and vent pressure before attempting repairs.

SECTION 7. STORAGE AND HANDLING

STORAGE: Cylinders should be stored upright in a well-ventilated, secure area, protected from the weather. Storage area temperatures should not exceed 125 °F (52 °C) and area should be free of combustible materials. Storage should be away from heavily traveled areas and emergency exits. Avoid areas where salt or other corrosive materials are present. Valve protection caps and valve outlet seals should remain on cylinders not connected for use. Separate full from empty cylinders. Avoid excessive inventory and storage time. Use a first-in first-out system. Keep good inventory records.

HANDLING: Do not drag, roll, or slide cylinder. Use a suitable handtruck designed for cylinder movement. Never attempt to lift a cylinder by its cap. Secure cylinders at all times while in use. Use a pressure reducing regulator or separate control valve to safely discharge gas from cylinder. Use a check valve to prevent reverse flow into cylinder. Do not overheat cylinder to increase pressure or discharge rate. If user experiences any difficulty operating cylinder valve, discontinue use and contact supplier. Never insert an object (e.g., wrench, screwdriver, pry bar, etc.) into valve cap openings. Doing so may damage valve causing a leak to occur. Use an adjustable strap-wrench to remove over-tight or rusted caps.

Helium is compatible with all common materials of construction. Pressure requirements should be considered when selecting materials and designing systems.

SPECIAL REQUIREMENTS: Always store and handle compressed gases in accordance with Compressed Gas Association, Inc. (ph. 703-412-0900) pamphlet CGA P-1, *Safe Handling of Compressed Gases in Containers*. Local regulations may require specific equipment for storage or use.

CAUTION: Compressed gas cylinders shall not be refilled except by qualified producers of compressed gases. Shipment of a cylinder which has not been filled by the owner or with the owner's written consent is a violation of federal law.

SECTION 8. PERSONAL PROTECTION / EXPOSURE CONTROL

ENGINEERING CONTROLS: Provide good ventilation and/or local exhaust to prevent accumulation of high concentrations of gas. Oxygen levels in work area should be monitored to ensure they do not fall below 19.5%.

RESPIRATORY PROTECTION:

GENERAL USE: None required.

EMERGENCY: Use SCBA or positive pressure air line with mask and escape pack in areas where oxygen concentration is less than 19.5%. Air purifying respirators will not provide protection.

OTHER PROTECTIVE EQUIPMENT: Safety shoes are recommended when handling cylinders.

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

APPEARANCE: Colorless gas

ODOR: Odorless

MOLECULAR WEIGHT: 4.00

BOILING POINT (1 atm): -452.1 °F (-268.9 °C)

SPECIFIC GRAVITY (Air =1): 0.138

SPECIFIC VOLUME (at 70 °F (21.1 °C) and 1 atm): 96.71 ft^3/lb (6.037 m^3/kg)

FREEZING POINT/MELTING POINT: None

VAPOR PRESSURE (AT 70°F): Not applicable

GAS DENSITY (at 70 °F (21.1 °C) and 1 atm): 0.0103 lb/ft^3 (0.165 kg/m^3)

SOLUBILITY IN WATER (Vol./Vol. at 32 °F (0 °C)): 0.0094

SECTION 10. REACTIVITY / STABILITY

CHEMICAL STABILITY: Stable

CONDITIONS TO AVOID: None

INCOMPATIBILITY: None

HAZARDOUS DECOMPOSITION PRODUCTS: None

HAZARDOUS POLYMERIZATION: Will not occur.

SECTION 11. TOXICOLOGICAL INFORMATION

Helium is a simple asphyxiant.

SECTION 12. ECOLOGICAL INFORMATION

Helium is not toxic. No adverse ecological effects are expected. Helium does not contain any Class I or Class II ozone depleting chemicals. Helium is not listed as a marine pollutant by DOT (49 CFR 171).

SECTION 13. DISPOSAL

UNUSED PRODUCT / EMPTY CONTAINER: Return container and unused product to supplier. Do not attempt to dispose of residual or unused quantities.

DISPOSAL: For emergency disposal, secure the cylinder and slowly discharge gas to the atmosphere in a well ventilated area or outdoors.

SECTION 14. TRANSPORTATION

DOT HAZARD CLASS: 2.2

DOT SHIPPING LABEL: Nonflammable Gas

DOT SHIPPING NAME: Helium, Compressed

IDENTIFICATION NUMBER: UN1046

REPORTABLE QUANTITY (RQ): None

SPECIAL SHIPPING INFORMATION: Cylinders should be transported in a secure upright position in a well ventilated truck. Never transport in passenger compartment of a vehicle.

SECTION 15. REGULATORY INFORMATION

U.S. FEDERAL REGULATIONS:

EPA - ENVIRONMENTAL PROTECTION AGENCY

CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act of 1980 requires notification to the National Response Center of a release of quantities of hazardous substances equal to or greater than the reportable quantities (RQ) in 40 CFR 302.4.

CERCLA Reportable Quantity: None

SARA TITLE III: SUPERFUND AMENDMENT AND REAUTHORIZATION ACT OF 1986

SECTION 302: Requires emergency planning based on threshold planning quantities (TPQ) and release reporting based on reportable quantities (RQ) of EPA's extremely hazardous substances (40 CFR 355).

Helium is not listed as an Extremely Hazardous Substance.

SECTIONS 311/312: Require submission of material safety data sheets (MSDSs) and chemical inventory reporting with identification of EPA defined hazard classes. The hazard classes for this product are:

IMMEDIATE HEALTH:	No	PRESSURE:	Yes
DELAYED HEALTH:	No	REACTIVITY:	No
		FIRE:	No

SECTION 313: Requires submission of annual reports of release of toxic chemicals that appear in 40 CFR 372. This information should be included in all MSDSs that are copied and distributed for this material.

Helium is not listed as a toxic chemical.

40 CFR PART 68: Risk Management for Chemical Accident Release Prevention. Requires the development and implementation of risk management programs at facilities that manufacture, use, store, or otherwise handle regulated substances in quantities that exceed specified thresholds.

Helium is not listed as a regulated substance.

TSCA - TOXIC SUBSTANCE CONTROL ACT : Helium is listed on the TSCA inventory.

OSHA - OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION

29 CFR 1910.119: Process Safety Management of Highly Hazardous Chemicals. Requires facilities to develop a process safety management program based on Threshold Quantities (TQ) of highly hazardous chemicals.

Helium is not listed as a Highly Hazardous Chemical.

STATE REGULATIONS:

CALIFORNIA:

Proposition 65: This product does NOT contain any listed substances which the State of California requires warning under this statute.

SCAQMD Rule: VOC = Not applicable

SECTION 16. SUPPLEMENTAL INFORMATION

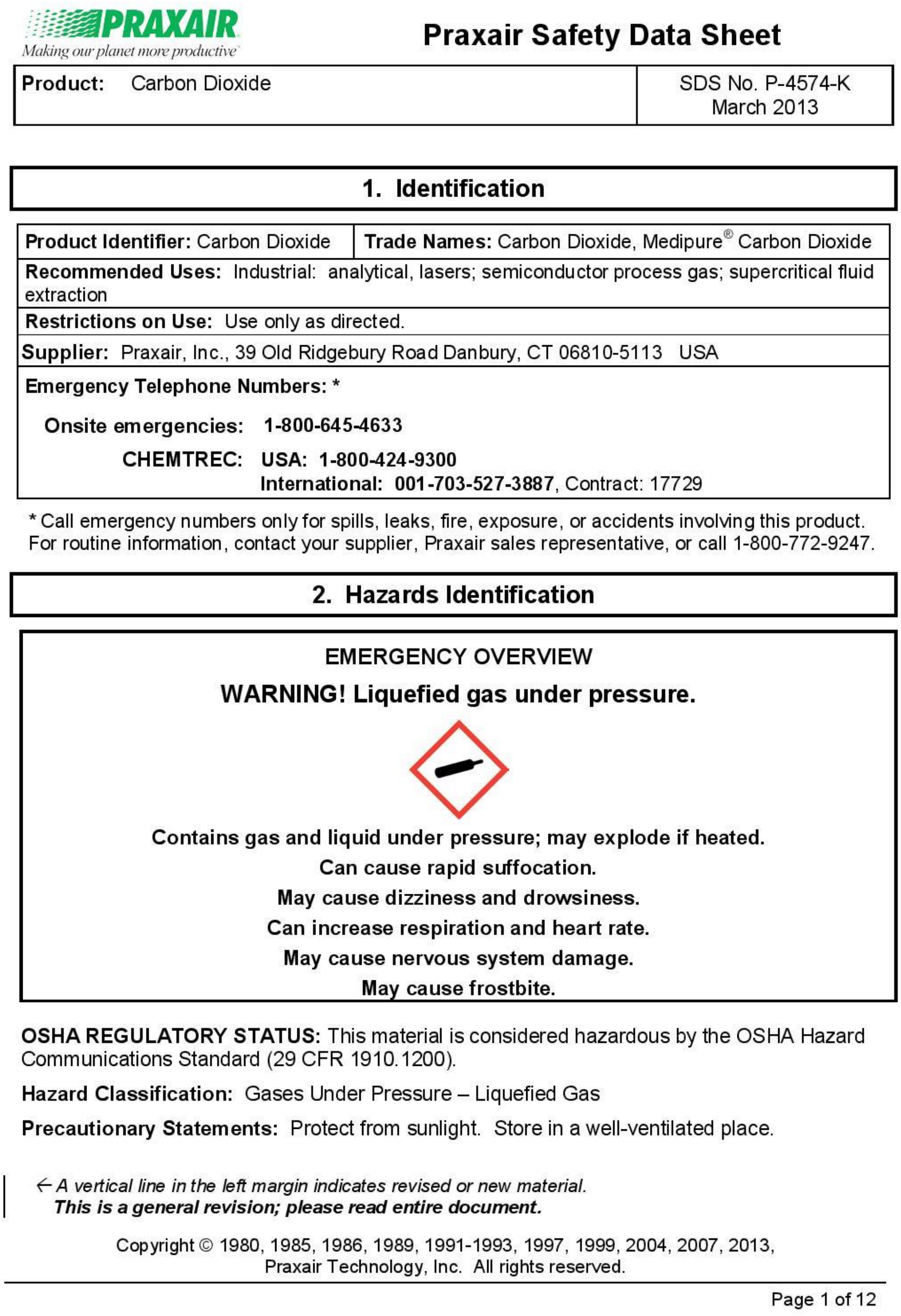
HAZARD RATINGS:

NFPA RATINGS:		**HMIS RATINGS:**	
HEALTH:	0	HEALTH:	0
FLAMMABILITY:	0	FLAMMABILITY:	0
REACTIVITY:	0	REACTIVITY:	0
SPECIAL:	SA*		

*Compressed Gas Association recommendation to designate simple asphyxiant.

***Documents with Effective Date of March 1994 and August 1997 are identical in content and either may be used.*

C.2 Carbon Dioxide



PRAXAIR
Making our planet more productive

Praxair Safety Data Sheet

Product: Carbon Dioxide	SDS No. P-4574-K March 2013

1. Identification

Product Identifier: Carbon Dioxide	**Trade Names:** Carbon Dioxide, Medipure® Carbon Dioxide
Recommended Uses: Industrial: analytical, lasers; semiconductor process gas; supercritical fluid extraction	
Restrictions on Use: Use only as directed.	
Supplier: Praxair, Inc., 39 Old Ridgebury Road Danbury, CT 06810-5113 USA	
Emergency Telephone Numbers: * **Onsite emergencies: 1-800-645-4633** **CHEMTREC: USA: 1-800-424-9300** **International: 001-703-527-3887**, Contract: 17729	

* Call emergency numbers only for spills, leaks, fire, exposure, or accidents involving this product. For routine information, contact your supplier, Praxair sales representative, or call 1-800-772-9247.

2. Hazards Identification

EMERGENCY OVERVIEW

WARNING! Liquefied gas under pressure.

Contains gas and liquid under pressure; may explode if heated.
Can cause rapid suffocation.
May cause dizziness and drowsiness.
Can increase respiration and heart rate.
May cause nervous system damage.
May cause frostbite.

OSHA REGULATORY STATUS: This material is considered hazardous by the OSHA Hazard Communications Standard (29 CFR 1910.1200).

Hazard Classification: Gases Under Pressure – Liquefied Gas

Precautionary Statements: Protect from sunlight. Store in a well-ventilated place.

← *A vertical line in the left margin indicates revised or new material.*
This is a general revision; please read entire document.

3. Composition/Information on Ingredients

This section covers materials of manufacture only. See sections 5, 8, 10, 11, and 16 for information on by-products generated during use in welding and cutting or as a result of exposure to fire.

See section 16 for important information about mixtures.

Chemical Name	Common Name and Synonyms	CAS NUMBER	CONCENTRATION
Carbon Dioxide	Carbonic anhydride, carbonic acid gas, refrigerant gas R744	124-38-9	>99%

** The symbol > means "greater than."*

4. First Aid Measures

INHALATION: Immediately remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, qualified personnel may give oxygen. Call a physician.

SKIN CONTACT: For exposure to cold vapor or solid carbon dioxide (dry ice), immediately warm frostbite area with warm water not to exceed 105°F (41°C). In case of massive exposure, remove contaminated clothing while showering with warm water. Call a physician.

EYE CONTACT: For exposure to cold vapor or solid carbon dioxide (dry ice), immediately flush eyes thoroughly with warm water for at least 15 minutes. Hold the eyelids open and away from the eyeballs to ensure that all surfaces are flushed thoroughly. See a physician, preferably an ophthalmologist, immediately.

SWALLOWING: An unlikely route of exposure. This product is a gas at normal temperature and pressure.

NOTES TO PHYSICIAN: *Treatment of overexposure should be directed at the control of symptoms and the clinical condition of the patient.*

5. Fire Fighting Measures

FLAMMABLE PROPERTIES: Nonflammable

Protective Equipment and Precautions for Firefighters: Firefighters should wear personal protective equipment and fire-fighting turnout gear as appropriate for surrounding fire.

SUITABLE EXTINGUISHING MEDIA: Carbon dioxide cannot catch fire but cylinders exposed to fire may explode. Use media appropriate for surrounding fire.

PRODUCTS OF COMBUSTION: Not applicable.

PROTECTION OF FIREFIGHTERS: WARNING! High-pressure liquid and gas. Evacuate all personnel from danger area. Immediately deluge cylinders with water from maximum distance until cool; then move them away from fire area if without risk. Self-contained breathing apparatus may be required by rescue workers. On-site fire brigades must comply with OSHA 29 CFR 1910.156 and applicable standards under 29 CFR 1910 Subpart L—Fire Protection.

Specific Physical and Chemical Hazards: Heat of fire can build pressure in cylinder and cause it to rupture. No part of cylinder should be subjected to a temperature higher than 125°F (52°C). Carbon dioxide cylinders are typically equipped with a pressure relief device. (Exceptions may exist where authorized by DOT.)

6. Accidental Release Measures

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED:

WARNING! High-pressure liquid and gas. Rapid release of gaseous carbon dioxide through a pressure relief device (PRD) or valve can result in the formation of dry ice, which is very cold and can cause frostbite.

PERSONAL PRECAUTIONS: Carbon dioxide is an asphyxiant. Lack of oxygen can kill. Use self-contained breathing apparatus where needed. See Section 11.

PERSONAL PROTECTIVE EQUIPMENT (PPE): See Section 8, Exposure Control/Personal Protection.

EMERGENCY PROCEDURES: Evacuate all personnel from danger area. Shut off leak if you can do so without risk. Ventilate area or move cylinder to a well-ventilated area. Test for sufficient oxygen, especially in confined spaces, before allowing reentry.

Methods and Materials for Containment and Cleaning Up: Prevent waste from contaminating the surrounding environment. Discard any product, residue, disposable container, or liner in an environmentally acceptable manner, in full compliance with federal, state, and local regulations. If necessary, call your local supplier for assistance.

7. Handling and Storage

PRECAUTIONS TO BE TAKEN IN HANDLING: Protect from sunlight.

Avoid breathing gas. Do not get liquid in eyes, on skin, or clothing. ***Protect cylinders from damage.*** Use a suitable hand truck to move cylinders; do not drag, roll, slide, or drop. Never attempt to lift a cylinder by its cap; the cap is intended solely to protect the valve. ***Never insert an object (e.g., wrench, screwdriver, pry bar) into cap openings***; doing so may damage the valve and cause a leak. Use an adjustable strap wrench to remove over-tight or rusted caps. ***Open valve slowly.*** If valve is hard to open, discontinue use and contact your supplier. Keep cylinder upright when in use. ***Never apply flame or localized heat directly to any part of the cylinder.*** High temperatures may damage the cylinder and could cause the pressure relief device to fail prematurely, venting the cylinder contents. For other precautions in using carbon dioxide, see section 16.

PRECAUTIONS TO BE TAKEN IN STORAGE: Store in a well-ventilated place.

Gas can cause rapid suffocation due to oxygen deficiency. Store and use with adequate ventilation. Store only where temperature will not exceed 125°F (52°C). Carbon dioxide is heavier than air. It tends to accumulate near the floor of an enclosed space, displacing air and pushing it upward. This creates an oxygen-deficient atmosphere near the floor or in pits and trenches. Ventilate space before entry. Verify sufficient oxygen concentration. Close cylinder valve after each use; keep closed even when empty. ***Prevent reverse flow.*** Reverse flow into cylinder may cause rupture. Use a check valve or other protective device in any line or piping from the cylinder. ***Do not strike an arc on the cylinder.*** The defect produced by an arc burn could lead to cylinder rupture. Do not ground the cylinder or allow it to become part of an electrical circuit. ***Firmly secure cylinders upright to keep them from falling or being knocked over.*** Screw valve protection cap firmly in place by hand. ***Store full and empty cylinders separately.*** Use a first-in, first-out inventory system to prevent storing full cylinders for long periods.

RECOMMENDED PUBLICATIONS: For further information on storage, handling, and use, see Praxair publications P-14-153, *Guidelines for Handling Gas Cylinders and Containers;* P-15-073, *Safety Precautions for Carbon Dioxide;* and P-3499, *Safety Precautions and Emergency Response Planning*. Obtain from your local supplier.

8. Exposure Controls/Personal Protection

See section 16 for important information on by-products generated during use in welding and cutting.

COMPONENT	OSHA PEL	ACGIH TLV (2012)
Carbon dioxide	5,000 ppm	5,000 ppm TWA, 30,000 ppm 15-min STEL

IDLH = 40,000 ppm.

ENGINEERING CONTROLS:

Local Exhaust. Use a local exhaust system, if necessary, to keep the concentration of carbon dioxide below all applicable exposure limits in the worker's breathing zone.

Mechanical (General). Under certain conditions, general exhaust ventilation may be acceptable to keep carbon dioxide below the exposure limits.

Special. WARNING: Concentration levels of carbon dioxide about 1 percent are dangerous—see Section 11. Praxair recommends continuous monitoring with alarms to indicate unsafe conditions before and during potential personnel exposure. Use appropriate monitoring devices to ensure a safe oxygen level (minimum of 19.5 percent) and a safe carbon dioxide level.

Other. None

PERSONAL PROTECTIVE EQUIPMENT (PPE):

Skin Protection. Wear insulated neoprene gloves for cylinder handling; welding gloves for welding. Metatarsal shoes for cylinder handling. Select in accordance with OSHA 29 CFR 1910.132, 1910.136, and 1910.138. See section 16 for requirements when using carbon dioxide or carbon dioxide mixtures in welding and cutting.

Eye/Face Protection. Select in accordance with OSHA 29 CFR 1910.133. See section 16 for requirements when using carbon dioxide or carbon dioxide mixtures in welding and cutting.

Respiratory Protection. None required under normal use. An air-supplied respirator must be used in confined spaces. Respiratory protection must conform to OSHA rules as specified in 29 CFR 1910.134. Select per OSHA 29 CFR 1910.134 and ANSI Z88.2.

9. Physical and Chemical Properties

APPEARANCE:	Colorless gas	
ODOR:	Odorless. It is felt by some to have a slight, pungent odor and biting taste.	
ODOR THRESHOLD:	Not applicable.	
PHYSICAL STATE:	Gas at normal temperature and pressure	
pH:	3.7 (for carbonic acid).	
MELTING POINT/FREEZING POINT at 1 atm:	Sublimation Point -109.3°F (-78.5°C)	
INITIAL BOILING POINT at 1 atm:	Sublimation Point -109.3°F (-78.5°C)	
BOILING RANGE at 1 atm:	Not applicable.	
FLASH POINT (test method):	Not applicable.	
EVAPORATION RATE (Butyl Acetate = 1):	High	
FLAMMABILITY:	Nonflammable	
FLAMMABLE LIMITS IN AIR, % by volume:	**LOWER:** N/A *	**UPPER:** N/A *
VAPOR PRESSURE at 68°F (20°C):	838 psig (5778 kPa)	
VAPOR DENSITY at 70°F (21.1°C) and 1 atm:	Liquid Density (saturated) 47.6 lb/ft^3 (762 kg/m^3)	
RELATIVE DENSITY/SPECIFIC GRAVITY (H_2O = 1) at 19.4°F (-7°C):	1.22	
RELATIVE DENSITY/SPECIFIC GRAVITY (Air = 1) at 70°F (21.1°C) and 1 atm:	1.52	
SOLUBILITY IN WATER, % by wt:	0.90	
PARTITION COEFFICIENT: n-octanol/water:	Not available.	
AUTOIGNITION TEMPERATURE:	Not applicable.	
DECOMPOSITION TEMPERATURE:	Not available.	
PERCENT VOLATILES BY VOLUME:	100	
VISCOSITY:	Not applicable.	
MOLECULAR WEIGHT:	44.01.	
MOLECULAR FORMULA:	CO_2	

** N/A – Not applicable*

10. Stability and Reactivity Information

REACTIVITY: ☐ Reactive ☒ Non-Reactive

CHEMICAL STABILITY: ☐ Unstable ☒ Stable

POSSIBILITY OF HAZARDOUS REACTIONS: ☐ May Occur ☒ Will Not Occur

Decomposition into toxic, flammable, and/or oxidizing materials under above-stated conditions.

CONDITIONS TO AVOID: Contact with incompatible materials, exposure to electrical discharges, and/or high temperatures as stated below.

INCOMPATIBLE MATERIALS: Alkali metals, alkaline earth metals, metal acetylides, chromium, titanium above 1022°F (550°C), uranium above 1382°F (750°C), magnesium above 1427°F (775°C)

HAZARDOUS DECOMPOSITION PRODUCTS: Carbon monoxide and oxygen may result from the decomposition of carbon dioxide exposed to electrical discharges and high temperatures.

11. Toxicological Information

POTENTIAL HEALTH EFFECTS:

Effects of a Single (Acute) Overexposure

Inhalation: Carbon dioxide gas is an asphyxiant with effects due to lack of oxygen. It is also physiologically active, affecting circulation and breathing. Moderate concentrations may cause headache, drowsiness, dizziness, stinging of the nose and throat, excitation, rapid breathing and heart rate, excess salivation, vomiting, and unconsciousness. Lack of oxygen can kill.

Carbon dioxide is an asphyxiant. It initially stimulates respiration and then causes respiratory depression. High concentrations result in narcosis. Symptoms in humans are as follows:

Carbon Dioxide Concentration Inhaled	EFFECTS
1%	Breathing rate increases slightly.
2%	Breathing rate increases to 50% above normal level. Prolonged exposure can cause headache, tiredness.
3%	**Breathing increases to twice normal rate and becomes labored.** Weak narcotic effect. Impaired hearing, headache, increased blood pressure and pulse rate.
4–5%	Breathing increases to approximately four times normal rate, symptoms of intoxication become evident, and slight choking may be felt.
5–10%	Characteristic sharp odor noticeable. **Very labored breathing, visual impairment,** headache, and ringing in the ears. **Judgment may be impaired, followed within minutes by loss of consciousness.**
10–100%	Unconsciousness occurs more rapidly above 10% level. **Prolonged exposure to high concentrations may eventually result in death from asphyxiation.**

The welding process may generate hazardous fumes/gases. (See sections 10 and 16.)

Skin Contact. No harm expected from vapor. Cold gas, or liquid or solid carbon dioxide may cause severe frostbite.

Swallowing. An unlikely route of exposure. This product is a gas at normal temperature and pressure.

Eye Contact: No harm expected from vapor. Cold gas, or liquid or solid carbon dioxide may cause severe frostbite.

Effects of Repeated (Chronic) Overexposure: No harm expected.

Other Effects of Overexposure: Damage to retinal or ganglion cells and central nervous system may occur.

Medical Conditions Aggravated by Overexposure: The toxicology and the physical and chemical properties of carbon dioxide suggest that overexposure is unlikely to aggravate existing medical conditions.

ACUTE DOSE EFFECTS: LC_{Lo} = 90,000 ppm, 5 min., human

REPRODUCTIVE EFFECTS: A single study has shown an increase in heart defects in rats exposed to 6% carbon dioxide in air for 24 hours at different times during gestation. There is no evidence that carbon dioxide is teratogenic in humans.

CARCINOGENICITY: Carbon dioxide is not listed by NTP, OSHA, or IARC.

12. Ecological Information

ECOTOXICITY: No known effects.

PERSISTANCE AND DEGRADABILITY: Not applicable.

BIOACCUMULATIVE POTENTIAL: Not applicable.

MOBILITY IN SOIL: Not applicable.

OTHER ADVERSE EFFECTS: No adverse ecological effects expected. The components of this mixture do not contain any Class I or Class II ozone-depleting chemicals.

13. Disposal Considerations

WASTE DISPOSAL METHOD: Do not attempt to dispose of residual or unused quantities. Return cylinder to supplier.

14. Transport Information

UN NUMBER: UN1013	**PROPER SHIPPING NAME:** Carbon Dioxide	
HAZARD CLASS(ES): 2.2	**PACKING GROUP** NA*	**PRODUCT RQ:** None
ENVIRONMENTAL HAZARDS: Not listed as a marine pollutant.		
SPECIAL SHIPPING INFORMATION:	• Cylinders should be transported in a secure position, in a well-ventilated vehicle. Cylinders transported in an enclosed, non-ventilated compartment of a vehicle can present serious safety hazards. • Shipment of compressed gas cylinders that have been filled without the owner's consent is a violation of federal law [49 CFR 173.301(e)].	
SHIPPING LABEL(s):	NONFLAMMABLE GAS	
PLACARD (when required):	NONFLAMMABLE GAS	

***NA = Not applicable.**

15. Regulatory Information

The following selected regulatory requirements may apply to this product. Not all such requirements are identified. Users of this product are solely responsible for compliance with all applicable federal, state, and local regulations.

U.S. FEDERAL REGULATIONS:

EPA (ENVIRONMENTAL PROTECTION AGENCY)

CERCLA: COMPREHENSIVE ENVIRONMENTAL RESPONSE, COMPENSATION, AND LIABILITY ACT OF 1980 (40 CFR Parts 117 and 302):

Reportable Quantity (RQ): None

SARA: SUPERFUND AMENDMENT AND REAUTHORIZATION ACT:

SECTIONS 302/304: Require emergency planning based on Threshold Planning Quantity (TPQ) and release reporting based on Reportable Quantities (RQ) of Extremely Hazardous Substances (EHS) (40 CFR Part 355):

TPQ: None
EHS RQ (40 CFR 355): None

SECTIONS 311/312: Require submission of SDSs and reporting of chemical inventories with identification of EPA hazard categories. The hazard categories for this product are as follows:

IMMEDIATE: Yes	**PRESSURE:** Yes
DELAYED: No	**REACTIVITY:** No
	FIRE: No

SECTION 313: Requires submission of annual reports of release of toxic chemicals that appear in 40 CFR Part 372.

Carbon dioxide is not subject to reporting under Section 313.

40 CFR 68: RISK MANAGEMENT PROGRAM FOR CHEMICAL ACCIDENTAL RELEASE PREVENTION: Requires development and implementation of risk management programs at facilities that manufacture, use, store, or otherwise handle regulated substances in quantities that exceed specified thresholds.

Carbon dioxide is not listed as a regulated substance.

TSCA: TOXIC SUBSTANCES CONTROL ACT: Carbon dioxide is listed on the TSCA inventory.

OSHA: OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION:

29 CFR 1910.119: PROCESS SAFETY MANAGEMENT OF HIGHLY HAZARDOUS CHEMICALS: Requires facilities to develop a process safety management program based on Threshold Quantities (TQ) of highly hazardous chemicals.

Carbon dioxide is not listed in Appendix A as a highly hazardous chemical.

STATE REGULATIONS:

CALIFORNIA: Carbon dioxide is not listed by California under the SAFE DRINKING WATER AND TOXIC ENFORCEMENT ACT OF 1986 (Proposition 65).

PENNSYLVANIA: Carbon dioxide is subject to the PENNSYLVANIA WORKER AND COMMUNITY RIGHT-TO-KNOW ACT (35 P.S. Sections 7301-7320).

16. Other Information

Be sure to read and understand all labels and instructions supplied with all containers of this product.

ADDITIONAL SAFETY AND HEALTH HAZARDS: Using carbon dioxide or mixtures containing carbon dioxide in welding and cutting may create additional hazards.

Read and understand the manufacturer's instructions and the precautionary labels on the products used in welding and cutting. Ask your welding products supplier for a copy of Praxair's free safety booklets, P-2035, *Precautions and Safe Practices for Gas Welding, Cutting, and Heating*, and P-52-529, *Precautions and Safe Practices for Electric Welding and Cutting,* and for other manufacturers' safety publications. For a detailed treatment, get ANSI Z49.1, *Safety in Welding and Cutting and Allied Processes*, published by the American Welding Society (AWS), 8669 Doral Blvd., #130, Doral, FL 33166, http://www.aws.org.

FUMES AND GASES can be dangerous to your health and may cause serious lung disease.

- **Keep your head out of fumes. Do not breathe fumes and gases. Use enough ventilation, local exhaust, or both to keep fumes and gases from your breathing zone and the general area. Short-term overexposure to fumes may cause dizziness; nausea; and dryness or irritation of the nose, throat, and eyes; or may cause other similar discomfort.**

Fumes and gases cannot be classified simply. The amount and type depend on the metal being worked and the process, procedure, equipment, and supplies used. Possible dangerous materials may be found in fluxes, electrodes, and other materials. Get an SDS for every material you use.

Contaminants in the air may add to the hazard of fumes and gases. One such contaminant, chlorinated hydrocarbon vapors from cleaning and degreasing activities, poses a special risk.

- **Do not use electric arcs in the presence of chlorinated hydrocarbon vapors—highly toxic phosgene may be produced.**

Metal coatings such as paint, plating, or galvanizing may generate harmful fumes when heated. Residues from cleaning materials may also be harmful.

- **Avoid arc operations on parts with phosphate residues (anti-rust, cleaning preparations)—highly toxic phosphine may be produced.**

To find the quantity and content of fumes and gases, you can take air samples. By analyzing these samples, you can find out what respiratory protection you need. One recommended sampling method is to take air from inside the worker's helmet or from the worker's breathing zone. See AWS F1.1, *Method for Sampling Airborne Particulates Generated by Welding and Allied Processes*, available from the American Welding Society, 8669 Doral Blvd., #130, Doral, FL 33166, http://www.aws.org.

NOTES TO PHYSICIAN:

Acute: *Gases, fumes, and dusts may cause irritation to the eyes, lungs, nose, and throat. Some toxic gases associated with welding and related processes may cause pulmonary edema, asphyxiation, and death. Acute overexposure may include signs and symptoms such as watery eyes, nose and throat irritation, headache, dizziness, difficulty breathing, frequent coughing, or chest pains.*

Chronic: *Protracted inhalation of air contaminants may lead to their accumulation in the lungs, a condition that may be seen as dense areas on chest x-rays. The severity of change is proportional to the length of exposure. The changes seen are not necessarily associated with symptoms or signs of reduced lung function or disease. In addition, the changes on x-rays may be caused by non-work-related factors such as smoking, etc.*

PROTECTIVE CLOTHING AND EQUIPMENT FOR WELDING OPERATIONS:

PROTECTIVE GLOVES: Wear welding gloves.

EYE PROTECTION: Wear a helmet or use a face shield with a filter lens. Select lens per ANSI Z49.1. Provide protective screens and flash goggles if needed to protect others; select per OSHA 29 CFR 1910.133.

OTHER PROTECTIVE EQUIPMENT: Wear hand, head, and body protection. (See ANSI Z49.1.) Worn as needed, these help prevent injury from radiation, sparks, and electrical shock. Minimum protection includes welder's gloves and a face shield. For added protection consider arm protectors, aprons, hats, shoulder protection, and dark, substantial clothing.

OTHER HAZARDOUS CONDITIONS OF HANDLING, STORAGE, AND USE: ***High-pressure liquid and gas.*** Use piping and equipment adequately designed to withstand pressures to be encountered. ***Prevent reverse flow.*** Reverse flow into cylinder may cause rupture. Use a check valve or other protective device in any line or piping from the cylinder. ***Do not strike an arc on the cylinder.*** The defect produced by an arc burn could lead to cylinder rupture. ***Never work on a pressurized system.*** If there is a leak, close the cylinder valve. Blow the system down in a safe and environmentally sound manner in compliance with all federal, state, and local laws; then repair the leak. ***Never place a compressed gas cylinder where it may***

become part of an electrical circuit. When using compressed gases in and around electric welding applications, never ground the cylinders. Grounding exposes the cylinders to damage by the electric welding arc.

Mixtures. When you mix two or more gases or liquefied gases, you can create additional, unexpected hazards. Obtain and evaluate the safety information for each component before you produce the mixture. Consult an industrial hygienist or other trained person when you evaluate the end product. Remember, gases and liquids have properties that can cause serious injury or death.

HAZARD RATING SYSTEMS:

NFPA RATINGS:		**HMIS RATINGS:**	
HEALTH	= 1	HEALTH	= 1
FLAMMABILITY	= 0	FLAMMABILITY	= 0
INSTABILITY	= 0	PHYSICAL HAZARD	= 3
SPECIAL	= SA (CGA recommends this to designate Simple Asphyxiant.)		

STANDARD VALVE CONNECTIONS FOR U.S. AND CANADA:

THREADED:	CGA-320
PIN-INDEXED YOKE:	CGA-940 (medical use)
ULTRA-HIGH-INTEGRITY CONNECTION:	CGA-716

Use the proper CGA connections. **DO NOT USE ADAPTERS.** Additional limited-standard connections may apply. See CGA pamphlet V-1 listed below.

Ask your supplier about free Praxair safety literature as referred to in this SDS and on the label for this product. Further information can be found in the following materials published by the Compressed Gas Association, Inc. (CGA), http://www.cganet.com.

AV-1	*Safe Handling and Storage of Compressed Gases*
AV-7	*Characteristics and Safe Handling of Carbon Dioxide*
G-6	*Carbon Dioxide*
G-6.1	*Standard for Low Pressure Carbon Dioxide Systems at Customer Sites*
G-6.2	*Commodity Specification for Carbon Dioxide*
P-1	*Safe Handling of Compressed Gases in Containers*
SB-2	*Oxygen-Deficient Atmospheres*
V-1	*Compressed Gas Cylinder Valve Inlet and Outlet Connections*
—	*Handbook of Compressed Gases*

Last revised 31 Mar 2013.

Praxair asks users of this product to study this SDS and become aware of product hazards and safety information. To promote safe use of this product, a user should (1) notify employees, agents, and contractors of the information in this SDS and of any other known product hazards and safety information, (2) furnish this information to each purchaser of the product, and (3) ask each purchaser to notify its employees and customers of the product hazards and safety information.

The opinions expressed herein are those of qualified experts within Praxair, Inc. We believe that the information contained herein is current as of the date of this Safety Data Sheet. Since the use of this information and the conditions of use of the product are not within the control of Praxair, Inc., it is the user's obligation to determine the conditions of safe use of the product.

Praxair SDSs are furnished on sale or delivery by Praxair or the independent distributors and suppliers who package and sell our products. To obtain current SDSs for these products, contact your Praxair sales representative or local distributor or supplier. If you have questions regarding Praxair SDSs, would like the form number and date of the latest SDS, or would like the names of the Praxair suppliers in your area, phone or write the Praxair Call Center (**Phone:** 1-800-PRAXAIR; **Address:** Praxair Call Center, Praxair, Inc., PO Box 44, Tonawanda, NY 14151-0044).

Praxair, Inc.
39 Old Ridgebury Road
Danbury, CT 06810-5113

Appendix D. Original Project Statement

9. High-temperature Pebble-bed Nuclear Reactor with "Lego" Modular Design Improvements

(recommended by Adam A. Brostow, Air Products and Chemicals)

Background

Figure 1 shows the process PFD of MIT's High-temperature Pebble-bed Nuclear Reactor. The system comprises a primary and secondary helium circuit. Helium in the primary circuit is heated to a high temperature in the nuclear reactor core. Helium in the secondary circuit is heated in the intermediate heat exchanger (IHX) against helium in the primary circuit to avoid possible radioactive contamination. It is then expanded in a series of expanders (isentropic turbines). Some of those turbines directly drive compressors (so-called companders). Then, the working fluid is expanded in a generator-loaded turbine to produce electric power. The expanded stream is cooled in the recuperator (economizer) heat exchanger, further cooled in a precooler, compressed, reheated in the recuperator, and sent back to the IHX. This is the so-called Brayton power cycle. The nuclear reactor is of pebble-bed type, which eliminates the possibility of a meltdown and is inherently safer than other types.

Figure 8, in *A Future for Nuclear Energy: Pebble Bed Reactors* (see Literature), shows a variation of the cycle with three expanders, rather than two, a different compressor arrangement, and slightly different conditions.

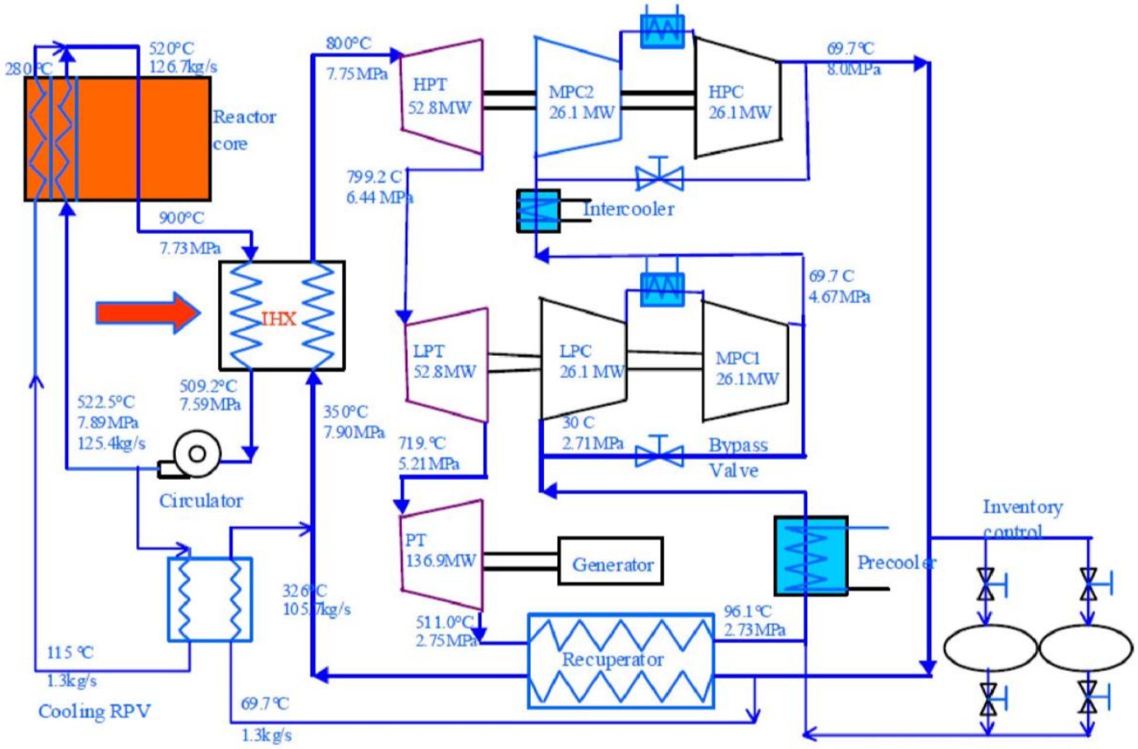


Figure 1 MIT Pebble-Bed Nuclear Reactor Power Cycle

Figure 2 shows the supercritical CO_2 Brayton cycle developed by the Sandia National Laboratories.

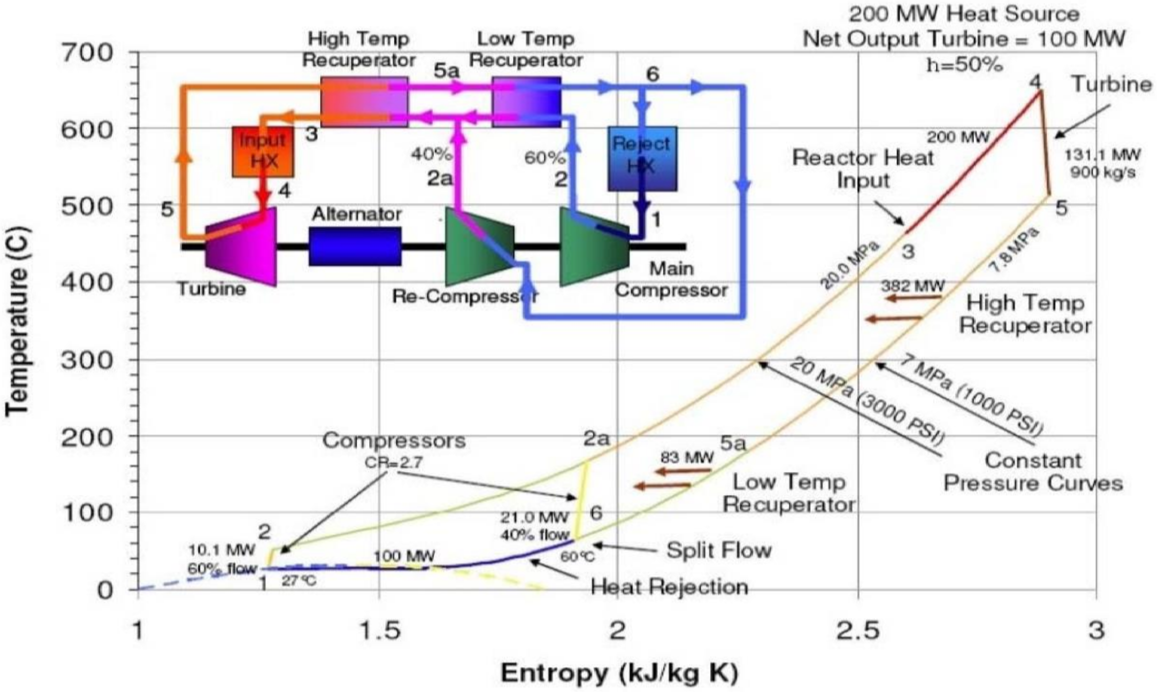


Figure 2 CO_2 Brayton cycle

Figure 3 shows a Supercritical Brayton cycle applied to a nuclear power plant similar to the ones shown on Figures 1 and 2.

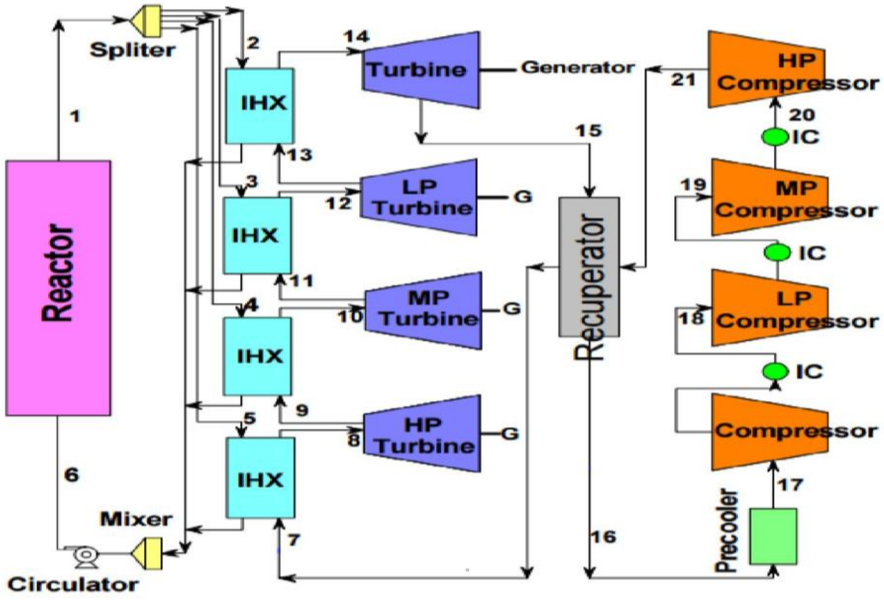


Figure 3 Supercritical Brayton cycle

Figure 4 (U.S. Patent Application 20120216536) shows a supercritical CO_2 Brayton cycle applied concentrated solar power plant.

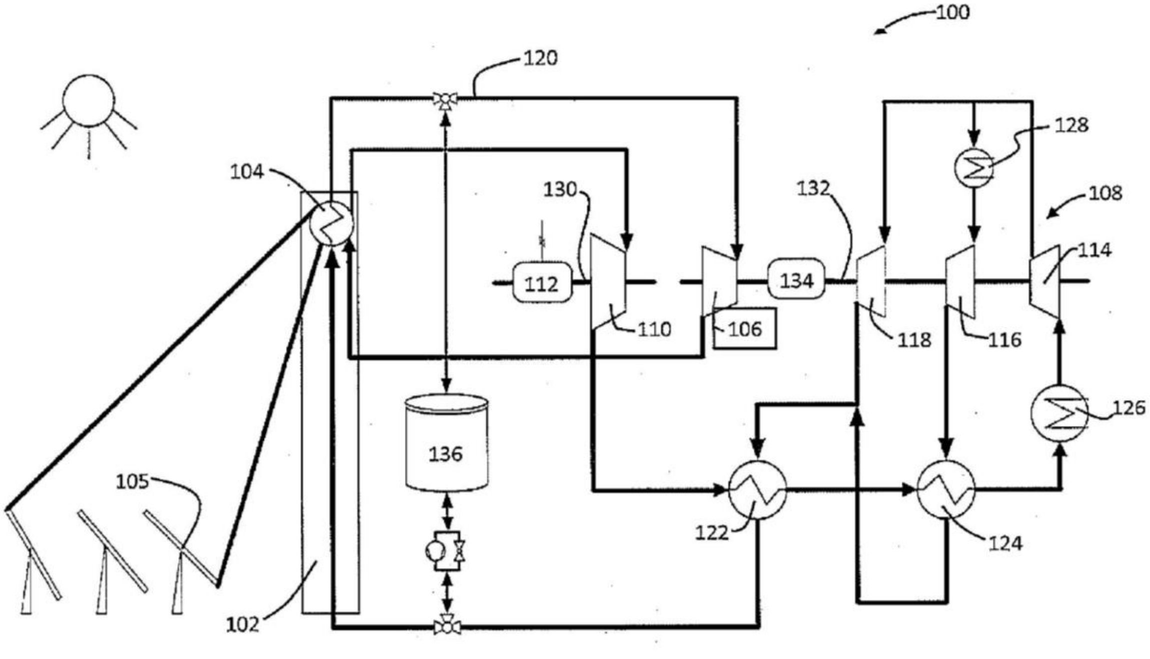


Figure 4 Supercritical CO_2 Brayton cycle applied concentrated solar power plant

Design Problem

An MIT-type modular, nuclear, power plant supplies 120 MW of electricity. Helium, as working fluid, is believed to be well suited for high temperature applications. However, helium requires exotic equipment and easily leaks out of the system. Equipment sizes are large.

This assignment is to model the helium-based plant as described in the literature using the ASPEN PLUS process simulator and to try to improve it by replacing helium in the secondary circuit at least partially with supercritical CO_2 (S-CO2) while maintaining the modular character of the design.

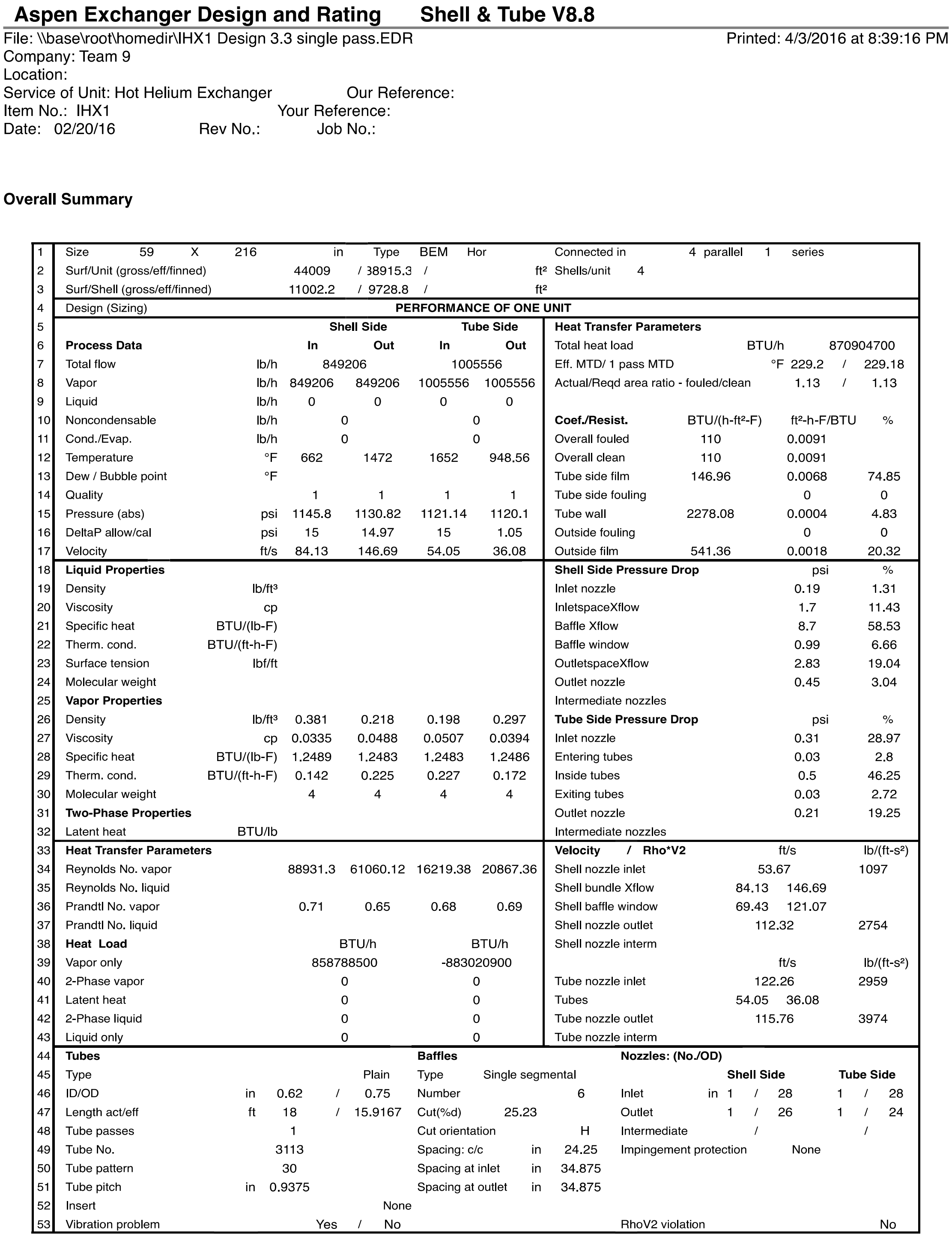
Another part of the assignment applies the same S-CO2 design to the high-temperature, concentrated, power plant also producing 120 MW of electricity. Because the design is modular, at least some modules should be identical, the difference being the possibly lower maximum temperature and primary circuit working fluid (oil, molten salt, etc.).

The students, then, would compare short-term and long-term economics of the two variants: nuclear and renewable.

Appendix E. Aspen Exchanger Design and Rating Results

E.1 Helium Process

HX-1



Aspen Exchanger Design and Rating   Shell & Tube V8.8

File: \\base\root\homedir\IHX1 Design 3.3 single pass.EDR   Printed: 4/3/2016 at 8:39:16 PM
Company: Team 9
Location:
Service of Unit: Hot Helium Exchanger   Our Reference:
Item No.: IHX1   Your Reference:
Date: 02/20/16   Rev No.:   Job No.:

Overall Summary

1	Size	59 X 216 in	Type	BEM	Hor		Connected in	4 parallel	1 series	
2	Surf/Unit (gross/eff/finned)		44009	/ 38915.3	/	ft²	Shells/unit	4		
3	Surf/Shell (gross/eff/finned)		11002.2	/ 9728.8	/	ft²				
4	Design (Sizing)			**PERFORMANCE OF ONE UNIT**						
5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h	870904700	
7	Total flow	lb/h	849206		1005556		Eff. MTD/ 1 pass MTD	°F	229.2	/ 229.18
8	Vapor	lb/h	849206	849206	1005556	1005556	Actual/Reqd area ratio - fouled/clean		1.13	/ 1.13
9	Liquid	lb/h	0	0	0	0				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	110	0.0091	
12	Temperature	°F	662	1472	1652	948.56	Overall clean	110	0.0091	
13	Dew / Bubble point	°F					Tube side film	146.96	0.0068	74.85
14	Quality		1	1	1	1	Tube side fouling		0	0
15	Pressure (abs)	psi	1145.8	1130.82	1121.14	1120.1	Tube wall	2278.08	0.0004	4.83
16	DeltaP allow/cal	psi	15	14.97	15	1.05	Outside fouling		0	0
17	Velocity	ft/s	84.13	146.69	54.05	36.08	Outside film	541.36	0.0018	20.32
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³					Inlet nozzle		0.19	1.31
20	Viscosity	cp					InletspaceXflow		1.7	11.43
21	Specific heat	BTU/(lb-F)					Baffle Xflow		8.7	58.53
22	Therm. cond.	BTU/(ft-h-F)					Baffle window		0.99	6.66
23	Surface tension	lbf/ft					OutletspaceXflow		2.83	19.04
24	Molecular weight						Outlet nozzle		0.45	3.04
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft³	0.381	0.218	0.198	0.297	**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0335	0.0488	0.0507	0.0394	Inlet nozzle		0.31	28.97
28	Specific heat	BTU/(lb-F)	1.2489	1.2483	1.2483	1.2486	Entering tubes		0.03	2.8
29	Therm. cond.	BTU/(ft-h-F)	0.142	0.225	0.227	0.172	Inside tubes		0.5	46.25
30	Molecular weight		4	4	4	4	Exiting tubes		0.03	2.72
31	**Two-Phase Properties**						Outlet nozzle		0.21	19.25
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor		88931.3	61060.12	16219.38	20867.36	Shell nozzle inlet	53.67		1097
35	Reynolds No. liquid						Shell bundle Xflow	84.13	146.69	
36	Prandtl No. vapor		0.71	0.65	0.68	0.69	Shell baffle window	69.43	121.07	
37	Prandtl No. liquid						Shell nozzle outlet	112.32		2754
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		858788500		-883020900			ft/s		lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet	122.26		2959
41	Latent heat		0		0		Tubes	54.05	36.08	
42	2-Phase liquid		0		0		Tube nozzle outlet	115.76		3974
43	Liquid only		0		0		Tube nozzle interm			
44	**Tubes**				**Baffles**		**Nozzles: (No./OD)**			
45	Type			Plain	Type	Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.62	/ 0.75	Number	6	Inlet	in	1 / 28	1 / 28
47	Length act/eff	ft	18	/ 15.9167	Cut(%d)	25.23	Outlet		1 / 26	1 / 24
48	Tube passes		1		Cut orientation	H	Intermediate		/	/
49	Tube No.		3113		Spacing: c/c	in 24.25	Impingement protection		None	
50	Tube pattern		30		Spacing at inlet	in 34.875				
51	Tube pitch	in	0.9375		Spacing at outlet	in 34.875				
52	Insert			None						
53	Vibration problem		Yes	/ No			RhoV2 violation			No

HX-2

Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\RECP Design 2.23.EDR Printed: 4/3/2016 at 8:41:26 PM
Company: Team 9
Location:
Service of Unit: Cold Helium Heat Exchanger Our Reference:
Item No.: Recuperator Your Reference:
Date: 02/23/16 Rev No.: Job No.:

Overall Summary

1	Size	100 X 200	in	Type	BEM	Hor	Connected in	5	parallel	1	series
2	Surf/Unit (gross/eff/finned)	153512.5	/ 147372	/	ft²	Shells/unit	5				
3	Surf/Shell (gross/eff/finned)	30702.5	/ 29474.4	/	ft²						

4	Design (Sizing)		**PERFORMANCE OF ONE UNIT**							
5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h	240594500	
7	Total flow	lb/h	849206		849206		Eff. MTD/ 1 pass MTD	°F	60 /	60
8	Vapor	lb/h	849206	849206	849206	849206	Actual/Reqd area ratio - fouled/clean		1.12 /	1.12
9	Liquid	lb/h	0	0	0	0				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	30.54	0.0327	
12	Temperature	°F	123	350	410	183	Overall clean	30.54	0.0327	
13	Dew / Bubble point	°F					Tube side film	39.18	0.0255	77.94
14	Quality		1	1	1	1	Tube side fouling		0	0
15	Pressure (abs)	psi	79	67.36	21	19.71	Tube wall	1644.51	0.0006	1.86
16	DeltaP allow/cal	psi	15	11.64	15	1.29	Outside fouling		0	0
17	Velocity	ft/s	538.38	868.28	266.55	209.86	Outside film	151.2	0.0066	20.2
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³					Inlet nozzle		0.28	2.45
20	Viscosity	cp					InletspaceXflow		1.54	13.23
21	Specific heat	BTU/(lb-F)					Baffle Xflow		7.41	63.79
22	Therm. cond.	BTU/(ft-h-F)					Baffle window		0.5	4.34
23	Surface tension	lbf/ft					OutletspaceXflow		2.3	19.82
24	Molecular weight						Outlet nozzle		0.52	4.51
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft³	0.051	0.031	0.009	0.011	**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0208	0.0264	0.0278	0.0223	Inlet nozzle		0.37	28.15
28	Specific heat	BTU/(lb-F)	1.2483	1.2482	1.2481	1.2481	Entering tubes		0.03	2.6
29	Therm. cond.	BTU/(ft-h-F)	0.096	0.117	0.121	0.102	Inside tubes		0.67	50.43
30	Molecular weight		4	4	4	4	Exiting tubes		0.04	2.88
31	**Two-Phase Properties**						Outlet nozzle		0.23	17.08
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor		121284.7	95512.75	6632.18	8265.72	Shell nozzle inlet	175.28		1553
35	Reynolds No. liquid						Shell bundle Xflow	538.38	868.28	
36	Prandtl No. vapor		0.66	0.68	0.69	0.66	Shell baffle window	390.39	629.6	
37	Prandtl No. liquid						Shell nozzle outlet	325.99		3296
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		240608700		-240580300			ft/s		lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet	623.99		3504
41	Latent heat		0		0		Tubes	266.55	209.86	
42	2-Phase liquid		0		0		Tube nozzle outlet	609.11		4240
43	Liquid only		0		0		Tube nozzle interm			

44	**Tubes**				**Baffles**			**Nozzles: (No./OD)**			
45	Type			Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.62 /	0.75	Number		8	Inlet	in	1 / 32	1 / 40
47	Length act/eff	ft	16.6667 /	16	Cut(%d)		10.22	Outlet		1 / 30	1 / 36
48	Tube passes		1		Cut orientation		H	Intermediate		/	/
49	Tube No.		9382		Spacing: c/c	in	14.75	Impingement protection		None	
50	Tube pattern		30		Spacing at inlet	in	44.375				
51	Tube pitch	in	0.9375		Spacing at outlet	in	44.375				
52	Insert			None							
53	Vibration problem		Yes /	No				RhoV2 violation			Yes

HX-3

Aspen Exchanger Design and Rating Shell & Tube V8.8

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Overall Summary

1	Size	48	X	120	in	Type	BEM	Hor	Connected in 5 parallel 1 series
2	Surf/Unit (gross/eff/finned)	18849.5	/ 18024.9	/				ft²	Shells/unit 5
3	Surf/Shell (gross/eff/finned)	3769.9	/ 3605	/				ft²	
4	Design (Sizing)				PERFORMANCE OF ONE UNIT				

5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		In	Out	In	Out	Total heat load	cal/s		20395640
7	Total flow	lb/h	849206		6455225		Eff. MTD/ 1 pass MTD	°F 87.95	/	87.68
8	Vapor	lb/h	849206	849206	0	0	Actual/Reqd area ratio - fouled/clean	1.03	/	1.03
9	Liquid	lb/h	0	0	6455225	6455225				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	188.49	0.0053	
12	Temperature	°F	361.4	85.96	68	113	Overall clean	188.49	0.0053	
13	Dew / Bubble point	°F					Tube side film	392.02	0.0026	48.08
14	Quality		1	1	0	0	Tube side fouling		0	0
15	Pressure (abs)	psi	304.58	290.02	14.7	14.13	Tube wall	3828.61	0.0003	4.92
16	DeltaP allow/cal	psi	15	14.56	3	0.56	Outside fouling		0	0
17	Velocity	ft/s	455.53	317.28	1.61	1.62	Outside film	401.07	0.0025	47
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³			62.355	61.972	Inlet nozzle		0.24	1.65
20	Viscosity	cp			1.0163	0.5981	InletspaceXflow		2.98	20.4
21	Specific heat	BTU/(lb-F)			1.0016	1	Baffle Xflow		7.02	48.01
22	Therm. cond.	BTU/(ft-h-F)			0.343	0.362	Baffle window		1.62	11.05
23	Surface tension	lbf/ft					OutletspaceXflow		2.36	16.11
24	Molecular weight				18.01	18.01	Outlet nozzle		0.41	2.79
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft³	0.138	0.198			**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0267	0.0198			Inlet nozzle		0.25	44.82
28	Specific heat	BTU/(lb-F)	1.2485	1.249			Entering tubes		0.01	1.53
29	Therm. cond.	BTU/(ft-h-F)	0.118	0.091			Inside tubes		0.11	20.06
30	Molecular weight		4	4			Exiting tubes		0.01	2.4
31	**Two-Phase Properties**						Outlet nozzle		0.18	31.2
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor		219435.1	294997.8			Shell nozzle inlet	98.11		1331
35	Reynolds No. liquid				7155.74	12160.04	Shell bundle Xflow	455.53	317.28	
36	Prandtl No. vapor		0.68	0.66			Shell baffle window	342.55	238.59	
37	Prandtl No. liquid				7.18	4	Shell nozzle outlet	117.83		2751
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		-292061500		0			ft/s		lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet	6.01		2250
41	Latent heat		0		0		Tubes	1.61	1.62	
42	2-Phase liquid		0		0		Tube nozzle outlet	7.37		3365
43	Liquid only		0		290680700		Tube nozzle interm			

44	**Tubes**			**Baffles**			**Nozzles: (No./OD)**			
45	Type		Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.584 / 0.75	Number		4	Inlet	in	1 / 26	1 / 14
47	Length act/eff	ft	10 / 9.5625	Cut(%d)		13.34	Outlet		1 / 20	1 / 12.75
48	Tube passes		1	Cut orientation		H	Intermediate		/	/
49	Tube No.		1920	Spacing: c/c	in	12.5	Impingement protection		None	
50	Tube pattern		30	Spacing at inlet	in	38.625				
51	Tube pitch	in	0.9375	Spacing at outlet	in	38.625				
52	Insert		None							
53	Vibration problem		ossibl / No				RhoV2 violation			No

HX-4

Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\Helium_B19 2.26.EDR Printed: 4/3/2016 at 8:44:07 PM
Company: Team 9
Location:
Service of Unit: HOT Helium/Cooling Water Our Reference:
Item No.: B19 Your Reference:
Date: 2/26/16 Rev No.: Job No.:

Overall Summary

1	Size		26 X 96	in	Type BEM	Hor	Connected in	9 parallel	1 series	
2	Surf/Unit (gross/eff/finned)		6870.7	/ 6575.4	/	ft^2	Shells/unit	9		
3	Surf/Shell (gross/eff/finned)		763.4	/ 730.6	/	ft^2				
4	Design (Sizing)		**PERFORMANCE OF ONE UNIT**							
5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h	50059560	
7	Total flow	lb/h	849206		5599868		Eff. MTD/ 1 pass MTD	°F	71.24 / 71.23	
8	Vapor	lb/h	849206	849206	0	0	Actual/Reqd area ratio - fouled/clean		2.45 / 2.45	
9	Liquid	lb/h	0	0	5599868	5599868				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft^2-F)	ft^2-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	262.33	0.0038	
12	Temperature	°F	168.8	122	68	77	Overall clean	262.33	0.0038	
13	Dew / Bubble point	°F					Tube side film	622.31	0.0016	42.15
14	Quality		1	1	0	0	Tube side fouling		0	0
15	Pressure (abs)	psi	507.63	504.2	14.7	13.95	Tube wall	3836.28	0.0003	6.84
16	DeltaP allow/cal	psi	3.75	3.44	3	0.74	Outside fouling		0	0
17	Velocity	ft/s	103.12	96.02	3.07	3.07	Outside film	514.3	0.0019	51.01
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft^3			62.355	62.32	Inlet nozzle		0.25	7.18
20	Viscosity	cp			1.0163	0.8974	InletspaceXflow		0.94	27.15
21	Specific heat	BTU/(lb-F)			1.0016	1.0012	Baffle Xflow		0.83	24.01
22	Therm. cond.	BTU/(ft-h-F)			0.343	0.347	Baffle window		0.36	10.39
23	Surface tension	lbf/ft					OutletspaceXflow		0.89	25.8
24	Molecular weight				18.01	18.01	Outlet nozzle		0.19	5.48
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft^3	0.301	0.323			**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.022	0.0208			Inlet nozzle		0.17	22.95
28	Specific heat	BTU/(lb-F)	1.2492	1.2494			Entering tubes		0.03	4.19
29	Therm. cond.	BTU/(ft-h-F)	0.101	0.096			Inside tubes		0.28	38.26
30	Molecular weight		4	4			Exiting tubes		0.05	6.54
31	**Two-Phase Properties**						Outlet nozzle		0.21	28.06
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s^2)
34	Reynolds No. vapor		131281.7	138806.6			Shell nozzle inlet	68.64		1418
35	Reynolds No. liquid				13624.27	15429.87	Shell bundle Xflow	103.12	96.02	
36	Prandtl No. vapor		0.66	0.66			Shell baffle window	96.94	90.25	
37	Prandtl No. liquid				7.18	6.26	Shell nozzle outlet	63.96		1322
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		-49651400		0			ft/s		lb/(ft-s^2)
40	2-Phase vapor		0		0		Tube nozzle inlet	5.06		1598
41	Latent heat		0		0		Tubes	3.07	3.07	
42	2-Phase liquid		0		0		Tube nozzle outlet	7.98		3972
43	Liquid only		0		50467720		Tube nozzle interm			

44	**Tubes**			**Baffles**			**Nozzles: (No./OD)**			
45	Type		Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.584 / 0.75	Number		2	Inlet	in	1 / 16	1 / 10.75
47	Length act/eff	ft	8 / 7.6562	Cut(%d)		40.63	Outlet		1 / 16	1 / 8.625
48	Tube passes		1	Cut orientation		H	Intermediate		/	/
49	Tube No.		486	Spacing: c/c	in	23.5	Impingement protection		None	
50	Tube pattern		30	Spacing at inlet	in	34.1875				
51	Tube pitch	in	0.9375	Spacing at outlet	in	34.1875				
52	Insert		None							
53	Vibration problem		Yes / No				RhoV2 violation			No

HX-5

Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\Helium_B20.EDR Printed: 4/3/2016 at 8:45:07 PM
Company: Team 9
Location:
Service of Unit: Hot Helium/Cooling Water Our Reference:
Item No.: B20 Your Reference:
Date: 2/26/16 Rev No.: Job No.:

Overall Summary

1	Size	23 X 96	in	Type	BEM	Hor	Connected in	10 parallel	1 series		
2	Surf/Unit (gross/eff/finned)		5749.1	/ 5502.1	/	ft^2	Shells/unit	10			
3	Surf/Shell (gross/eff/finned)		574.9	/ 550.2	/	ft^2					
4	Design (Sizing)			**PERFORMANCE OF ONE UNIT**							
5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**				
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h	50194100		
7	Total flow	lb/h	849206		5628792		Eff. MTD/ 1 pass MTD	°F	107.8 / 107.8		
8	Vapor	lb/h	849206	849206	0	0	Actual/Reqd area ratio - fouled/clean		3.39 / 3.39		
9	Liquid	lb/h	0	0	5628792	5628792					
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft^2-F)	ft^2-h-F/BTU	%	
11	Cond./Evap.	lb/h	0		0		Overall fouled	286.76	0.0035		
12	Temperature	°F	204.8	158	68	77	Overall clean	286.76	0.0035		
13	Dew / Bubble point	°F					Tube side film	733.93	0.0014	39.07	
14	Quality		1	1	0	0	Tube side fouling		0	0	
15	Pressure (abs)	psi	652.67	649.7	14.7	13.67	Tube wall	3836.28	0.0003	7.47	
16	DeltaP allow/cal	psi	3.75	2.97	3	1.02	Outside fouling		0	0	
17	Velocity	ft/s	86.18	80.43	3.68	3.69	Outside film	536.47	0.0019	53.45	
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%	
19	Density	lb/ft^3			62.355	62.32	Inlet nozzle		0.18	5.87	
20	Viscosity	cp			1.0163	0.8974	InletspaceXflow		0.78	26.06	
21	Specific heat	BTU/(lb-F)			1.0016	1.0012	Baffle Xflow		0.7	23.42	
22	Therm. cond.	BTU/(ft-h-F)			0.343	0.347	Baffle window		0.37	12.27	
23	Surface tension	lbf/ft					OutletspaceXflow		0.74	24.81	
24	Molecular weight				18.01	18.01	Outlet nozzle		0.23	7.57	
25	**Vapor Properties**						Intermediate nozzles				
26	Density	lb/ft^3	0.366	0.392			**Tube Side Pressure Drop**		psi	%	
27	Viscosity	cp	0.0229	0.0217			Inlet nozzle		0.35	34.53	
28	Specific heat	BTU/(lb-F)	1.2494	1.2496			Entering tubes		0.04	4.4	
29	Therm. cond.	BTU/(ft-h-F)	0.104	0.1			Inside tubes		0.38	37.38	
30	Molecular weight		4	4			Exiting tubes		0.07	6.86	
31	**Two-Phase Properties**						Outlet nozzle		0.17	16.83	
32	Latent heat	BTU/lb					Intermediate nozzles				
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s^2)	
34	Reynolds No. vapor		128121.7	135055.2			Shell nozzle inlet	52.5		1009	
35	Reynolds No. liquid				16366.22	18535.2	Shell bundle Xflow	86.18	80.43		
36	Prandtl No. vapor		0.66	0.66			Shell baffle window	91.78	85.66		
37	Prandtl No. liquid				7.18	6.26	Shell nozzle outlet	62.84		1548	
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm				
39	Vapor only		-49659790		0			ft/s		lb/(ft-s^2)	
40	2-Phase vapor		0		0		Tube nozzle inlet	7.22		3249	
41	Latent heat		0		0		Tubes	3.68	3.69		
42	2-Phase liquid		0		0		Tube nozzle outlet	7.22		3250	
43	Liquid only		0		50728370		Tube nozzle interm				
44	**Tubes**				**Baffles**			**Nozzles: (No./OD)**			
45	Type			Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.584	/ 0.75	Number		2	Inlet	in	1 / 16	1 / 8.625
47	Length act/eff	ft	8	/ 7.6562	Cut(%d)		39.41	Outlet		1 / 14	1 / 8.625
48	Tube passes		1		Cut orientation		H	Intermediate		/	/
49	Tube No.		366		Spacing: c/c	in	23.5	Impingement protection		None	
50	Tube pattern		30		Spacing at inlet	in	34.1875				
51	Tube pitch	in	0.9375		Spacing at outlet	in	34.1875				
52	Insert			None							
53	Vibration problem		Yes	/ No				RhoV2 violation			No

HX-6

Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\Helium_B21.EDR Printed: 4/3/2016 at 8:46:00 PM
Company: Team 9
Location:
Service of Unit: Hot Helium/Cooling Water Our Reference:
Item No.: B21 Your Reference:
Date: 2/26/16 Rev No.: Job No.:

Overall Summary

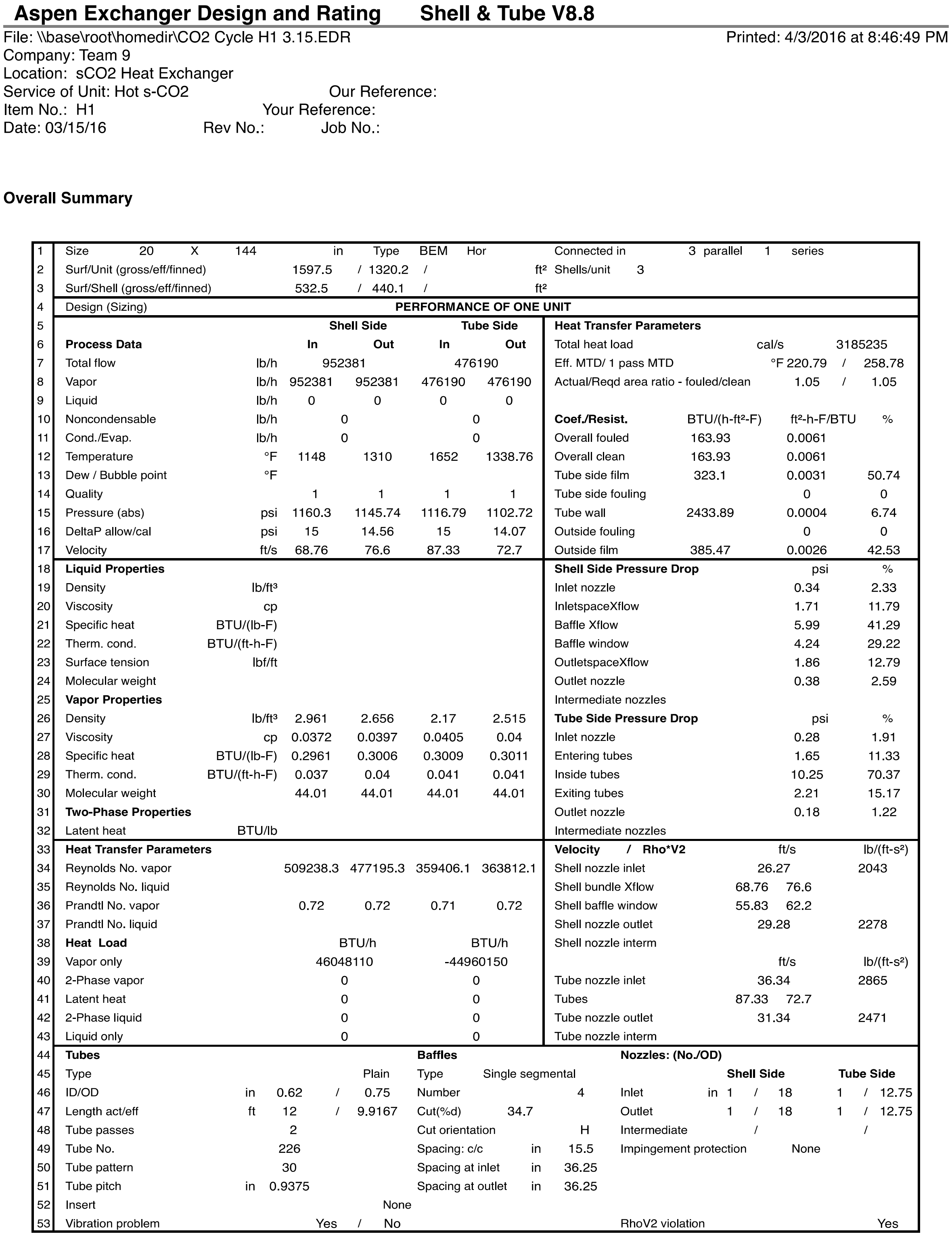
1	Size	69	X	138	in	Type	BEM	Hor		Connected in	8	parallel	1 series
2	Surf/Unit (gross/eff/finned)	77278.4	/ 73848.5	/					ft²	Shells/unit	8		
3	Surf/Shell (gross/eff/finned)	9659.8	/ 9231.1	/					ft²				
4	Design (Sizing)	**PERFORMANCE OF ONE UNIT**											

5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h	87856630	
7	Total flow	lb/h	849206		4880445		Eff. MTD/ 1 pass MTD	°F	119.5	/ 119.49
8	Vapor	lb/h	849206	849206	0	0	Actual/Reqd area ratio - fouled/clean		5.59	/ 5.59
9	Liquid	lb/h	0	0	4880445	4880445				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	55.65	0.018	
12	Temperature	°F	240.8	158	68	86	Overall clean	55.65	0.018	
13	Dew / Bubble point	°F					Tube side film	80.83	0.0124	68.85
14	Quality		1	1	0	0	Tube side fouling		0	0
15	Pressure (abs)	psi	58	45.1	1.01	0.98	Tube wall	3834.36	0.0003	1.45
16	DeltaP allow/cal	psi	15	12.9	0.2	0.03	Outside fouling		0	0
17	Velocity	ft/s	769.19	856.71	0.34	0.34	Outside film	187.4	0.0053	29.7
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³			62.355	62.262	Inlet nozzle		0.24	1.83
20	Viscosity	cp			1.0163	0.7998	InletspaceXflow		2.57	19.94
21	Specific heat	BTU/(lb-F)			1.0016	1.0008	Baffle Xflow		5.96	46.27
22	Therm. cond.	BTU/(ft-h-F)			0.343	0.351	Baffle window		0.67	5.18
23	Surface tension	lbf/ft					OutletspaceXflow		2.81	21.78
24	Molecular weight				18.01	18.01	Outlet nozzle		0.64	4.99
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft³	0.031	0.027			**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0238	0.0217			Inlet nozzle		0.01	36.2
28	Specific heat	BTU/(lb-F)	1.2482	1.2482			Entering tubes		0	1.11
29	Therm. cond.	BTU/(ft-h-F)	0.108	0.1			Inside tubes		0.01	18.16
30	Molecular weight		4	4			Exiting tubes		0	1.73
31	**Two-Phase Properties**						Outlet nozzle		0.01	42.8
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor		92577.74	101424.4			Shell nozzle inlet	204.74		1294
35	Reynolds No. liquid				1517.55	1928.39	Shell bundle Xflow	769.19	856.71	
36	Prandtl No. vapor		0.67	0.66			Shell baffle window	647.15	720.78	
37	Prandtl No. liquid				7.18	5.52	Shell nozzle outlet	367.56		3676
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		-87762530		0			ft/s		lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet	1.34		113
41	Latent heat		0		0		Tubes	0.34	0.34	
42	2-Phase liquid		0		0		Tube nozzle outlet	2.15		287
43	Liquid only		0		87950740		Tube nozzle interm			

44	**Tubes**			**Baffles**			**Nozzles: (No./OD)**			
45	Type		Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.584 / 0.75	Number		4	Inlet	in	1 / 30	1 / 20
47	Length act/eff	ft	11.5 / 10.9896	Cut(%d)		11.36	Outlet		1 / 24	1 / 16
48	Tube passes		1	Cut orientation		H	Intermediate		/	/
49	Tube No.		4278	Spacing: c/c	in	15	Impingement protection		None	
50	Tube pattern		30	Spacing at inlet	in	43.4375				
51	Tube pitch	in	0.9375	Spacing at outlet	in	43.4375				
52	Insert		None							
53	Vibration problem		Yes / No				RhoV2 violation			Yes

E.2 S-CO_2 Process

HX-1



Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\CO2 Cycle H1 3.15.EDR Printed: 4/3/2016 at 8:46:49 PM
Company: Team 9
Location: sCO2 Heat Exchanger
Service of Unit: Hot s-CO2 Our Reference:
Item No.: H1 Your Reference:
Date: 03/15/16 Rev No.: Job No.:

Overall Summary

1	Size	20	X	144	in	Type BEM Hor	Connected in	3 parallel	1	series
2	Surf/Unit (gross/eff/finned)		1597.5	/ 1320.2	/	ft²	Shells/unit	3		
3	Surf/Shell (gross/eff/finned)		532.5	/ 440.1	/	ft²				
4	Design (Sizing)			PERFORMANCE OF ONE UNIT						
5			Shell Side		Tube Side		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	cal/s	3185235	
7	Total flow	lb/h	952381		476190		Eff. MTD/ 1 pass MTD	°F 220.79	/	258.78
8	Vapor	lb/h	952381	952381	476190	476190	Actual/Reqd area ratio - fouled/clean	1.05	/	1.05
9	Liquid	lb/h	0	0	0	0				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	163.93	0.0061	
12	Temperature	°F	1148	1310	1652	1338.76	Overall clean	163.93	0.0061	
13	Dew / Bubble point	°F					Tube side film	323.1	0.0031	50.74
14	Quality		1	1	1	1	Tube side fouling		0	0
15	Pressure (abs)	psi	1160.3	1145.74	1116.79	1102.72	Tube wall	2433.89	0.0004	6.74
16	DeltaP allow/cal	psi	15	14.56	15	14.07	Outside fouling		0	0
17	Velocity	ft/s	68.76	76.6	87.33	72.7	Outside film	385.47	0.0026	42.53
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³					Inlet nozzle		0.34	2.33
20	Viscosity	cp					InletspaceXflow		1.71	11.79
21	Specific heat	BTU/(lb-F)					Baffle Xflow		5.99	41.29
22	Therm. cond.	BTU/(ft-h-F)					Baffle window		4.24	29.22
23	Surface tension	lbf/ft					OutletspaceXflow		1.86	12.79
24	Molecular weight						Outlet nozzle		0.38	2.59
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft³	2.961	2.656	2.17	2.515	**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0372	0.0397	0.0405	0.04	Inlet nozzle		0.28	1.91
28	Specific heat	BTU/(lb-F)	0.2961	0.3006	0.3009	0.3011	Entering tubes		1.65	11.33
29	Therm. cond.	BTU/(ft-h-F)	0.037	0.04	0.041	0.041	Inside tubes		10.25	70.37
30	Molecular weight		44.01	44.01	44.01	44.01	Exiting tubes		2.21	15.17
31	**Two-Phase Properties**						Outlet nozzle		0.18	1.22
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor		509238.3	477195.3	359406.1	363812.1	Shell nozzle inlet	26.27		2043
35	Reynolds No. liquid						Shell bundle Xflow	68.76	76.6	
36	Prandtl No. vapor		0.72	0.72	0.71	0.72	Shell baffle window	55.83	62.2	
37	Prandtl No. liquid						Shell nozzle outlet	29.28		2278
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		46048110		-44960150			ft/s		lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet	36.34		2865
41	Latent heat		0		0		Tubes	87.33	72.7	
42	2-Phase liquid		0		0		Tube nozzle outlet	31.34		2471
43	Liquid only		0		0		Tube nozzle interm			

44	**Tubes**			**Baffles**			**Nozzles: (No./OD)**			
45	Type		Plain	Type	Single segmental				**Shell Side**	**Tube Side**
46	ID/OD	in	0.62 / 0.75	Number		4	Inlet	in	1 / 18	1 / 12.75
47	Length act/eff	ft	12 / 9.9167	Cut(%d)	34.7		Outlet		1 / 18	1 / 12.75
48	Tube passes		2	Cut orientation		H	Intermediate		/	/
49	Tube No.		226	Spacing: c/c	in	15.5	Impingement protection		None	
50	Tube pattern		30	Spacing at inlet	in	36.25				
51	Tube pitch	in	0.9375	Spacing at outlet	in	36.25				
52	Insert		None							
53	Vibration problem		Yes / No				RhoV2 violation			Yes

HX-2

Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\CO2 Cycle H2 3.15.EDR Printed: 4/3/2016 at 8:47:29 PM
Company: Team 9
Location: CO2 Heat Exchanger
Service of Unit: Hot s-CO2 Our Reference:
Item No.: H2 Your Reference:
Date: 3/15/16 Rev No.: Job No.:

Overall Summary

1	Size	20 X 72		in	Type	BEM Hor	Connected in	3 parallel	1 series	
2	Surf/Unit (gross/eff/finned)		795.2 / 698.6 /			ft²	Shells/unit	3		
3	Surf/Shell (gross/eff/finned)		265.1 / 232.9 /			ft²				
4	Design (Sizing)		PERFORMANCE OF ONE UNIT							
5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h	6521279	
7	Total flow	lb/h	952381		476190		Eff. MTD/ 1 pass MTD	°F	107.64 /	107.65
8	Vapor	lb/h	952381	952381	476190	476190	Actual/Reqd area ratio - fouled/clean		1.54 /	1.54
9	Liquid	lb/h	0	0	0	0				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	133.49	0.0075	
12	Temperature	°F	1196.6	1220	1338.8	1293.8	Overall clean	133.49	0.0075	
13	Dew / Bubble point	°F					Tube side film	252.23	0.004	52.93
14	Quality		1	1	1	1	Tube side fouling		0	0
15	Pressure (abs)	psi	797.71	783.76	1116.79	1109.59	Tube wall	803.85	0.0012	16.61
16	DeltaP allow/cal	psi	15	13.95	15	7.2	Outside fouling		0	0
17	Velocity	ft/s	105.93	109.19	79.96	78.46	Outside film	438.17	0.0023	30.47
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³					Inlet nozzle		0.52	3.74
20	Viscosity	cp					InletspaceXflow		3.29	23.65
21	Specific heat	BTU/(lb-F)					Baffle Xflow		3.92	28.15
22	Therm. cond.	BTU/(ft-h-F)					Baffle window		2.28	16.35
23	Surface tension	lbf/ft					OutletspaceXflow		3.36	24.16
24	Molecular weight						Outlet nozzle		0.55	3.95
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft³	1.976	1.914	2.547	2.596	**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0377	0.038	0.04	0.0394	Inlet nozzle		0.25	3.38
28	Specific heat	BTU/(lb-F)	0.2958	0.2966	0.3011	0.3	Entering tubes		0.88	12.08
29	Therm. cond.	BTU/(ft-h-F)	0.037	0.038	0.041	0.04	Inside tubes		4.41	60.55
30	Molecular weight		44.01	44.01	44.01	44.01	Exiting tubes		1.61	22.12
31	**Two-Phase Properties**						Outlet nozzle		0.14	1.87
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor		516432.9	511366	264945.4	269282.7	Shell nozzle inlet	39.37		3062
35	Reynolds No. liquid						Shell bundle Xflow	105.93 109.19		
36	Prandtl No. vapor		0.72	0.72	0.72	0.72	Shell baffle window	99.05 102.1		
37	Prandtl No. liquid						Shell nozzle outlet	40.63		3160
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		6601538		-6441028			ft/s		lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet	30.95		2440
41	Latent heat		0		0		Tubes	79.96 78.46		
42	2-Phase liquid		0		0		Tube nozzle outlet	30.37		2395
43	Liquid only		0		0		Tube nozzle interm			
44	**Tubes**				**Baffles**		**Nozzles: (No./OD)**			
45	Type		Plain		Type	Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.42 / 0.75		Number	2	Inlet	in	1 / 18	1 / 12.75
47	Length act/eff	ft	6 / 5.2708		Cut(%d)	28.34	Outlet		1 / 18	1 / 12.75
48	Tube passes		1		Cut orientation	H	Intermediate		/	/
49	Tube No.		225		Spacing: c/c	in 11.75	Impingement protection		None	
50	Tube pattern		30		Spacing at inlet	in 25.75				
51	Tube pitch	in	0.9375		Spacing at outlet	in 25.75				
52	Insert		None							
53	Vibration problem		Yes / No				RhoV2 violation			Yes

HX-3

Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\CO2 Cycle H3 3.15.EDR Printed: 4/3/2016 at 8:48:28 PM
Company: Team 9
Location: s-CO2 Heat Exchanger
Service of Unit: HOT s-CO2 Our Reference:
Item No.: H3 Your Reference:
Date: 3/15/16 Rev No.: Job No.:

Overall Summary

1	Size	32 X 216	in	Type	BEM	Hor	Connected in	4 parallel	2 series	
2	Surf/Unit (gross/eff/finned)		12751.7	/ 11666.9	/	ft²	Shells/unit	8		
3	Surf/Shell (gross/eff/finned)		1594	/ 1458.4	/	ft²				
4	Design (Sizing)			**PERFORMANCE OF ONE UNIT**						

5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	cal/s	1526880	
7	Total flow	lb/h	952381		476190		Eff. MTD/ 1 pass MTD	°F	28.51	/ 28.46
8	Vapor	lb/h	952381	952381	476190	476190	Actual/Reqd area ratio - fouled/clean		1	/ 1
9	Liquid	lb/h	0	0	0	0				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	65.72	0.0152	
12	Temperature	°F	1133.6	1211	1293.8	1139	Overall clean	65.72	0.0152	
13	Dew / Bubble point	°F					Tube side film	112.44	0.0089	58.45
14	Quality		1	1	1	1	Tube side fouling		0	0
15	Pressure (abs)	psi	594.65	586.22	1116.79	1111.17	Tube wall	777.88	0.0013	8.45
16	DeltaP allow/cal	psi	15	8.44	15	5.62	Outside fouling		0	0
17	Velocity	ft/s	16.55	17.59	29.17	26.73	Outside film	198.51	0.005	33.1
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³					Inlet nozzle		0.2	2.39
20	Viscosity	cp					InletspaceXflow		0.96	11.43
21	Specific heat	BTU/(lb-F)					Baffle Xflow		3.8	45.01
22	Therm. cond.	BTU/(ft-h-F)					Baffle window		1.48	17.6
23	Surface tension	lbf/ft					OutletspaceXflow		0.99	11.75
24	Molecular weight						Outlet nozzle		0.3	3.56
25	**Vapor Properties**						Intermediate nozzles		0.7	8.26
26	Density	lb/ft³	1.531	1.439	2.613	2.851	**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0365	0.0378	0.0394	0.037	Inlet nozzle		0.3	5.35
28	Specific heat	BTU/(lb-F)	0.2926	0.2953	0.3	0.2955	Entering tubes		0.23	4.09
29	Therm. cond.	BTU/(ft-h-F)	0.036	0.038	0.04	0.036	Inside tubes		4.17	73.65
30	Molecular weight		44.01	44.01	44.01	44.01	Exiting tubes		0.41	7.32
31	**Two-Phase Properties**						Outlet nozzle		0.13	2.28
32	Latent heat	BTU/lb					Intermediate nozzles		0.41	7.3
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor		64566.05	62417.5	100758	107351.8	Shell nozzle inlet	29.09		1296
35	Reynolds No. liquid						Shell bundle Xflow	16.55	17.59	
36	Prandtl No. vapor		0.72	0.72	0.72	0.72	Shell baffle window	26.08	27.71	
37	Prandtl No. liquid						Shell nozzle outlet	45.8		3020
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm	43.78		2887
39	Vapor only		21671180		-21954680			ft/s		lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet	32.12		2695
41	Latent heat		0		0		Tubes	29.17	26.73	
42	2-Phase liquid		0		0		Tube nozzle outlet	29.43		2470
43	Liquid only		0		0		Tube nozzle interm	29.93		2512

44	**Tubes**			**Baffles**			**Nozzles: (No./OD)**			
45	Type		Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.42 / 0.75	Number		6	Inlet	in	1 / 20	1 / 10.75
47	Length act/eff	ft	18 / 16.4688	Cut(%d)		39.85	Outlet		1 / 16	1 / 10.75
48	Tube passes		1	Cut orientation		H	Intermediate		1 / 16	1 / 10.75
49	Tube No.		451	Spacing: c/c	in	27	Impingement protection		None	
50	Tube pattern		30	Spacing at inlet	in	31.3125				
51	Tube pitch	in	0.9375	Spacing at outlet	in	31.3125				
52	Insert		None							
53	Vibration problem		Yes / No				RhoV2 violation			No

HX-4

Aspen Exchanger Design and Rating Shell & Tube V8.8

File: \\base\root\homedir\CO2 Cycle H4 3.15.EDR Printed: 4/3/2016 at 8:49:36 PM
Company: Team 9
Location: s-CO2 cycle
Service of Unit: s-CO2 Our Reference:
Item No.: H4 Your Reference:
Date: 3/15/16 Rev No.: Job No.:

Overall Summary

1	Size	44 X 288	in	Type	BEM	Hor	Connected in	5 parallel	5 series	
2	Surf/Unit (gross/eff/finned)		213353.2 / 01592. /			ft²	Shells/unit	25		
3	Surf/Shell (gross/eff/finned)		8534.1 / 8063.7 /			ft²				
4	Design (Sizing)		PERFORMANCE OF ONE UNIT							
5			Shell Side		Tube Side		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h	264983400	
7	Total flow	lb/h	952381		952381		Eff. MTD/ 1 pass MTD	°F	45.44 / 45.4	
8	Vapor	lb/h	952381	952381	952381	952381	Actual/Reqd area ratio - fouled/clean		1.01 / 1.01	
9	Liquid	lb/h	0	0	0	0				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	29.35	0.0341	
12	Temperature	°F	176.26	1148.72	1211.8	190.98	Overall clean	29.35	0.0341	
13	Dew / Bubble point	°F					Tube side film	40.09	0.0249	73.22
14	Quality		1	1	1	1	Tube side fouling		0	0
15	Pressure (abs)	psi	1160.3	1147.24	592.04	588.68	Tube wall	854.49	0.0012	3.44
16	DeltaP allow/cal	psi	15	13.07	15	3.36	Outside fouling		0	0
17	Velocity	ft/s	4.92	17.16	15.87	5.48	Outside film	125.71	0.008	23.35
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³					Inlet nozzle		0.16	1.19
20	Viscosity	cp					InletspaceXflow		0.63	4.85
21	Specific heat	BTU/(lb-F)					Baffle Xflow		7.63	58.5
22	Therm. cond.	BTU/(ft-h-F)					Baffle window		1.55	11.89
23	Surface tension	lbf/ft					OutletspaceXflow		0.8	6.11
24	Molecular weight						Outlet nozzle		0.19	1.42
25	**Vapor Properties**						Intermediate nozzles		2.09	16.04
26	Density	lb/ft³	10.204	2.926	1.453	4.204	**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp	0.0235	0.0372	0.0378	0.0213	Inlet nozzle		0.21	6.19
28	Specific heat	BTU/(lb-F)	0.3111	0.296	0.2954	0.2627	Entering tubes		0.07	1.96
29	Therm. cond.	BTU/(ft-h-F)	0.018	0.037	0.038	0.016	Inside tubes		1.56	45.59
30	Molecular weight		44.01	44.01	44.01	44.01	Exiting tubes		0.1	2.82
31	**Two-Phase Properties**						Outlet nozzle		0.17	5.05
32	Latent heat	BTU/lb					Intermediate nozzles		1.31	38.4
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**		ft/s	lb/(ft-s²)
34	Reynolds No. vapor		198474.5	125637.4	36492.21	64703.7	Shell nozzle inlet		9.27	877
35	Reynolds No. liquid						Shell bundle Xflow		4.92 17.16	
36	Prandtl No. vapor		0.96	0.72	0.72	0.85	Shell baffle window		3.86 13.47	
37	Prandtl No. liquid						Shell nozzle outlet		20.2	1194
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm		26.07	2466
39	Vapor only		263842800		-266124100				ft/s	lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet		36.3	1915
41	Latent heat		0		0		Tubes		15.87 5.48	
42	2-Phase liquid		0		0		Tube nozzle outlet		28.1	3319
43	Liquid only		0		0		Tube nozzle interm		39.22	2727
44	**Tubes**			**Baffles**			**Nozzles: (No./OD)**			
45	Type		Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.482 / 0.75	Number		12	Inlet	in	1 / 12.75	1 / 16
47	Length act/eff	ft	24 / 22.6771	Cut(%d)		29.7	Outlet		1 / 16	1 / 10.75
48	Tube passes		1	Cut orientation		H	Intermediate		1 / 12.75	1 / 14
49	Tube No.		1811	Spacing: c/c	in	18.25	Impingement protection		None	
50	Tube pattern		30	Spacing at inlet	in	35.6875				
51	Tube pitch	in	0.9375	Spacing at outlet	in	35.6875				
52	Insert		None							
53	Vibration problem		Yes / No				RhoV2 violation			No

HX-5

Aspen Exchanger Design and Rating Shell & Tube V8.8

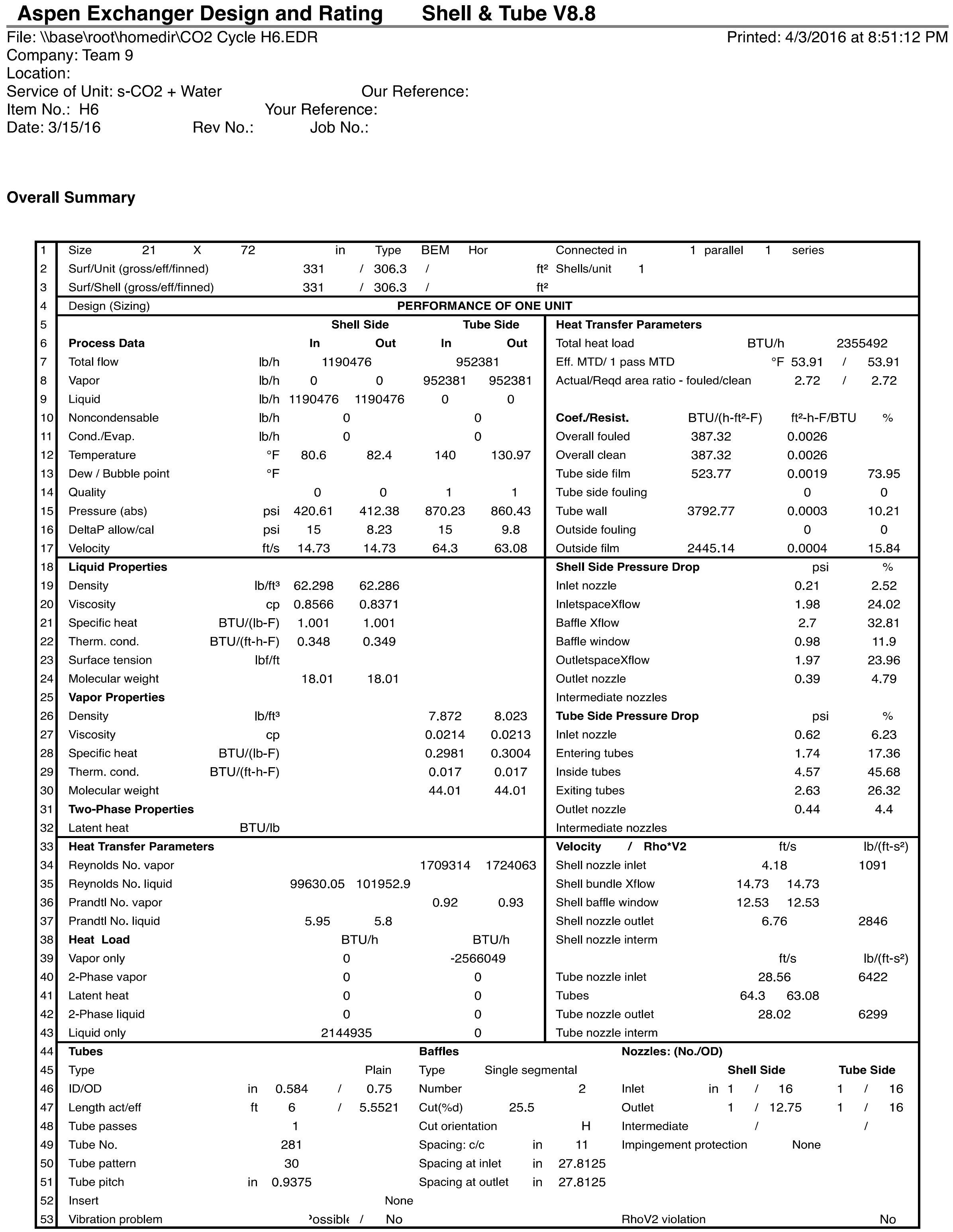
File: \\base\root\homedir\CO2 Cycle H5 3.15.EDR Printed: 4/3/2016 at 8:50:20 PM
Company: Team 9
Location: s-CO2 Cycle
Service of Unit: s-CO2+Water Our Reference:
Item No.: H5 Your Reference:
Date: 3/15/16 Rev No.: Job No.:

Overall Summary

1	Size 32 X 240	in	Type	BEM	Hor		Connected in	1 parallel	2 series		
2	Surf/Unit (gross/eff/finned)		6683.7	/ 6495.8	/	ft²	Shells/unit	2			
3	Surf/Shell (gross/eff/finned)		3341.9	/ 3247.9	/	ft²					
4	Design (Sizing)				PERFORMANCE OF ONE UNIT						
5			Shell Side		Tube Side		**Heat Transfer Parameters**				
6	**Process Data**		In	Out	In	Out	Total heat load	cal/s			1664240
7	Total flow	lb/h	1190476		952381		Eff. MTD/ 1 pass MTD	°F	21.77	/	21.52
8	Vapor	lb/h	0	0	952381	952381	Actual/Reqd area ratio - fouled/clean		1.02	/	1.02
9	Liquid	lb/h	1190476	1190476	0	0					
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%	
11	Cond./Evap.	lb/h	0		0		Overall fouled	172.01	0.0058		
12	Temperature	°F	80.6	98.6	183.2	82.65	Overall clean	172.01	0.0058		
13	Dew / Bubble point	°F					Tube side film	202.36	0.0049	85	
14	Quality		0	0	1	1	Tube side fouling		0	0	
15	Pressure (abs)	psi	420.61	405.78	594.65	586.86	Tube wall	3795.19	0.0003	4.53	
16	DeltaP allow/cal	psi	15	14.83	15	7.79	Outside fouling		0	0	
17	Velocity	ft/s	4.97	4.98	38.6	29.19	Outside film	1643.92	0.0006	10.46	
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%	
19	Density	lb/ft³	62.299	62.147			Inlet nozzle		0.19	1.28	
20	Viscosity	cp	0.8561	0.6917			InletspaceXflow		1.37	9.22	
21	Specific heat	BTU/(lb-F)	1.001	1.0004			Baffle Xflow		8.4	56.65	
22	Therm. cond.	BTU/(ft-h-F)	0.348	0.356			Baffle window		2.14	14.4	
23	Surface tension	lbf/ft					OutletspaceXflow		1.34	9.03	
24	Molecular weight		18.01	18.01			Outlet nozzle		0.49	3.31	
25	**Vapor Properties**						Intermediate nozzles		0.9	6.1	
26	Density	lb/ft³			4.33	5.726	**Tube Side Pressure Drop**		psi	%	
27	Viscosity	cp			0.0212	0.0188	Inlet nozzle		0.27	3.33	
28	Specific heat	BTU/(lb-F)			0.264	0.2865	Entering tubes		0.61	7.54	
29	Therm. cond.	BTU/(ft-h-F)			0.016	0.014	Inside tubes		5.88	72.25	
30	Molecular weight				44.01	44.01	Exiting tubes		0.82	10.12	
31	**Two-Phase Properties**						Outlet nozzle		0.19	2.37	
32	Latent heat	BTU/lb					Intermediate nozzles		0.36	4.4	
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**	ft/s		lb/(ft-s²)	
34	Reynolds No. vapor				572261	642173.8	Shell nozzle inlet	4.18		1091	
35	Reynolds No. liquid		33639.77	41637.09			Shell bundle Xflow	4.97	4.98		
36	Prandtl No. vapor				0.85	0.91	Shell baffle window	4.55	4.56		
37	Prandtl No. liquid		5.95	4.7			Shell nozzle outlet	6.78		2853	
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm	6.76		2847	
39	Vapor only		0		-26107750			ft/s		lb/(ft-s²)	
40	2-Phase vapor		0		0		Tube nozzle inlet	25.4		2794	
41	Latent heat		0		0		Tubes	38.6	29.19		
42	2-Phase liquid		0		0		Tube nozzle outlet	23.47		3153	
43	Liquid only		21442760		0		Tube nozzle interm	20.01		2201	

44	**Tubes**					**Baffles**			**Nozzles: (No./OD)**			
45	Type				Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.584	/	0.75	Number		8	Inlet	in	1 / 16	1 / 22
47	Length act/eff	ft	20	/	19.4375	Cut(%d)		39.85	Outlet		1 / 12.75	1 / 20
48	Tube passes		1			Cut orientation		H	Intermediate		1 / 12.75	1 / 22
49	Tube No.		851			Spacing: c/c	in	23.25	Impingement protection		None	
50	Tube pattern		30			Spacing at inlet	in	35.25				
51	Tube pitch	in	0.9375			Spacing at outlet	in	35.25				
52	Insert				None							
53	Vibration problem		Yes	/	No				RhoV2 violation			No

HX-6



Aspen Exchanger Design and Rating   Shell & Tube V8.8

File: \\base\root\homedir\CO2 Cycle H6.EDR   Printed: 4/3/2016 at 8:51:12 PM
Company: Team 9
Location:
Service of Unit: s-CO2 + Water   Our Reference:
Item No.: H6   Your Reference:
Date: 3/15/16   Rev No.:   Job No.:

Overall Summary

1	Size	21	X	72	in	Type BEM Hor	Connected in	1 parallel	1 series	
2	Surf/Unit (gross/eff/finned)		331 /	306.3 /		ft²	Shells/unit	1		
3	Surf/Shell (gross/eff/finned)		331 /	306.3 /		ft²				
4	Design (Sizing)			**PERFORMANCE OF ONE UNIT**						
5			**Shell Side**		**Tube Side**		**Heat Transfer Parameters**			
6	**Process Data**		**In**	**Out**	**In**	**Out**	Total heat load	BTU/h		2355492
7	Total flow	lb/h	1190476		952381		Eff. MTD/ 1 pass MTD	°F	53.91 /	53.91
8	Vapor	lb/h	0	0	952381	952381	Actual/Reqd area ratio - fouled/clean		2.72 /	2.72
9	Liquid	lb/h	1190476	1190476	0	0				
10	Noncondensable	lb/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%
11	Cond./Evap.	lb/h	0		0		Overall fouled	387.32	0.0026	
12	Temperature	°F	80.6	82.4	140	130.97	Overall clean	387.32	0.0026	
13	Dew / Bubble point	°F					Tube side film	523.77	0.0019	73.95
14	Quality		0	0	1	1	Tube side fouling		0	0
15	Pressure (abs)	psi	420.61	412.38	870.23	860.43	Tube wall	3792.77	0.0003	10.21
16	DeltaP allow/cal	psi	15	8.23	15	9.8	Outside fouling		0	0
17	Velocity	ft/s	14.73	14.73	64.3	63.08	Outside film	2445.14	0.0004	15.84
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%
19	Density	lb/ft³	62.298	62.286			Inlet nozzle		0.21	2.52
20	Viscosity	cp	0.8566	0.8371			InletspaceXflow		1.98	24.02
21	Specific heat	BTU/(lb-F)	1.001	1.001			Baffle Xflow		2.7	32.81
22	Therm. cond.	BTU/(ft-h-F)	0.348	0.349			Baffle window		0.98	11.9
23	Surface tension	lbf/ft					OutletspaceXflow		1.97	23.96
24	Molecular weight		18.01	18.01			Outlet nozzle		0.39	4.79
25	**Vapor Properties**						Intermediate nozzles			
26	Density	lb/ft³			7.872	8.023	**Tube Side Pressure Drop**		psi	%
27	Viscosity	cp			0.0214	0.0213	Inlet nozzle		0.62	6.23
28	Specific heat	BTU/(lb-F)			0.2981	0.3004	Entering tubes		1.74	17.36
29	Therm. cond.	BTU/(ft-h-F)			0.017	0.017	Inside tubes		4.57	45.68
30	Molecular weight				44.01	44.01	Exiting tubes		2.63	26.32
31	**Two-Phase Properties**						Outlet nozzle		0.44	4.4
32	Latent heat	BTU/lb					Intermediate nozzles			
33	**Heat Transfer Parameters**						**Velocity / Rho*V2**		ft/s	lb/(ft-s²)
34	Reynolds No. vapor				1709314	1724063	Shell nozzle inlet		4.18	1091
35	Reynolds No. liquid		99630.05	101952.9			Shell bundle Xflow		14.73 14.73	
36	Prandtl No. vapor				0.92	0.93	Shell baffle window		12.53 12.53	
37	Prandtl No. liquid		5.95	5.8			Shell nozzle outlet		6.76	2846
38	**Heat Load**		BTU/h		BTU/h		Shell nozzle interm			
39	Vapor only		0		-2566049				ft/s	lb/(ft-s²)
40	2-Phase vapor		0		0		Tube nozzle inlet		28.56	6422
41	Latent heat		0		0		Tubes		64.3 63.08	
42	2-Phase liquid		0		0		Tube nozzle outlet		28.02	6299
43	Liquid only		2144935		0		Tube nozzle interm			
44	**Tubes**				**Baffles**			**Nozzles: (No./OD)**		
45	Type			Plain	Type	Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.584 /	0.75	Number		2	Inlet	in 1 / 16	1 / 16
47	Length act/eff	ft	6 /	5.5521	Cut(%d)	25.5		Outlet	1 / 12.75	1 / 16
48	Tube passes		1		Cut orientation		H	Intermediate	/	/
49	Tube No.		281		Spacing: c/c	in	11	Impingement protection	None	
50	Tube pattern		30		Spacing at inlet	in	27.8125			
51	Tube pitch	in	0.9375		Spacing at outlet	in	27.8125			
52	Insert			None						
53	Vibration problem		ossibl /	No				RhoV2 violation		No

Appendix D. Aspen Block Results

D.1 Helium Process

```
 BLOCK:  IHX1     MODEL: MHEATX
 ------------------------------
HOT SIDE:    INLET STREAM     OUTLET STREAM
             ------------     -------------
             HOT1             6
COLD SIDE:   INLET STREAM     OUTLET STREAM
             ------------     -------------
             COLD1            2

PROPERTIES FOR STREAM HOT1
  PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

  PROPERTIES FOR STREAM COLD1
  PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                              IN              OUT         RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )           210193.         210193.         0.00000
     MASS(KG/HR   )           841320.         841320.         0.00000
     ENTHALPY(CAL/SEC )       0.182024E+09    0.182024E+09   -0.163727E-15
                     ***  INPUT DATA  ***
  SPECIFICATIONS FOR STREAM HOT1    :
  ONE    PHASE  TP  FLASH   SPECIFIED PHASE IS  VAPOR
  SPECIFIED TEMPERATURE              C                    509.200
  SPECIFIED PRESSURE                 BAR                  7.59000
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                     0.000100000

  SPECIFICATIONS FOR STREAM COLD1   :
  TWO    PHASE      FLASH
  PRESSURE DROP                      BAR                  0.0
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                     0.000100000

                     ***  RESULTS  ***

 INLET                OUTLET       OUTLET       OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C            BAR

 HOT1      -0.62108E+08    509.20      7.5900        1.0000
 COLD1      0.62108E+08    817.68      79.000        1.0000

           -----------------------------------
           |                                 |
 HOT1      |                                 | 6
  --------->| 0.11396E+06 KMOL/HR   |--------->
  900.00   |                                 |   509.20
           |                                 |
```

```
  2         |                              | COLD1
<---------|   96237.     KMOL/HR     |<---------
  817.68 |                              |   350.00
            |                              |
            ---------------------------------

                    ***  INTERNAL ANALYSIS  ***

  FLOW IS COUNTERCURRENT.
  DUTY                           0.62108E+08 CAL/SEC
  UA                           0.53262E+06 CAL/SEC-K
  AVERAGE LMTD (DUTY/UA)           116.61     C
  MIN TEMP APPROACH                82.317     C
  HOT-SIDE TEMP APPROACH           82.317     C
  COLD-SIDE TEMP APPROACH          159.20     C
  HOT-SIDE NTU                  3.3514
  COLD-SIDE NTU                  4.0107

  DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                                          POINT  BUBBLE POINT
  CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

   0.000       509.20    350.00    159.20
  0.1035E+08    574.36    427.92    146.43    152.73  0.6778E+05  0.1035E+08  0.6778E+05
  0.2070E+08    639.50    505.86    133.64    139.94  0.7397E+05  0.1035E+08  0.1417E+06
  0.3105E+08    704.64    583.81    120.83    127.13  0.8142E+05  0.1035E+08  0.2232E+06
  0.4141E+08    769.77    661.76    108.00    114.30  0.9056E+05  0.1035E+08  0.3137E+06
  0.5176E+08    834.89    739.72     95.17    101.45  0.1020E+06  0.1035E+08  0.4158E+06
  0.6211E+08    900.00    817.68     82.32     88.59  0.1169E+06  0.1035E+08  0.5326E+06  GBL

  GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

 BLOCK:  IHX1     MODEL: MHEATX
 ------------------------------
   HOT SIDE:    INLET STREAM     OUTLET STREAM
             ------------     -------------
             HOT1           6

   COLD SIDE:   INLET STREAM     OUTLET STREAM
             ------------     -------------
             COLD1           2

   PROPERTIES FOR STREAM HOT1
   PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

   PROPERTIES FOR STREAM COLD1
   PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                          IN             OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           210193.         210193.         0.00000
       MASS(KG/HR   )           841320.         841320.         0.00000
       ENTHALPY(CAL/SEC )       0.182024E+09    0.182024E+09   -0.163727E-15
```

```
                 ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E             0.00000      KG/HR
   PRODUCT STREAMS CO2E          0.00000      KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM HOT1    :
  ONE    PHASE  TP  FLASH   SPECIFIED PHASE IS  VAPOR
  SPECIFIED TEMPERATURE              C                    509.200
  SPECIFIED PRESSURE                 BAR                  7.59000
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                  0.000100000

  SPECIFICATIONS FOR STREAM COLD1   :
  TWO    PHASE      FLASH
  PRESSURE DROP                      BAR                  0.0
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                  0.000100000

                    ***  RESULTS  ***

 INLET                 OUTLET       OUTLET       OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C           BAR

 HOT1      -0.62108E+08    509.20      7.5900        1.0000
 COLD1      0.62108E+08    817.68      79.000        1.0000


           -----------------------------------
            |                                 |
 HOT1   |                                 | 6
--------->|   0.11396E+06 KMOL/HR   |--------->
  900.00 |                                 |   509.20
           |                                 |
    2       |                                 | COLD1
<---------|    96237.     KMOL/HR       |<---------
   817.68 |                                |   350.00
            |                                 |
           ------------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                          0.62108E+08 CAL/SEC
 UA                            0.53262E+06 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)           116.61     C
 MIN TEMP APPROACH                82.317     C
 HOT-SIDE TEMP APPROACH           82.317     C
 COLD-SIDE TEMP APPROACH          159.20     C
 HOT-SIDE NTU                  3.3514
 COLD-SIDE NTU                 4.0107
```

```
  DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA         PINCH  STREAM
IN/OUT/DEW/
                                                              POINT  BUBBLE POINT
  CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

   0.000       509.20    350.00    159.20
  0.1035E+08    574.36    427.92    146.43    152.73  0.6778E+05  0.1035E+08  0.6778E+05
  0.2070E+08    639.50    505.86    133.64    139.94  0.7397E+05  0.1035E+08  0.1417E+06
  0.3105E+08    704.64    583.81    120.83    127.13  0.8142E+05  0.1035E+08  0.2232E+06
  0.4141E+08    769.77    661.76    108.00    114.30  0.9056E+05  0.1035E+08  0.3137E+06
  0.5176E+08    834.89    739.72     95.17    101.45  0.1020E+06  0.1035E+08  0.4158E+06
  0.6211E+08    900.00    817.68     82.32     88.59  0.1169E+06  0.1035E+08  0.5326E+06  GBL

  GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

 BLOCK:  RECP     MODEL: MHEATX
 ------------------------------
   HOT SIDE:    INLET STREAM     OUTLET STREAM
                ------------     -------------
                HOTIN            S23

   COLD SIDE:   INLET STREAM     OUTLET STREAM
                ------------     -------------
                COLDIN           COLD1

   PROPERTIES FOR STREAM COLDIN
   PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

   PROPERTIES FOR STREAM HOTIN
   PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                   ***  MASS AND ENERGY BALANCE  ***
                                IN             OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )            192475.         192475.         0.00000
       MASS(KG/HR   )            770400.         770400.         0.00000
       ENTHALPY(CAL/SEC )        0.648615E+08    0.648615E+08     0.00000
                      ***  INPUT DATA  ***
   SPECIFICATIONS FOR STREAM COLDIN  :
   ONE    PHASE  TP  FLASH   SPECIFIED PHASE IS  VAPOR
   SPECIFIED TEMPERATURE                C                   350.000
   PRESSURE DROP                    BAR                  0.0
   MAXIMUM NO. ITERATIONS                                  30
   CONVERGENCE TOLERANCE                                    0.000100000

   SPECIFICATIONS FOR STREAM HOTIN   :
   ONE    PHASE      FLASH   SPECIFIED PHASE IS  VAPOR
   PRESSURE DROP                    BAR                  0.0
   MAXIMUM NO. ITERATIONS                                  30
   CONVERGENCE TOLERANCE                                    0.000100000

                      ***  RESULTS  ***

  INLET               OUTLET       OUTLET       OUTLET
  STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
           CAL/SEC      C           BAR
```

```
 COLDIN     0.30148E+08    350.00      79.000         1.0000
 HOTIN     -0.30148E+08    182.90      21.155         1.0000

              ----------------------------------
              |                                |
 COLDIN |                                | COLD1
   --------->|   96237.     KMOL/HR      |--------->
     123.17 |                                |   350.00
              |                                |
     S23      |                                | HOTIN
   <---------|   96237.     KMOL/HR       |<---------
     182.90 |                                |   409.97
              |                                |
              ----------------------------------

                     ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                             -.30148E+08 CAL/SEC
 UA                            0.50360E+06 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)            59.866     C
 MIN TEMP APPROACH                 59.727     C
 HOT-SIDE TEMP APPROACH            59.974     C
 COLD-SIDE TEMP APPROACH           59.727     C
 HOT-SIDE NTU                   3.7931
 COLD-SIDE NTU                   3.7890

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                           POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000       409.97    350.00     59.97
 0.5025E+07    372.12    312.18     59.94     59.96  0.8380E+05  0.5025E+07  0.8380E+05
 0.1005E+08    334.27    274.36     59.91     59.93  0.8385E+05  0.5025E+07  0.1676E+06
 0.1507E+08    296.43    236.55     59.87     59.89  0.8390E+05  0.5025E+07  0.2515E+06
 0.2010E+08    258.58    198.75     59.83     59.85  0.8395E+05  0.5025E+07  0.3355E+06
 0.2512E+08    220.74    160.95     59.78     59.81  0.8402E+05  0.5025E+07  0.4195E+06
 0.3015E+08    182.90    123.17     59.73     59.76  0.8409E+05  0.5025E+07  0.5036E+06  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

 BLOCK:  RECP     MODEL: MHEATX
 ------------------------------
  HOT SIDE:    INLET STREAM     OUTLET STREAM
             ------------     -------------
             HOTIN            S23

  COLD SIDE:   INLET STREAM     OUTLET STREAM
             ------------     -------------
             COLDIN           COLD1

  PROPERTIES FOR STREAM COLDIN
  PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE
```

```
 PROPERTIES FOR STREAM HOTIN
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                              IN             OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )           192475.         192475.         0.00000
    MASS(KG/HR   )           770400.         770400.         0.00000
    ENTHALPY(CAL/SEC )       0.648615E+08    0.648615E+08     0.00000

                 ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

 SPECIFICATIONS FOR STREAM COLDIN  :
 ONE    PHASE  TP  FLASH   SPECIFIED PHASE IS  VAPOR
 SPECIFIED TEMPERATURE               C                     350.000
 PRESSURE DROP                     BAR                   0.0
 MAXIMUM NO. ITERATIONS                                    30
 CONVERGENCE TOLERANCE                                       0.000100000

 SPECIFICATIONS FOR STREAM HOTIN   :
 ONE    PHASE      FLASH   SPECIFIED PHASE IS  VAPOR
 PRESSURE DROP                     BAR                   0.0
 MAXIMUM NO. ITERATIONS                                    30
 CONVERGENCE TOLERANCE                                       0.000100000

                    ***  RESULTS  ***

INLET                OUTLET       OUTLET       OUTLET
STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C            BAR

COLDIN     0.30148E+08    350.00      79.000        1.0000
HOTIN     -0.30148E+08    182.90      21.155        1.0000


              -----------------------------
              |                            |
COLDIN   |                            | COLD1
   --------->|  96237.   KMOL/HR    |--------->
     123.17 |                            |   350.00
              |                            |
     S23      |                            | HOTIN
   <---------|   96237.   KMOL/HR    |<---------
     182.90 |                            |   409.97
              |                            |
             ------------------------------

                    ***  INTERNAL ANALYSIS  ***

FLOW IS COUNTERCURRENT.
```

```
 DUTY                         -.30148E+08 CAL/SEC
 UA                        0.50360E+06 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)           59.866     C
 MIN TEMP APPROACH               59.727     C
 HOT-SIDE TEMP APPROACH           59.974     C
 COLD-SIDE TEMP APPROACH          59.727     C
 HOT-SIDE NTU                   3.7931
 COLD-SIDE NTU                   3.7890

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                              POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000        409.97    350.00     59.97
 0.5025E+07    372.12    312.18     59.94     59.96  0.8380E+05  0.5025E+07  0.8380E+05
 0.1005E+08    334.27    274.36     59.91     59.93  0.8385E+05  0.5025E+07  0.1676E+06
 0.1507E+08    296.43    236.55     59.87     59.89  0.8390E+05  0.5025E+07  0.2515E+06
 0.2010E+08    258.58    198.75     59.83     59.85  0.8395E+05  0.5025E+07  0.3355E+06
 0.2512E+08    220.74    160.95     59.78     59.81  0.8402E+05  0.5025E+07  0.4195E+06
 0.3015E+08    182.90    123.17     59.73     59.76  0.8409E+05  0.5025E+07  0.5036E+06  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  B19      MODEL: HEATER
------------------------------
  INLET STREAM:          S21
  OUTLET STREAM:         S22
  PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                               IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )           96237.4         96237.4         0.00000
      MASS(KG/HR   )           385200.         385200.         0.00000
      ENTHALPY(CAL/SEC )       0.707679E+07    0.355869E+07    0.497133

                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            0.00000      KG/HR
   PRODUCT STREAMS CO2E         0.00000      KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                      ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE               C                      50.0000
  SPECIFIED PRESSURE                 BAR                    35.5000
  MAXIMUM NO. ITERATIONS                                      30
  CONVERGENCE TOLERANCE                                         0.000100000

                       ***  RESULTS  ***
  OUTLET TEMPERATURE    C                              50.000
  OUTLET PRESSURE       BAR                           35.500
  HEAT DUTY             CAL/SEC                     -0.35181E+07
  OUTLET VAPOR FRACTION                                 1.0000
```

```
  V-L PHASE EQUILIBRIUM :

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

BLOCK:  B20      MODEL: HEATER
------------------------------
  INLET STREAM:          S11
  OUTLET STREAM:         S18
  PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                               IN            OUT        RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )          96237.4        96237.4        0.00000
     MASS(KG/HR   )          385200.        385200.        0.00000
     ENTHALPY(CAL/SEC )      0.979256E+07   0.625629E+07   0.361119

                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            0.00000      KG/HR
   PRODUCT STREAMS CO2E         0.00000      KG/HR
   NET STREAMS CO2E PRODUCTION  0.00000      KG/HR
   UTILITIES CO2E PRODUCTION    0.00000      KG/HR
   TOTAL CO2E PRODUCTION        0.00000      KG/HR

                      ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE              C                    69.7000
  SPECIFIED PRESSURE                 BAR                  46.7000
  MAXIMUM NO. ITERATIONS                                  30
  CONVERGENCE TOLERANCE                                   0.000100000

                       ***  RESULTS  ***
  OUTLET TEMPERATURE    C                          69.700
  OUTLET PRESSURE       BAR                        46.700
  HEAT DUTY             CAL/SEC                    -0.35363E+07
  OUTLET VAPOR FRACTION                            1.0000

  V-L PHASE EQUILIBRIUM :

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

BLOCK:  B21      MODEL: HEATER
------------------------------
  INLET STREAM:          S19
  OUTLET STREAM:         S20
  PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                               IN            OUT        RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )          96237.4        96237.4        0.00000
```

```
    MASS(KG/HR   )            385200.         385200.         0.00000
    ENTHALPY(CAL/SEC )       0.124902E+08    0.635935E+07    0.490851

               ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000     KG/HR
  UTILITIES CO2E PRODUCTION     0.00000     KG/HR
  TOTAL CO2E PRODUCTION         0.00000     KG/HR

                   ***  INPUT DATA  ***
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE              C                    69.7000
 SPECIFIED PRESSURE                BAR                   61.1000
 MAXIMUM NO. ITERATIONS                                    30
 CONVERGENCE TOLERANCE                                    0.000100000

                    ***  RESULTS  ***
 OUTLET TEMPERATURE    C                          69.700
 OUTLET PRESSURE       BAR                        61.100
 HEAT DUTY             CAL/SEC                  -0.61308E+07
 OUTLET VAPOR FRACTION                            1.0000

 V-L PHASE EQUILIBRIUM :

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

BLOCK:  B22      MODEL: HEATER
------------------------------
 INLET STREAM:          S23
 OUTLET STREAM:         S24
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                            IN             OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )            96237.4         96237.4         0.00000
    MASS(KG/HR   )            385200.         385200.         0.00000
    ENTHALPY(CAL/SEC )       0.211104E+08     842917.       0.960071

               ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000     KG/HR
  UTILITIES CO2E PRODUCTION     0.00000     KG/HR
  TOTAL CO2E PRODUCTION         0.00000     KG/HR

                   ***  INPUT DATA  ***
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE              C                    30.0000
 SPECIFIED PRESSURE                BAR                   27.1000
 MAXIMUM NO. ITERATIONS                                    30
 CONVERGENCE TOLERANCE                                    0.000100000
```

```
                    ***  RESULTS  ***
 OUTLET TEMPERATURE    C                               30.000
 OUTLET PRESSURE       BAR                             27.100
 HEAT DUTY             CAL/SEC                     -0.20268E+08
 OUTLET VAPOR FRACTION                                  1.0000

 V-L PHASE EQUILIBRIUM :

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

BLOCK:  COM1     MODEL: COMPR
-----------------------------
 INLET STREAM:         S24
 OUTLET STREAM:        S21
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                             IN              OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )          96237.4         96237.4         0.00000
    MASS(KG/HR   )          385200.         385200.         0.00000
    ENTHALPY(CAL/SEC )      842917.      0.707679E+07   -0.880890

                ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION    0.00000      KG/HR
  TOTAL CO2E PRODUCTION        0.00000      KG/HR

                    ***  INPUT DATA  ***

 ISENTROPIC CENTRIFUGAL COMPRESSOR
  POWER SUPPLIED  KW                           26,100.0
  ISENTROPIC EFFICIENCY                            0.70000
  MECHANICAL EFFICIENCY                            1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW              26,100.0
  BRAKE      HORSEPOWER REQUIREMENT  KW              26,100.0
  NET WORK REQUIRED                  KW              26,100.0
  POWER LOSSES                       KW                   0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW              18,270.0
  CALCULATED OUTLET PRES  BAR                          34.9352
  CALCULATED OUTLET TEMP  C                            76.4994
  ISENTROPIC TEMPERATURE  C                            62.4278
  EFFICIENCY (POLYTR/ISENTR) USED                       0.70000
  OUTLET VAPOR FRACTION                                 1.00000
  HEAD DEVELOPED,       M-KGF/KG                     17,411.4
  MECHANICAL EFFICIENCY USED                            1.00000
  INLET HEAT CAPACITY RATIO                             1.67042
  INLET VOLUMETRIC FLOW RATE , L/MIN                1,511,420.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN                1,354,770.
```

```
  INLET  COMPRESSIBILITY FACTOR                          1.01316
  OUTLET COMPRESSIBILITY FACTOR                          1.01502
  AV. ISENT. VOL. EXPONENT                          1.69361
  AV. ISENT. TEMP EXPONENT                          1.66712
  AV. ACTUAL VOL. EXPONENT                            2.32094
  AV. ACTUAL TEMP EXPONENT                            2.28263

BLOCK:  COM2     MODEL: COMPR
----------------------------
 INLET STREAM:          S22
 OUTLET STREAM:         S11
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                         IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )           96237.4         96237.4         0.00000
    MASS(KG/HR   )           385200.         385200.         0.00000
    ENTHALPY(CAL/SEC )       0.355869E+07    0.979256E+07    -0.636593

                ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

 ISENTROPIC CENTRIFUGAL COMPRESSOR
  POWER SUPPLIED  KW                           26,100.0
  ISENTROPIC EFFICIENCY                            0.70000
  MECHANICAL EFFICIENCY                              1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW              26,100.0
  BRAKE      HORSEPOWER REQUIREMENT  KW              26,100.0
  NET WORK REQUIRED                  KW              26,100.0
  POWER LOSSES                       KW                 0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW              18,270.0
  CALCULATED OUTLET PRES  BAR                         45.0487
  CALCULATED OUTLET TEMP  C                           96.3900
  ISENTROPIC TEMPERATURE  C                           82.3209
  EFFICIENCY (POLYTR/ISENTR) USED                      0.70000
  OUTLET VAPOR FRACTION                              1.00000
  HEAD DEVELOPED,       M-KGF/KG                    17,411.4
  MECHANICAL EFFICIENCY USED                           1.00000
  INLET HEAT CAPACITY RATIO                          1.67079
  INLET VOLUMETRIC FLOW RATE , L/MIN               1,233,800.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN               1,114,190.
  INLET  COMPRESSIBILITY FACTOR                      1.01636
  OUTLET COMPRESSIBILITY FACTOR                        1.01850
  AV. ISENT. VOL. EXPONENT                          1.69977
  AV. ISENT. TEMP EXPONENT                          1.66716
  AV. ACTUAL VOL. EXPONENT                            2.33613
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   AV. ACTUAL TEMP EXPONENT                           2.28898

BLOCK:  COM3     MODEL: COMPR
-----------------------------
  INLET STREAM:          S18
  OUTLET STREAM:         S19
  PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                              IN             OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )           96237.4         96237.4         0.00000
      MASS(KG/HR   )           385200.         385200.         0.00000
      ENTHALPY(CAL/SEC )      0.625629E+07    0.124902E+08   -0.499103

                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            0.00000      KG/HR
   PRODUCT STREAMS CO2E         0.00000      KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                       ***  INPUT DATA  ***

  ISENTROPIC CENTRIFUGAL COMPRESSOR
   POWER SUPPLIED  KW                          26,100.0
   ISENTROPIC EFFICIENCY                           0.70000
   MECHANICAL EFFICIENCY                           1.00000

                       ***  RESULTS  ***

   INDICATED  HORSEPOWER REQUIREMENT  KW              26,100.0
   BRAKE      HORSEPOWER REQUIREMENT  KW              26,100.0
   NET WORK REQUIRED                  KW              26,100.0
   POWER LOSSES                       KW                   0.0
   ISENTROPIC HORSEPOWER REQUIREMENT  KW              18,270.0
   CALCULATED OUTLET PRES  BAR                        58.4365
   CALCULATED OUTLET TEMP  C                          115.949
   ISENTROPIC TEMPERATURE  C                          101.883
   EFFICIENCY (POLYTR/ISENTR) USED                    0.70000
   OUTLET VAPOR FRACTION                              1.00000
   HEAD DEVELOPED,       M-KGF/KG                  17,411.4
   MECHANICAL EFFICIENCY USED                         1.00000
   INLET HEAT CAPACITY RATIO                          1.67123
   INLET VOLUMETRIC FLOW RATE , L/MIN               999,142.
   OUTLET VOLUMETRIC FLOW RATE, L/MIN               908,390.
   INLET  COMPRESSIBILITY FACTOR                      1.02052
   OUTLET COMPRESSIBILITY FACTOR                      1.02300
   AV. ISENT. VOL. EXPONENT                           1.70773
   AV. ISENT. TEMP EXPONENT                           1.66720
   AV. ACTUAL VOL. EXPONENT                           2.35442
   AV. ACTUAL TEMP EXPONENT                           2.29580

BLOCK:  COM4     MODEL: COMPR
-----------------------------
  INLET STREAM:          S20
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 OUTLET STREAM:         COLDIN
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                          IN             OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )          96237.4        96237.4        0.00000
    MASS(KG/HR   )          385200.        385200.        0.00000
    ENTHALPY(CAL/SEC )      0.635935E+07    0.136027E+08   -0.532492

               ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E           0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                   ***  INPUT DATA  ***

 ISENTROPIC CENTRIFUGAL COMPRESSOR
  OUTLET PRESSURE  BAR                             79.0000
  ISENTROPIC EFFICIENCY                            0.70000
  MECHANICAL EFFICIENCY                              1.00000

                   ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW             30,326.3
  BRAKE      HORSEPOWER REQUIREMENT  KW             30,326.3
  NET WORK REQUIRED                 KW              30,326.3
  POWER LOSSES                      KW                 0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW             21,228.4
  CALCULATED OUTLET TEMP  C                          123.168
  ISENTROPIC TEMPERATURE  C                          106.831
  EFFICIENCY (POLYTR/ISENTR) USED                      0.70000
  OUTLET VAPOR FRACTION                              1.00000
  HEAD DEVELOPED,       M-KGF/KG                    20,230.8
  MECHANICAL EFFICIENCY USED                          1.00000
  INLET HEAT CAPACITY RATIO                          1.67211
  INLET VOLUMETRIC FLOW RATE , L/MIN                  768,497.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN                  689,584.
  INLET  COMPRESSIBILITY FACTOR                       1.02697
  OUTLET COMPRESSIBILITY FACTOR                       1.03074
  AV. ISENT. VOL. EXPONENT                          1.72122
  AV. ISENT. TEMP EXPONENT                          1.66726
  AV. ACTUAL VOL. EXPONENT                           2.37140
  AV. ACTUAL TEMP EXPONENT                           2.29384

BLOCK:  T1      MODEL: COMPR
-----------------------------
 INLET STREAM:          2
 OUTLET STREAM:         S6
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

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

```
    MOLE(KMOL/HR )          96237.4        96237.4        0.00000
    MASS(KG/HR   )          385200.        385200.        0.00000
    ENTHALPY(CAL/SEC )      0.105859E+09   0.932480E+08   0.119131

               ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION  0.00000      KG/HR
  UTILITIES CO2E PRODUCTION    0.00000      KG/HR
  TOTAL CO2E PRODUCTION        0.00000      KG/HR

                    ***  INPUT DATA  ***

 ISENTROPIC TURBINE
  POWER SUPPLIED  KW                         52,800.0
  ISENTROPIC EFFICIENCY                          0.90000
  MECHANICAL EFFICIENCY                          1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW            -52,800.0
  BRAKE      HORSEPOWER REQUIREMENT  KW            -52,800.0
  NET WORK REQUIRED                 KW            -52,800.0
  POWER LOSSES                      KW                 0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW            -58,666.7
  CALCULATED OUTLET PRES  BAR                        61.4283
  CALCULATED OUTLET TEMP  C                          723.796
  ISENTROPIC TEMPERATURE  C                          713.242
  EFFICIENCY (POLYTR/ISENTR) USED                     0.90000
  OUTLET VAPOR FRACTION                              1.00000
  HEAD DEVELOPED,       M-KGF/KG                  -55,909.7
  MECHANICAL EFFICIENCY USED                          1.00000
  INLET HEAT CAPACITY RATIO                          1.66855
  INLET VOLUMETRIC FLOW RATE , L/MIN               1,863,320.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN               2,186,130.
  INLET  COMPRESSIBILITY FACTOR                       1.01190
  OUTLET COMPRESSIBILITY FACTOR                       1.01007
  AV. ISENT. VOL. EXPONENT                           1.68585
  AV. ISENT. TEMP EXPONENT                           1.66680
  AV. ACTUAL VOL. EXPONENT                           1.57462
  AV. ACTUAL TEMP EXPONENT                           1.55701

BLOCK:  T2      MODEL: COMPR
-----------------------------
 INLET STREAM:         S6
 OUTLET STREAM:        S7
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                             IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )          96237.4        96237.4        0.00000
    MASS(KG/HR   )          385200.        385200.        0.00000
    ENTHALPY(CAL/SEC )      0.932480E+08   0.806369E+08   0.135242

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

```
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION        0.00000      KG/HR

                  ***  INPUT DATA  ***

 ISENTROPIC TURBINE
  POWER SUPPLIED  KW                          52,800.0
  ISENTROPIC EFFICIENCY                            0.90000
  MECHANICAL EFFICIENCY                             1.00000

                  ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW             -52,800.0
  BRAKE      HORSEPOWER REQUIREMENT  KW             -52,800.0
  NET WORK REQUIRED                  KW             -52,800.0
  POWER LOSSES                   KW                  0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW             -58,666.7
  CALCULATED OUTLET PRES  BAR                          46.5595
  CALCULATED OUTLET TEMP  C                          629.727
  ISENTROPIC TEMPERATURE  C                          619.173
  EFFICIENCY (POLYTR/ISENTR) USED                       0.90000
  OUTLET VAPOR FRACTION                              1.00000
  HEAD DEVELOPED,       M-KGF/KG                  -55,909.7
  MECHANICAL EFFICIENCY USED                          1.00000
  INLET HEAT CAPACITY RATIO                          1.66849
  INLET VOLUMETRIC FLOW RATE , L/MIN              2,186,130.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN               2,607,740.
  INLET  COMPRESSIBILITY FACTOR                       1.01007
  OUTLET COMPRESSIBILITY FACTOR                        1.00838
  AV. ISENT. VOL. EXPONENT                         1.68283
  AV. ISENT. TEMP EXPONENT                         1.66679
  AV. ACTUAL VOL. EXPONENT                           1.57151
  AV. ACTUAL TEMP EXPONENT                            1.55670

BLOCK:  T3       MODEL: COMPR
-----------------------------
 INLET STREAM:          S7
 OUTLET STREAM:         HOTIN
 PROPERTY OPTION SET:   PENG-ROB  STANDARD PR EQUATION OF STATE

               ***  MASS AND ENERGY BALANCE  ***
                           IN             OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )           96237.4         96237.4         0.00000
    MASS(KG/HR   )          385200.        385200.         0.00000
    ENTHALPY(CAL/SEC )       0.806369E+08    0.512588E+08    0.364325

               ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.00000      KG/HR
  PRODUCT STREAMS CO2E         0.00000      KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION        0.00000      KG/HR
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                   ***  INPUT DATA  ***

 ISENTROPIC TURBINE
  POWER SUPPLIED  KW                        123,000.
  ISENTROPIC EFFICIENCY                         0.90000
  MECHANICAL EFFICIENCY                         1.00000

                   ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW            -123,000.
  BRAKE      HORSEPOWER REQUIREMENT  KW            -123,000.
  NET WORK REQUIRED                 KW           -123,000.
  POWER LOSSES                      KW                  0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW            -136,667.
  CALCULATED OUTLET PRES  BAR                         21.1553
  CALCULATED OUTLET TEMP  C                          409.974
  ISENTROPIC TEMPERATURE  C                          385.385
  EFFICIENCY (POLYTR/ISENTR) USED                     0.90000
  OUTLET VAPOR FRACTION                               1.00000
  HEAD DEVELOPED,       M-KGF/KG                   -130,244.
  MECHANICAL EFFICIENCY USED                          1.00000
  INLET HEAT CAPACITY RATIO                           1.66843
  INLET VOLUMETRIC FLOW RATE , L/MIN               2,607,740.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN               4,327,520.
  INLET  COMPRESSIBILITY FACTOR                       1.00838
  OUTLET COMPRESSIBILITY FACTOR                       1.00494
  AV. ISENT. VOL. EXPONENT                            1.67831
  AV. ISENT. TEMP EXPONENT                            1.66678
  AV. ACTUAL VOL. EXPONENT                            1.55740
  AV. ACTUAL TEMP EXPONENT                            1.54695
```

D.2 S-CO_2 Process

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 BLOCK:  H1       MODEL: MHEATX
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  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               HOT              S6

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               COLDIN           COLDOUT

  PROPERTIES FOR STREAM COLDIN
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM HOT
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                            IN           OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )         147240.       147240.       0.00000
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```
     MASS(KG/HR   )           0.648000E+07    0.648000E+07     0.00000
     ENTHALPY(CAL/SEC )      -0.352581E+10   -0.352581E+10    0.135242E-15

               ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E           0.648000E+07  KG/HR
   PRODUCT STREAMS CO2E         0.648000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM COLDIN  :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE              C                    710.000
  PRESSURE DROP                      BAR                  0.0
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                       0.000100000

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

                    ***  RESULTS  ***

 INLET              OUTLET      OUTLET      OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C          BAR

 COLDIN    0.31628E+08    710.00      80.000        1.0000
 HOT       -0.31628E+08    725.87      77.300        1.0000


            ---------------------------------
            |                               |
 COLDIN     |                               | COLDOUT
   --------->|   98160.     KMOL/HR         |--------->
    620.40  |                               |  710.00
            |                               |
     S6     |                               | HOT
   <---------|  49080.     KMOL/HR          |<---------
    725.87  |                               |  900.00
            |                               |
            ---------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                          -.31628E+08 CAL/SEC
 UA                           0.21978E+06 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)           143.90     C
 MIN TEMP APPROACH               105.46     C
 HOT-SIDE TEMP APPROACH           190.00     C
 COLD-SIDE TEMP APPROACH           105.46     C
 HOT-SIDE NTU                   1.2101
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 COLD-SIDE NTU                  0.62263

 DUTY        T HOT    T COLD   DELTA T   LMTD    UA ZONE     Q ZONE     UA         PINCH  STREAM
IN/OUT/DEW/
                                                            POINT  BUBBLE POINT
 CAL/SEC       C        C        C        C    CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000       900.00   710.00   190.00
 0.5271E+07   871.34   695.19   176.15   182.99  0.2881E+05  0.5271E+07  0.2881E+05
 0.1054E+08   842.54   680.33   162.22   169.09  0.3117E+05  0.5271E+07  0.5998E+05
 0.1581E+08   813.61   665.42   148.19   155.10  0.3399E+05  0.5271E+07  0.9397E+05
 0.2109E+08   784.52   650.46   134.06   141.00  0.3738E+05  0.5271E+07  0.1314E+06
 0.2636E+08   755.28   635.46   119.82   126.80  0.4157E+05  0.5271E+07  0.1729E+06
 0.3163E+08   725.86   620.40   105.46   112.49  0.4686E+05  0.5271E+07  0.2198E+06  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H1       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               HOT              S6

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               COLDIN           COLDOUT

  PROPERTIES FOR STREAM COLDIN
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM HOT
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )            147240.         147240.         0.00000
     MASS(KG/HR   )          0.648000E+07    0.648000E+07     0.00000
     ENTHALPY(CAL/SEC )      -0.352581E+10   -0.352581E+10    0.135242E-15

                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            0.648000E+07  KG/HR
   PRODUCT STREAMS CO2E         0.648000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                     ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM COLDIN  :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE                C                     710.000
  PRESSURE DROP                        BAR                   0.0
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                      0.000100000
```

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

                    ***  RESULTS  ***

 INLET                OUTLET      OUTLET      OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C           BAR

 COLDIN     0.31628E+08    710.00      80.000         1.0000
 HOT       -0.31628E+08    725.87      77.300         1.0000

               --------------------------------
               |                              |
 COLDIN  |                              | COLDOUT
   --------->|  98160.     KMOL/HR    |--------->
     620.40 |                              |  710.00
               |                              |
      S6      |                              | HOT
   <---------|   49080.    KMOL/HR     |<---------
     725.87 |                              |  900.00
               |                              |
               ---------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                          -.31628E+08 CAL/SEC
 UA                          0.21978E+06 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)           143.90     C
 MIN TEMP APPROACH                105.46     C
 HOT-SIDE TEMP APPROACH           190.00     C
 COLD-SIDE TEMP APPROACH          105.46     C
 HOT-SIDE NTU                  1.2101
 COLD-SIDE NTU                 0.62263

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                          POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000       900.00    710.00    190.00
 0.5271E+07    871.34    695.19    176.15    182.99  0.2881E+05  0.5271E+07  0.2881E+05
 0.1054E+08    842.54    680.33    162.22    169.09  0.3117E+05  0.5271E+07  0.5998E+05
 0.1581E+08    813.61    665.42    148.19    155.10  0.3399E+05  0.5271E+07  0.9397E+05
 0.2109E+08    784.52    650.46    134.06    141.00  0.3738E+05  0.5271E+07  0.1314E+06
 0.2636E+08    755.28    635.46    119.82    126.80  0.4157E+05  0.5271E+07  0.1729E+06
 0.3163E+08    725.86    620.40    105.46    112.49  0.4686E+05  0.5271E+07  0.2198E+06  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

 BLOCK:  H2       MODEL: MHEATX
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  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               S6               RCTR1

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               S5               3

  PROPERTIES FOR STREAM S5
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM S6
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                             IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )            147240.         147240.         0.00000
     MASS(KG/HR   )          0.648000E+07    0.648000E+07     0.00000
     ENTHALPY(CAL/SEC )      -0.354763E+10   -0.354763E+10     0.00000

                 ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E           0.648000E+07  KG/HR
   PRODUCT STREAMS CO2E        0.648000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                   ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM S5      :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE              C                    660.000
  PRESSURE DROP                    BAR                   0.0
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                       0.000100000

  SPECIFICATIONS FOR STREAM S6      :
  TWO    PHASE      FLASH
  PRESSURE DROP                    BAR                   0.0
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                       0.000100000

                   ***  RESULTS  ***

 INLET               OUTLET       OUTLET       OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C           BAR

 S5        0.44620E+07    660.00      55.000        1.0000
 S6       -0.44620E+07    700.83      77.300        1.0000

           --------------------------------
           |                              |
```

```
   S5      |                              | 3
 --------->|    98160.    KMOL/HR         |--------->
  647.26 |                                |   660.00
         |                                |
 RCTR1 |                                  | S6
 <---------|   49080.    KMOL/HR          |<---------
 700.83 |                                 |   725.87
         |                                |
          ------------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                        -.44620E+07 CAL/SEC
 UA                         74978.     CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)           59.511     C
 MIN TEMP APPROACH               53.566     C
 HOT-SIDE TEMP APPROACH           65.868     C
 COLD-SIDE TEMP APPROACH          53.566     C
 HOT-SIDE NTU                  0.42067
 COLD-SIDE NTU                  0.21401

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                          POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000        725.87    660.00     65.87
 0.7437E+06    721.70    657.88     63.82     64.84  0.1147E+05  0.7437E+06  0.1147E+05
 0.1487E+07    717.53    655.76     61.78     62.79  0.1184E+05  0.7437E+06  0.2331E+05
 0.2231E+07    713.36    653.64     59.73     60.75  0.1224E+05  0.7437E+06  0.3556E+05
 0.2975E+07    709.19    651.51     57.68     58.70  0.1267E+05  0.7437E+06  0.4823E+05
 0.3718E+07    705.01    649.39     55.62     56.64  0.1313E+05  0.7437E+06  0.6135E+05
 0.4462E+07    700.83    647.26     53.57     54.59  0.1362E+05  0.7437E+06  0.7498E+05  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H2       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
             ------------     -------------
             S6               RCTR1

  COLD SIDE:   INLET STREAM     OUTLET STREAM
             ------------     -------------
             S5               3

  PROPERTIES FOR STREAM S5
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM S6
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

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

```
  TOTAL BALANCE
    MOLE(KMOL/HR )         147240.        147240.        0.00000
    MASS(KG/HR   )       0.648000E+07   0.648000E+07    0.00000
    ENTHALPY(CAL/SEC )   -0.354763E+10  -0.354763E+10    0.00000

               ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E           0.648000E+07  KG/HR
  PRODUCT STREAMS CO2E        0.648000E+07  KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000     KG/HR
  UTILITIES CO2E PRODUCTION     0.00000     KG/HR
  TOTAL CO2E PRODUCTION         0.00000     KG/HR

                  ***  INPUT DATA  ***

 SPECIFICATIONS FOR STREAM S5      :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE              C                    660.000
 PRESSURE DROP                      BAR                  0.0
 MAXIMUM NO. ITERATIONS                                   30
 CONVERGENCE TOLERANCE                                     0.000100000

 SPECIFICATIONS FOR STREAM S6      :
 TWO    PHASE      FLASH
 PRESSURE DROP                      BAR                  0.0
 MAXIMUM NO. ITERATIONS                                   30
 CONVERGENCE TOLERANCE                                     0.000100000

                  ***  RESULTS  ***

 INLET              OUTLET      OUTLET      OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
        CAL/SEC      C          BAR

 S5        0.44620E+07    660.00     55.000       1.0000
 S6       -0.44620E+07    700.83     77.300       1.0000


           ----------------------------------
           |                                |
   S5      |                                | 3
---------> |   98160.     KMOL/HR           |--------->
   647.26  |                                |   660.00
           |                                |
 RCTR1     |                                | S6
 <---------|   49080.     KMOL/HR           |<---------
   700.83  |                                |   725.87
           |                                |
           ----------------------------------

                  ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                         -.44620E+07 CAL/SEC
 UA                         74978.     CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)             59.511     C
 MIN TEMP APPROACH               53.566     C
 HOT-SIDE TEMP APPROACH            65.868     C
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```
 COLD-SIDE TEMP APPROACH          53.566     C
 HOT-SIDE NTU                  0.42067
 COLD-SIDE NTU                  0.21401

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                                POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000        725.87    660.00    65.87
 0.7437E+06    721.70    657.88    63.82     64.84  0.1147E+05  0.7437E+06  0.1147E+05
 0.1487E+07    717.53    655.76    61.78     62.79  0.1184E+05  0.7437E+06  0.2331E+05
 0.2231E+07    713.36    653.64    59.73     60.75  0.1224E+05  0.7437E+06  0.3556E+05
 0.2975E+07    709.19    651.51    57.68     58.70  0.1267E+05  0.7437E+06  0.4823E+05
 0.3718E+07    705.01    649.39    55.62     56.64  0.1313E+05  0.7437E+06  0.6135E+05
 0.4462E+07    700.83    647.26    53.57     54.59  0.1362E+05  0.7437E+06  0.7498E+05  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H3       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               RCTR1            11

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               1                2

  PROPERTIES FOR STREAM RCTR1
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM 1
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                           IN              OUT         RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )            147240.         147240.        0.00000
     MASS(KG/HR   )          0.648000E+07    0.648000E+07     0.00000
     ENTHALPY(CAL/SEC )      -0.356413E+10   -0.356413E+10     0.00000

                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            0.648000E+07  KG/HR
   PRODUCT STREAMS CO2E         0.648000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM RCTR1   :
  ONE    PHASE  TP  FLASH   SPECIFIED PHASE IS  VAPOR
  SPECIFIED TEMPERATURE               C                     615.000
  PRESSURE DROP                    BAR                   0.0
```

```
 MAXIMUM NO. ITERATIONS                        30
 CONVERGENCE TOLERANCE                          0.000100000

 SPECIFICATIONS FOR STREAM 1       :
 THREE  PHASE      FLASH
 PRESSURE DROP                BAR            0.0
 MAXIMUM NO. ITERATIONS                        30
 CONVERGENCE TOLERANCE                          0.000100000

                *** RESULTS ***

INLET               OUTLET      OUTLET      OUTLET
STREAM    DUTY       TEMPERATURE  PRESSURE     VAPOR FRAC  BETA
        CAL/SEC      C           BAR

RCTR1     -0.15116E+08    615.00      77.300        1.0000
1         0.15116E+08    655.44      40.820        1.0000      1.0000


          ---------------------------------
          |                               |
RCTR1     |                               | 11
--------->|   49080.     KMOL/HR          |--------->
  700.83  |                               |   615.00
          |                               |
    2     |                               | 1
<---------|   98160.     KMOL/HR          |<---------
  655.44  |                               |   611.96
          |                               |
          ----------------------------------

                *** INTERNAL ANALYSIS ***

FLOW IS COUNTERCURRENT.
DUTY                       0.15116E+08 CAL/SEC
UA                       0.95952E+06 CAL/SEC-K
AVERAGE LMTD (DUTY/UA)            15.754     C
MIN TEMP APPROACH                 3.0444     C
HOT-SIDE TEMP APPROACH            45.389     C
COLD-SIDE TEMP APPROACH           3.0444     C
HOT-SIDE NTU                    5.4483
COLD-SIDE NTU                   2.7605

DUTY        T HOT    T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                          POINT  BUBBLE POINT
CAL/SEC       C        C        C        C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

 0.000       615.00    611.96      3.04                                      GBL
0.2519E+07    629.42    619.24     10.18      5.91  0.4261E+06  0.2519E+07  0.4261E+06
0.5039E+07    643.79    626.51     17.29     13.42  0.1877E+06  0.2519E+07  0.6138E+06
0.7558E+07    658.12    633.76     24.36     20.62  0.1222E+06  0.2519E+07  0.7360E+06
0.1008E+08    672.40    641.00     31.40     27.73  0.9085E+05  0.2519E+07  0.8268E+06
0.1260E+08    686.64    648.23     38.41     34.79  0.7243E+05  0.2519E+07  0.8992E+06
0.1512E+08    700.83    655.44     45.39     41.80  0.6027E+05  0.2519E+07  0.9595E+06
```

```
 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H3       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               RCTR1            11

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               1                2

  PROPERTIES FOR STREAM RCTR1
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM 1
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                               IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )           147240.         147240.         0.00000
      MASS(KG/HR   )          0.648000E+07    0.648000E+07     0.00000
      ENTHALPY(CAL/SEC )      -0.356413E+10   -0.356413E+10    0.00000

                    ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            0.648000E+07  KG/HR
   PRODUCT STREAMS CO2E         0.648000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                        ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM RCTR1   :
  ONE    PHASE  TP  FLASH   SPECIFIED PHASE IS  VAPOR
  SPECIFIED TEMPERATURE                C                     615.000
  PRESSURE DROP                   BAR                   0.0
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                        0.000100000

  SPECIFICATIONS FOR STREAM 1       :
  THREE  PHASE      FLASH
  PRESSURE DROP                   BAR                   0.0
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                        0.000100000

                        ***  RESULTS  ***

 INLET                  OUTLET       OUTLET       OUTLET
 STREAM     DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC  BETA
          CAL/SEC      C            BAR

 RCTR1     -0.15116E+08    615.00       77.300         1.0000
```

```
 1         0.15116E+08    655.44      40.820        1.0000      1.0000

           --------------------------------
           |                              |
 RCTR1 |                              | 11
--------->|   49080.     KMOL/HR     |--------->
  700.83 |                              |   615.00
           |                              |
    2      |                              | 1
 <---------|   98160.     KMOL/HR     |<---------
  655.44 |                              |   611.96
           |                              |
           --------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                          0.15116E+08 CAL/SEC
 UA                            0.95952E+06 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)            15.754     C
 MIN TEMP APPROACH                 3.0444     C
 HOT-SIDE TEMP APPROACH            45.389     C
 COLD-SIDE TEMP APPROACH           3.0444     C
 HOT-SIDE NTU                  5.4483
 COLD-SIDE NTU                 2.7605

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                                           POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000       615.00    611.96      3.04                                        GBL
 0.2519E+07    629.42    619.24     10.18      5.91  0.4261E+06  0.2519E+07  0.4261E+06
 0.5039E+07    643.79    626.51     17.29     13.42  0.1877E+06  0.2519E+07  0.6138E+06
 0.7558E+07    658.12    633.76     24.36     20.62  0.1222E+06  0.2519E+07  0.7360E+06
 0.1008E+08    672.40    641.00     31.40     27.73  0.9085E+05  0.2519E+07  0.8268E+06
 0.1260E+08    686.64    648.23     38.41     34.79  0.7243E+05  0.2519E+07  0.8992E+06
 0.1512E+08    700.83    655.44     45.39     41.80  0.6027E+05  0.2519E+07  0.9595E+06

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H4       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               2                S8

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               COLD             COLDIN

  PROPERTIES FOR STREAM COLD
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM 2
```

```
 PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                              IN              OUT         RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )            196320.         196320.         0.00000
    MASS(KG/HR   )          0.864000E+07    0.864000E+07     0.00000
    ENTHALPY(CAL/SEC )      -0.493891E+10   -0.493891E+10     0.00000

                 ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.864000E+07  KG/HR
  PRODUCT STREAMS CO2E         0.864000E+07  KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                   ***  INPUT DATA  ***

 SPECIFICATIONS FOR STREAM COLD    :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE              C                    620.400
 PRESSURE DROP                      BAR                  0.0
 MAXIMUM NO. ITERATIONS                                    30
 CONVERGENCE TOLERANCE                                      0.000100000

 SPECIFICATIONS FOR STREAM 2       :
 TWO    PHASE      FLASH
 PRESSURE DROP                      BAR                  0.0
 MAXIMUM NO. ITERATIONS                                    30
 CONVERGENCE TOLERANCE                                      0.000100000

                   ***  RESULTS  ***

INLET                OUTLET       OUTLET       OUTLET
STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C           BAR

COLD       0.18367E+09    620.40      80.000        1.0000
2        -0.18367E+09     88.47      40.820        1.0000


              ------------------------------------
              |                                  |
COLD     |                                  | COLDIN
 --------->|      98160.     KMOL/HR      |--------->
    80.14 |                                  |  620.40
              |                                  |
   S8       |                                  | 2
 <---------|   98160.     KMOL/HR        |<---------
    88.47 |                                  |  655.44
              |                                  |
              -------------------------------------

                   ***  INTERNAL ANALYSIS  ***

FLOW IS COUNTERCURRENT.
DUTY                          -.18367E+09 CAL/SEC
```

```
 UA                          0.67011E+07 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)           27.409     C
 MIN TEMP APPROACH              8.3237     C
 HOT-SIDE TEMP APPROACH           35.044     C
 COLD-SIDE TEMP APPROACH          8.3237     C
 HOT-SIDE NTU                   20.686
 COLD-SIDE NTU                   19.711

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                              POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000       655.44    620.40    35.04
 0.3061E+08    566.86    531.88     34.97     35.01  0.8744E+06  0.3061E+08  0.8744E+06
 0.6122E+08    476.02    441.40     34.63     34.80  0.8797E+06  0.3061E+08  0.1754E+07
 0.9184E+08    382.58    348.92     33.66     34.14  0.8966E+06  0.3061E+08  0.2651E+07
 0.1224E+09    286.25    255.02     31.23     32.43  0.9439E+06  0.3061E+08  0.3595E+07
 0.1531E+09    187.32    162.24     25.08     28.04  0.1092E+07  0.3061E+08  0.4686E+07
 0.1837E+09     88.47     80.14      8.32     15.19  0.2015E+07  0.3061E+08  0.6701E+07  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H4       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
             ------------     -------------
             2               S8

  COLD SIDE:   INLET STREAM     OUTLET STREAM
             ------------     -------------
             COLD            COLDIN

  PROPERTIES FOR STREAM COLD
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM 2
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                              IN             OUT        RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )           196320.         196320.         0.00000
     MASS(KG/HR   )          0.864000E+07    0.864000E+07     0.00000
     ENTHALPY(CAL/SEC )      -0.493891E+10   -0.493891E+10     0.00000

                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E           0.864000E+07  KG/HR
   PRODUCT STREAMS CO2E         0.864000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                     ***  INPUT DATA  ***
```

```
 SPECIFICATIONS FOR STREAM COLD    :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE              C                    620.400
 PRESSURE DROP                      BAR                  0.0
 MAXIMUM NO. ITERATIONS                                     30
 CONVERGENCE TOLERANCE                                        0.000100000

 SPECIFICATIONS FOR STREAM 2       :
 TWO    PHASE      FLASH
 PRESSURE DROP                      BAR                  0.0
 MAXIMUM NO. ITERATIONS                                     30
 CONVERGENCE TOLERANCE                                        0.000100000

                    ***  RESULTS  ***

 INLET                 OUTLET      OUTLET      OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC     C          BAR

 COLD      0.18367E+09    620.40      80.000        1.0000
 2        -0.18367E+09     88.47      40.820        1.0000


           ---------------------------------
           |                               |
 COLD      |                               | COLDIN
 --------->|   98160.     KMOL/HR          |--------->
    80.14  |                               |   620.40
           |                               |
   S8      |                               | 2
 <---------|   98160.     KMOL/HR          |<---------
   88.47   |                               |   655.44
           |                               |
           ----------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                          -.18367E+09 CAL/SEC
 UA                           0.67011E+07 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)            27.409     C
 MIN TEMP APPROACH                8.3237     C
 HOT-SIDE TEMP APPROACH           35.044     C
 COLD-SIDE TEMP APPROACH          8.3237     C
 HOT-SIDE NTU                   20.686
 COLD-SIDE NTU                   19.711

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                               POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K


  0.000        655.44    620.40     35.04
 0.3061E+08    566.86    531.88     34.97      35.01  0.8744E+06  0.3061E+08  0.8744E+06
 0.6122E+08    476.02    441.40     34.63      34.80  0.8797E+06  0.3061E+08  0.1754E+07
 0.9184E+08    382.58    348.92     33.66      34.14  0.8966E+06  0.3061E+08  0.2651E+07
 0.1224E+09    286.25    255.02     31.23      32.43  0.9439E+06  0.3061E+08  0.3595E+07
```

```
 0.1531E+09    187.32    162.24     25.08     28.04  0.1092E+07  0.3061E+08  0.4686E+07
 0.1837E+09     88.47     80.14      8.32     15.19  0.2015E+07  0.3061E+08  0.6701E+07  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H5       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               S8               4

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               WATERIN          WATEROUT

  PROPERTIES FOR STREAM S8
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM WATERIN
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                 IN              OUT        RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )            397906.          397906.          0.00000
     MASS(KG/HR   )          0.972000E+07    0.972000E+07     0.00000
     ENTHALPY(CAL/SEC )      -0.830262E+10   -0.830262E+10     0.00000

                    ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            0.432000E+07  KG/HR
   PRODUCT STREAMS CO2E         0.432000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                       ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM S8      :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE               C                      28.0000
  PRESSURE DROP                  BAR                    0.0
  MAXIMUM NO. ITERATIONS                                 30
  CONVERGENCE TOLERANCE                                    0.000100000

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

                       ***  RESULTS  ***

 INLET                OUTLET       OUTLET       OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
          CAL/SEC      C            BAR
```

```
 S8        -0.20972E+08     28.00      40.820        1.0000
 WATERIN    0.20972E+08     38.04      29.000         0.0000

                  ------------------------------------
                  |                                  |
         S8       |                                  | 4
       --------->|    98160.     KMOL/HR       |--------->
         88.47 |                                  |   28.00
                  |                                  |
 WATEROUT |                                  | WATERIN
       <---------|  0.29975E+06 KMOL/HR   |<---------
         38.04 |                                  |   27.00
                  |                                  |
                  ------------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                            0.20972E+08 CAL/SEC
 UA                            0.17977E+07 CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)            11.666     C
 MIN TEMP APPROACH                1.0000     C
 HOT-SIDE TEMP APPROACH            50.431     C
 COLD-SIDE TEMP APPROACH           1.0000     C
 HOT-SIDE NTU                    5.1832
 COLD-SIDE NTU                    0.94609

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                                 POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000        28.00     27.00     1.00                                        GBL
 0.3495E+07     37.02     28.84      8.17      3.41  0.1024E+07  0.3495E+07  0.1024E+07
 0.6991E+07     46.59     30.69     15.90     11.61  0.3010E+06  0.3495E+07  0.1325E+07
 0.1049E+08     56.61     32.53     24.08     19.71  0.1773E+06  0.3495E+07  0.1502E+07
 0.1398E+08     66.97     34.37     32.61     28.13  0.1243E+06  0.3495E+07  0.1626E+07
 0.1748E+08     77.61     36.20     41.41     36.83  0.9490E+05  0.3495E+07  0.1721E+07
 0.2097E+08     88.47     38.04     50.43     45.77  0.7636E+05  0.3495E+07  0.1798E+07

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H5       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
             ------------     -------------
             S8             4

  COLD SIDE:   INLET STREAM     OUTLET STREAM
             ------------     -------------
             WATERIN         WATEROUT

  PROPERTIES FOR STREAM S8
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE
```

```
 PROPERTIES FOR STREAM WATERIN
 PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                 ***  MASS AND ENERGY BALANCE  ***
                              IN              OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )            397906.          397906.         0.00000
    MASS(KG/HR   )          0.972000E+07    0.972000E+07     0.00000
    ENTHALPY(CAL/SEC )      -0.830262E+10   -0.830262E+10     0.00000

                 ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E           0.432000E+07  KG/HR
  PRODUCT STREAMS CO2E         0.432000E+07  KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

 SPECIFICATIONS FOR STREAM S8      :
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE               C                      28.0000
 PRESSURE DROP                    BAR                   0.0
 MAXIMUM NO. ITERATIONS                                  30
 CONVERGENCE TOLERANCE                                     0.000100000

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

                    ***  RESULTS  ***

INLET                OUTLET       OUTLET       OUTLET
STREAM    DUTY         TEMPERATURE  PRESSURE     VAPOR FRAC
        CAL/SEC      C           BAR

S8       -0.20972E+08     28.00      40.820         1.0000
WATERIN    0.20972E+08     38.04      29.000         0.0000


                ----------------------------------
                |                                 |
        S8      |                                 | 4
      --------->|      98160.    KMOL/HR      |--------->
         88.47 |                                  |   28.00
                |                                 |
WATEROUT |                                 | WATERIN
      <---------|  0.29975E+06 KMOL/HR  |<---------
         38.04 |                                  |   27.00
                |                                 |
                ------------------------------------
```

```
                    ***  INTERNAL ANALYSIS  ***

  FLOW IS COUNTERCURRENT.
  DUTY                          0.20972E+08 CAL/SEC
  UA                          0.17977E+07 CAL/SEC-K
  AVERAGE LMTD (DUTY/UA)            11.666     C
  MIN TEMP APPROACH                1.0000     C
  HOT-SIDE TEMP APPROACH            50.431     C
  COLD-SIDE TEMP APPROACH           1.0000     C
  HOT-SIDE NTU                   5.1832
  COLD-SIDE NTU                  0.94609

  DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                                  POINT  BUBBLE POINT
  CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

   0.000        28.00     27.00     1.00                                      GBL
  0.3495E+07     37.02     28.84      8.17      3.41  0.1024E+07  0.3495E+07  0.1024E+07
  0.6991E+07     46.59     30.69     15.90     11.61  0.3010E+06  0.3495E+07  0.1325E+07
  0.1049E+08     56.61     32.53     24.08     19.71  0.1773E+06  0.3495E+07  0.1502E+07
  0.1398E+08     66.97     34.37     32.61     28.13  0.1243E+06  0.3495E+07  0.1626E+07
  0.1748E+08     77.61     36.20     41.41     36.83  0.9490E+05  0.3495E+07  0.1721E+07
  0.2097E+08     88.47     38.04     50.43     45.77  0.7636E+05  0.3495E+07  0.1798E+07

  GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

 BLOCK:  H6       MODEL: MHEATX
 ------------------------------

   HOT SIDE:    INLET STREAM     OUTLET STREAM
              ------------     -------------
              5                6

   COLD SIDE:   INLET STREAM     OUTLET STREAM
              ------------     -------------
              9                10

   PROPERTIES FOR STREAM 9
   PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

   PROPERTIES FOR STREAM 5
   PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                   ***  MASS AND ENERGY BALANCE  ***
                             IN              OUT        RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )           397906.         397906.        0.00000
       MASS(KG/HR   )          0.972000E+07    0.972000E+07     0.00000
       ENTHALPY(CAL/SEC )      -0.831801E+10   -0.831801E+10    0.229304E-15

                   ***  CO2 EQUIVALENT SUMMARY ***
    FEED STREAMS CO2E           0.432000E+07  KG/HR
    PRODUCT STREAMS CO2E         0.432000E+07  KG/HR
    NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
    UTILITIES CO2E PRODUCTION     0.00000      KG/HR
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```
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM 9       :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE              C                    28.0000
  PRESSURE DROP                    BAR                   0.0
  MAXIMUM NO. ITERATIONS                                  30
  CONVERGENCE TOLERANCE                                     0.000100000

  SPECIFICATIONS FOR STREAM 5       :
  TWO    PHASE      FLASH
  PRESSURE DROP                    BAR                   0.0
  MAXIMUM NO. ITERATIONS                                  30
  CONVERGENCE TOLERANCE                                     0.000100000

                    ***  RESULTS  ***

 INLET               OUTLET       OUTLET       OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
          CAL/SEC      C           BAR

 9         0.18946E+07     28.00      29.000        0.0000
 5        -0.18946E+07     55.20      60.000        1.0000


            -------------------------------------
            |                                   |
  9         |                                   | 10
 --------->|   0.29975E+06 KMOL/HR     |--------->
    27.00 |                                    |   28.00
            |                                    |
    6       |                                    | 5
 <---------|         98160.     KMOL/HR     |<---------
    55.20 |                                    |   59.66
            |                                    |
            --------------------------------------

                    ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                          -.18946E+07 CAL/SEC
 UA                          63399.     CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)            29.884     C
 MIN TEMP APPROACH                28.203     C
 HOT-SIDE TEMP APPROACH            31.660     C
 COLD-SIDE TEMP APPROACH           28.203     C
 HOT-SIDE NTU                   0.14915
 COLD-SIDE NTU                   0.33463E-01

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA          PINCH  STREAM
IN/OUT/DEW/
                                                              POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000        59.66     28.00     31.66
```

```
 0.3158E+06     58.91     27.83     31.07     31.36  0.1007E+05  0.3158E+06  0.1007E+05
 0.6315E+06     58.16     27.67     30.49     30.78  0.1026E+05  0.3158E+06  0.2033E+05
 0.9473E+06     57.41     27.50     29.91     30.20  0.1046E+05  0.3158E+06  0.3078E+05
 0.1263E+07     56.67     27.33     29.34     29.62  0.1066E+05  0.3158E+06  0.4144E+05
 0.1579E+07     55.93     27.17     28.77     29.05  0.1087E+05  0.3158E+06  0.5231E+05
 0.1895E+07     55.20     27.00     28.20     28.48  0.1109E+05  0.3158E+06  0.6340E+05  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  H6       MODEL: MHEATX
------------------------------

  HOT SIDE:    INLET STREAM     OUTLET STREAM
               ------------     -------------
               5                6

  COLD SIDE:   INLET STREAM     OUTLET STREAM
               ------------     -------------
               9                10

  PROPERTIES FOR STREAM 9
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

  PROPERTIES FOR STREAM 5
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                  ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT         RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )            397906.          397906.         0.00000
      MASS(KG/HR   )          0.972000E+07    0.972000E+07     0.00000
      ENTHALPY(CAL/SEC )       -0.831801E+10   -0.831801E+10    0.229304E-15

                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E           0.432000E+07  KG/HR
   PRODUCT STREAMS CO2E         0.432000E+07  KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION         0.00000      KG/HR

                      ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM 9       :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE               C                     28.0000
  PRESSURE DROP                   BAR                    0.0
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                       0.000100000

  SPECIFICATIONS FOR STREAM 5       :
  TWO    PHASE     FLASH
  PRESSURE DROP                   BAR                    0.0
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                       0.000100000

                      ***  RESULTS  ***
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```
 INLET                OUTLET      OUTLET      OUTLET
 STREAM    DUTY        TEMPERATURE  PRESSURE     VAPOR FRAC
         CAL/SEC      C           BAR

 9         0.18946E+07     28.00      29.000        0.0000
 5        -0.18946E+07     55.20      60.000        1.0000

            -------------------------------------
           |                                     |
 9         |                                     | 10
--------->|   0.29975E+06 KMOL/HR     |--------->
   27.00 |                                     |    28.00
           |                                     |
   6       |                                     | 5
<---------|   98160.     KMOL/HR          |<---------
   55.20 |                                     |    59.66
           |                                     |
           --------------------------------------

                      ***  INTERNAL ANALYSIS  ***

 FLOW IS COUNTERCURRENT.
 DUTY                          -.18946E+07 CAL/SEC
 UA                          63399.     CAL/SEC-K
 AVERAGE LMTD (DUTY/UA)           29.884     C
 MIN TEMP APPROACH               28.203     C
 HOT-SIDE TEMP APPROACH           31.660     C
 COLD-SIDE TEMP APPROACH          28.203     C
 HOT-SIDE NTU                  0.14915
 COLD-SIDE NTU                  0.33463E-01

 DUTY         T HOT     T COLD    DELTA T   LMTD    UA ZONE     Q ZONE      UA         PINCH  STREAM
IN/OUT/DEW/
                                                               POINT  BUBBLE POINT
 CAL/SEC        C         C         C         C     CAL/SEC-K   CAL/SEC     CAL/SEC-K

  0.000        59.66     28.00     31.66
 0.3158E+06     58.91     27.83     31.07     31.36  0.1007E+05  0.3158E+06  0.1007E+05
 0.6315E+06     58.16     27.67     30.49     30.78  0.1026E+05  0.3158E+06  0.2033E+05
 0.9473E+06     57.41     27.50     29.91     30.20  0.1046E+05  0.3158E+06  0.3078E+05
 0.1263E+07     56.67     27.33     29.34     29.62  0.1066E+05  0.3158E+06  0.4144E+05
 0.1579E+07     55.93     27.17     28.77     29.05  0.1087E+05  0.3158E+06  0.5231E+05
 0.1895E+07     55.20     27.00     28.20     28.48  0.1109E+05  0.3158E+06  0.6340E+05  GBL

 GBL = GLOBAL     LOC = LOCAL     DP  = DEW POINT     BP  = BUBBLE POINT

BLOCK:  B2       MODEL: COMPR
-----------------------------
  INLET STREAM:          3
  OUTLET STREAM:         1
  PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

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

```
    MOLE(KMOL/HR )          98160.0        98160.0        0.00000
    MASS(KG/HR   )        0.432000E+07    0.432000E+07     0.00000
    ENTHALPY(CAL/SEC )     -0.236980E+10   -0.238629E+10    0.691129E-02

              ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.432000E+07  KG/HR
  PRODUCT STREAMS CO2E         0.432000E+07  KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                   ***  INPUT DATA  ***

 POLYTROPIC COMPRESSOR USING ASME METHOD
  OUTLET PRESSURE  BAR                              40.8200
  POLYTROPIC EFFICIENCY                              0.90000
  MECHANICAL EFFICIENCY                              1.00000

                   ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW             -69,050.2
  BRAKE      HORSEPOWER REQUIREMENT  KW             -69,050.2
  NET WORK REQUIRED                  KW             -69,050.2
  POWER LOSSES                       KW                   0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW             -62,309.6
  CALCULATED OUTLET TEMP  C                           611.956
  EFFICIENCY (POLYTR/ISENTR) USED                     0.90000
  OUTLET VAPOR FRACTION                               1.00000
  HEAD DEVELOPED,      M-KGF/KG                     -5,280.87
  MECHANICAL EFFICIENCY USED                          1.00000
  INLET HEAT CAPACITY RATIO                           1.19628
  INLET VOLUMETRIC FLOW RATE , L/MIN               2,339,690.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN               2,976,960.
  INLET  COMPRESSIBILITY FACTOR                       1.01382
  OUTLET COMPRESSIBILITY FACTOR                       1.00935
  AV. ISENT. VOL. EXPONENT                            1.21098
  AV. ISENT. TEMP EXPONENT                            1.19004
  AV. ACTUAL VOL. EXPONENT                            1.23777
  AV. ACTUAL TEMP EXPONENT                            1.21549

BLOCK:  B5       MODEL: COMPR
------------------------------
 INLET STREAM:          4
 OUTLET STREAM:         5
 PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

              ***  MASS AND ENERGY BALANCE  ***
                           IN             OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )          98160.0        98160.0        0.00000
    MASS(KG/HR   )        0.432000E+07    0.432000E+07     0.00000
    ENTHALPY(CAL/SEC )     -0.257582E+10   -0.257024E+10   -0.216648E-02

              ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E            0.432000E+07  KG/HR
  PRODUCT STREAMS CO2E         0.432000E+07  KG/HR
```

```
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

 POLYTROPIC COMPRESSOR USING ASME METHOD
  OUTLET PRESSURE  BAR                              60.0000
  POLYTROPIC EFFICIENCY                              0.90000
  MECHANICAL EFFICIENCY                              1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW              23,364.3
  BRAKE      HORSEPOWER REQUIREMENT  KW              23,364.3
  NET WORK REQUIRED                  KW              23,364.3
  POWER LOSSES                       KW                   0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW              20,915.8
  CALCULATED OUTLET TEMP  C                          59.6597
  EFFICIENCY (POLYTR/ISENTR) USED                     0.90000
  OUTLET VAPOR FRACTION                               1.00000
  HEAD DEVELOPED,       M-KGF/KG                    1,786.87
  MECHANICAL EFFICIENCY USED                          1.00000
  INLET HEAT CAPACITY RATIO                           1.79260
  INLET VOLUMETRIC FLOW RATE , L/MIN                764,161.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN                573,253.
  INLET  COMPRESSIBILITY FACTOR                       0.76149
  OUTLET COMPRESSIBILITY FACTOR                       0.75979
  AV. ISENT. VOL. EXPONENT                            1.29255
  AV. ISENT. TEMP EXPONENT                            1.33090
  AV. ACTUAL VOL. EXPONENT                            1.33996
  AV. ACTUAL TEMP EXPONENT                            1.35049

BLOCK:  COMPR    MODEL: COMPR
-----------------------------
 INLET STREAM:          6
 OUTLET STREAM:         COLD
 PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                              IN            OUT       RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )           98160.0        98160.0        0.00000
    MASS(KG/HR   )         0.432000E+07    0.432000E+07     0.00000
    ENTHALPY(CAL/SEC )      -0.257213E+10   -0.256774E+10   -0.170839E-02

                ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E           0.432000E+07  KG/HR
  PRODUCT STREAMS CO2E        0.432000E+07  KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

 POLYTROPIC COMPRESSOR USING ASME METHOD
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  OUTLET PRESSURE  BAR                          80.0000
  POLYTROPIC EFFICIENCY                          0.90000
  MECHANICAL EFFICIENCY                          1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW             18,397.6
  BRAKE      HORSEPOWER REQUIREMENT  KW             18,397.6
  NET WORK REQUIRED                KW             18,397.6
  POWER LOSSES                 KW                  0.0
  ISENTROPIC HORSEPOWER REQUIREMENT  KW             16,493.1
  CALCULATED OUTLET TEMP  C                           80.1447
  EFFICIENCY (POLYTR/ISENTR) USED                      0.90000
  OUTLET VAPOR FRACTION                             1.00000
  HEAD DEVELOPED,       M-KGF/KG                   1,407.03
  MECHANICAL EFFICIENCY USED                          1.00000
  INLET HEAT CAPACITY RATIO                          1.85845
  INLET VOLUMETRIC FLOW RATE , L/MIN                553,730.
  OUTLET VOLUMETRIC FLOW RATE, L/MIN                 448,888.
  INLET  COMPRESSIBILITY FACTOR                       0.74387
  OUTLET COMPRESSIBILITY FACTOR                        0.74728
  AV. ISENT. VOL. EXPONENT                          1.32193
  AV. ISENT. TEMP EXPONENT                          1.32350
  AV. ACTUAL VOL. EXPONENT                           1.37054
  AV. ACTUAL TEMP EXPONENT                            1.34138

BLOCK:  TURB     MODEL: COMPR
-----------------------------
 INLET STREAM:          COLDOUT
 OUTLET STREAM:         S5
 PROPERTY OPTION SET:   LK-PLOCK  LEE-KESLER-PLOCKER EQUATION OF STATE

                ***  MASS AND ENERGY BALANCE  ***
                             IN             OUT        RELATIVE DIFF.
  TOTAL BALANCE
    MOLE(KMOL/HR )           98160.0         98160.0         0.00000
    MASS(KG/HR   )          0.432000E+07    0.432000E+07     0.00000
    ENTHALPY(CAL/SEC )      -0.235244E+10   -0.237426E+10    0.919097E-02

                ***  CO2 EQUIVALENT SUMMARY ***
  FEED STREAMS CO2E           0.432000E+07  KG/HR
  PRODUCT STREAMS CO2E         0.432000E+07  KG/HR
  NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
  UTILITIES CO2E PRODUCTION     0.00000      KG/HR
  TOTAL CO2E PRODUCTION         0.00000      KG/HR

                    ***  INPUT DATA  ***

 POLYTROPIC COMPRESSOR USING ASME METHOD
  OUTLET PRESSURE  BAR                          55.0000
  POLYTROPIC EFFICIENCY                          0.90000
  MECHANICAL EFFICIENCY                          1.00000

                    ***  RESULTS  ***

  INDICATED  HORSEPOWER REQUIREMENT  KW            -91,363.4
```

```
BRAKE      HORSEPOWER REQUIREMENT  KW             -91,363.4
NET WORK REQUIRED                 KW             -91,363.4
POWER LOSSES                  KW                  0.0
ISENTROPIC HORSEPOWER REQUIREMENT  KW             -82,498.6
CALCULATED OUTLET TEMP  C                          647.264
EFFICIENCY (POLYTR/ISENTR) USED                       0.90000
OUTLET VAPOR FRACTION                            1.00000
HEAD DEVELOPED,       M-KGF/KG                  -6,987.35
MECHANICAL EFFICIENCY USED                           1.00000
INLET HEAT CAPACITY RATIO                          1.19636
INLET VOLUMETRIC FLOW RATE , L/MIN              1,707,730.
OUTLET VOLUMETRIC FLOW RATE, L/MIN               2,307,220.
INLET  COMPRESSIBILITY FACTOR                        1.02160
OUTLET COMPRESSIBILITY FACTOR                          1.01358
AV. ISENT. VOL. EXPONENT                         1.21836
AV. ISENT. TEMP EXPONENT                          1.18835
AV. ACTUAL VOL. EXPONENT                           1.24533
AV. ACTUAL TEMP EXPONENT                            1.21356
```