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# Oxy Fuel for Clean Energy Generation

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# Oxy Fuel for Clean Energy Generation

## **Abstract**

This process explores several concentrations of oxygen-enriched air streams (oxy fuel) in combination with natural gas to generate steam for a steam turbine power plant with 30 MW capacity. The proposed location for this plant is the gulf coast of the United States. The oxy fuel concentrations tested were 36 mol. %, 53 mol. %, and 95 mol. %. Nitrogen removed from air would be sold as well as the 30 MW of electricity. The three oxygen purities were not profitable for the most realistic prices of electricity, nitrogen, and natural gas. However, the scenarios were all profitable with prices of nitrogen above \$0.015/lb. Additionally, the profitability could be improved with higher electricity prices or better thermal efficiency. A key takeaway is that the level of oxygen purity did not have a major effect on profitability for a given nitrogen price.

## **Disciplines**

Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering



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Dr. Wen K. Shieh  
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Philadelphia, PA 19104  
April 17, 2018

Dear Dr. Vrana, Dr. Seider, Dr. Shieh, and Mr. Adam Brostow,

Enclosed is a proposed pilot plant using oxy fuel for clean energy generation, a project proposed by Mr. Adam A. Brostow. Various scenarios of enriched oxygen streams were investigated to determine which enrichment was the most economical and made the most sense.

The process was designed using ASPEN simulations and each scenario was rigorously modeled. Oxygen purities of 36 mol. %, 53 mol. %, and 95 mol. % were modeled and the net power produced was 30 MW. The combustion portion of the process was treated as a black box. The various scenarios were assumed to operate 90% of days at 100% capacity.

Profitability analysis revealed the three scenarios to be unprofitable. Therefore, we do not recommend investing in this technology given our current design. However, the profitability is sensitive to nitrogen price and the monetizing of oxy fuel benefits.

Sincerely,

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Patrick Hally

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Najib Muqem

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Colin Richter

---

Tim Schanstra



# Oxy Fuel for Clean Energy Generation

*Patrick Hally | Najib Muqem | Colin Richter | Tim Schanstra*

Project submitted to:

Dr. Wen K. Shieh

Prof. Bruce M. Vrana

Project proposed by:

Mr. Adam A. Brostow

Department of Chemical and Biomolecular Engineering

School of Engineering and Applied Sciences

April 17, 2018



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# **Section 1**

## **Abstract**



**1.1 Abstract**

This process explores several concentrations of oxygen-enriched air streams (oxy fuel) in combination with natural gas to generate steam for a steam turbine power plant with 30 MW capacity. The proposed location for this plant is the gulf coast of the United States. The oxy fuel concentrations tested were 36 mol. %, 53 mol. %, and 95 mol. %. Nitrogen removed from air would be sold as well as the 30 MW of electricity. The three oxygen purities were not profitable for the most realistic prices of electricity, nitrogen, and natural gas. However, the scenarios were all profitable with prices of nitrogen above \$0.015/lb. Additionally, the profitability could be improved with higher electricity prices or better thermal efficiency. A key takeaway is that the level of oxygen purity did not have a major effect on profitability for a given nitrogen price.





## **Section 2**

# **Introduction and Objective-time Chart**



## **2.1 Introduction**

The motivation for this project comes from Linde's Schwarze Pumpe which was a coal fired power plant that used oxy fuel technology. This oxy fuel technology uses Air Separation Units (ASU) to take air and make an oxygen enriched stream and a nitrogen enriched stream. The goal for this project is to create a similar pilot plant, but one that uses natural gas instead of coal and uses the ASU technology from Air Products. The project uses three different oxygen enrichment levels (36%, 53%, and 95%). The oxy fuel energy generation process burns natural gas in an enriched oxygen stream as the primary oxidant. This enriched oxygen stream is an improvement over the amount of oxygen in air (21%) which is typically used in combustion. Higher oxygen concentrations allow for higher flame temperatures for certain processes. However, for this process since a higher flame temp would not be beneficial to the process, the flue gas can be recycled to reduce it to an appropriate level. A higher flame temp would promote more production of NO<sub>x</sub>, which is a pollutant that this process tries to reduce.

An advantage of the oxy fuel process is that it will produce up to 75% less flue gas by volume. This means less equipment will be needed to manage the flue gas coming out of the system which reduces capital costs. Less flue gas is the result of less nitrogen present in the furnace when combustion takes place. A huge benefit for using an oxygen enriched stream in combustion is that the flue gas is essentially all carbon dioxide and water. NO<sub>x</sub> is reduced due to a lower amount of nitrogen in the furnace. Since the flue gas has reduced NO<sub>x</sub>, the carbon dioxide becomes easier to separate from the rest of the flue gas making this process extremely attractive for carbon sequestration.



In the future, where there is a price on emitting carbon and/or fossil fuels become more expensive, this technology could become more economical. However, in its current state, this process is more expensive than a traditional power plant that uses air. The amount of power needed to separate the oxygen from the air ranged from 25-37.5% of total production of the pilot plant. This means that in order to produce the 30 MWs of net power that was required, 40-48 MWs of raw power needed to be produced. This is a large quantity of energy that goes into making an enriched oxygen stream.

Another benefit of this process is that you can extract a nearly pure nitrogen stream which can be sold as a valuable product. This helps make the plant more economical, assuming that there is a customer nearby willing to buy nitrogen. Most ASUs see nitrogen as the main product and the enriched oxygen stream as more of a waste stream. This process tries to use the oxygen stream to make something useful in the form of electricity. This plant will be built in the Gulf Region with a customer close by who will buy the nitrogen produced at a purity of greater than 99%. This project will weigh the economic potential of each oxygen enriched stream (36%, 53%, or 95%).



**2.2 Objective Time Chart**

<b>Project Name</b>	Oxy Fuel for Clean Energy Generation
<b>Project Advisors</b>	Adam A. Brostow, Wen K. Shieh, Bruce M. Vrana
<b>Project Leaders</b>	Patrick Hally, Najib Muqem, Colin Richter, Tim Schanstra
<b>Specific Goals</b>	Develop a pilot plant that produces 30 net Megawatts of electricity using a conventional steam turbine. The feed to the plant will be an oxygen enriched stream at 36, 53, or 95% oxygen and natural gas. The different costs of using the three streams should be analyzed.
<b>Project Scope</b>	
<i>In Scope:</i>	<ul style="list-style-type: none"><li>-Produce 30 net MW of electricity</li><li>-Produce a Nitrogen rich stream to sell as by-product</li><li>-Determine equipment needed and operating conditions</li><li>-Size equipment used</li><li>-Analyze profitability and economics of the three different oxygen enriched streams</li><li>-Develop a model for double column and single column ASUs</li></ul>
<i>Out of Scope:</i>	<ul style="list-style-type: none"><li>-Rigorously model the combustion unit</li><li>-Test assumptions made based on thermodynamic principles</li><li>-Building Pilot Plant to test Aspen results</li><li>-Rigorously model the costs and profitability of carbon capture</li></ul>
<b>Deliverables</b>	<ul style="list-style-type: none"><li>-Flowsheet outlining double column and single column ASU</li><li>-Aspen simulation for three different oxygen concentrations</li><li>-Financial analysis of the ASU</li><li>-Mass and Energy balance of the process</li></ul>
<b>Timeline</b>	<ul style="list-style-type: none"><li>-Complete mid-semester presentation by February 27th, 2018</li><li>-Complete deliverables over the course of the spring semester with the final report finished by April 17th, 2018</li></ul>



## **Section 3**

# **Market and Competitive Analysis**



**3.1 Market Analysis**

**3.1.1 Energy**

The United States consumed approximately 97.18 quadrillion BTUs of energy in 2016, 28.43 quadrillion of which were natural gas.

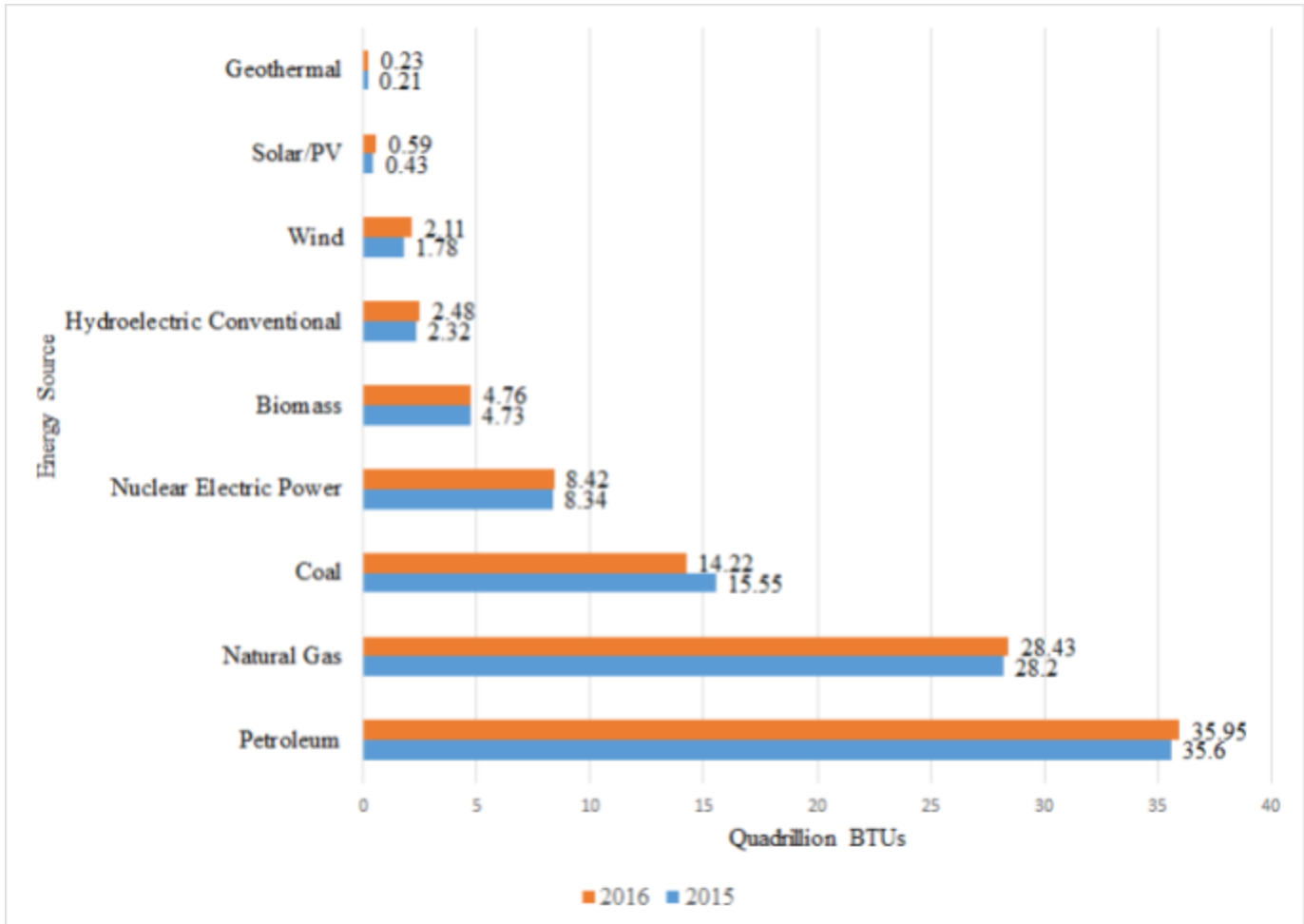


Figure 3.1. Energy consumption in the US in quadrillion British thermal units by source.

For a project of this scale, finding customers to buy the electricity generated from the combustion process should not be an issue. For the natural gas required in the combustion process, there are many distributors in the US. Atmos Energy, headquartered in Dallas, Texas, is one of the largest proprietors of natural gas, and is conveniently located so as to minimize



transportation fees. Its location is advantageous for this project because, in the United States, the region with the largest energy consumption per capita is the South, primarily Louisiana at 912 million BTUs.

Table 3.1. US Energy Production and Consumption Rankings from the EIA.

US Energy Consumption Rankings per capita			US Energy Production Rankings		
Rank	State	Consumption per Capita (million BTUs)	Rank	State	Total Production (trillion BTUs)
1	Louisiana	912.2	1	Texas	1554.3
2	Wyoming	892.9	2	Florida	812.4
3	Alaska	840.3	3	Pennsylvania	733
4	North Dakota	802.8	4	California	679.1
5	Iowa	478.8	5	Illinois	637.9
6	Texas	470.2	6	Alabama	488
7	Nebraska	450.5	7	New York	458.1
8	South Dakota	447	8	Georgia	454.9
9	Indiana	430.4	9	North Carolina	448.6
10	West Virginia	420.9	10	Ohio	407.3
11	Oklahoma	417.4	11	Washington	384.8
12	Alabama	393.4	12	Michigan	384.6
13	Kentucky	390	13	Arizona	371.1
14	Montana	379.3	14	Louisiana	364
15	Mississippi	378.9	15	Indiana	347.4



This makes the Gulf Coast area ideal for a process of this nature. Texas holds the highest rank at 20.6% of total US energy production. This means that the energy produced by this process can easily be sold to the grid. However, in this region, electricity can only be sold for around 8 cents per kilowatt-hour, well below the US average retail price of 10.41 cents per kilowatt-hour. Nonetheless, the statistics look good in the long run, as electricity prices have slowly been rising each year, from 9.74 cents in 2008 to 10.54 cents in 2017 per kilowatt-hour on average.

Table 3.2. Annual totals for average electricity prices for ultimate customers in cents per kilowatt-hour.

Period	Residential	Commercial	Industrial	Transportation	All Sectors
Annual Totals					
2008	11.26	10.26	6.96	10.71	9.74
2009	11.51	10.16	6.83	10.86	9.82
2010	11.54	10.19	6.77	10.56	9.83
2011	11.72	10.24	6.82	10.46	9.9
2012	11.88	10.09	6.67	10.21	9.84
2013	12.13	10.26	6.89	10.55	10.07
2014	12.52	10.74	7.1	10.45	10.44
2015	12.65	10.64	6.91	10.09	10.41
2016	12.55	10.43	6.76	9.63	10.27
2017	12.9	10.68	6.91	9.67	10.54





### 3.1.2 Nitrogen

There exist many industrial applications for high purity nitrogen gas. One of these is the aerospace and aircraft industry. The implementation of nitrogen gas in this area includes aircraft tyre inflation. High purity nitrogen is required for these tyres lest they become deflated due to oxygen permeation. It also reduces the risk of fire hazards (Nitrogen).

Other utilizations of nitrogen gas in the aerospace industry include, but are not limited to, inflatable slides and life rafts, fuel tank inerting, and shock-absorbing springs that dampen aircraft landing loads. This is largely due to pure nitrogen's non-reactiveness and inflammability.

In the automotive industry, nitrogen gas is used to make sodium azide,  $\text{NaN}_3$ . This chemical decomposes when a car detects that a collision has occurred, releasing the nitrogen into the airbag. Due to its non-explosive nature, it is the key factor in saving the lives of drivers and front-seat passengers in many automobile accidents ("How").

It is also used in welding alongside other welding gases to make frames, chasses, mufflers, and other components which require a proper atmosphere to produce adequate welds.

In the chemicals industry, nitrogen is used as a pressurizing gas due to its tendency to not react with many other gases. It can help propel liquids through pipelines and is the primary gas used to shield oxygen-sensitive materials from the air. These encapsulate just some of the many applications of nitrogen gas. Some more industries include foods and beverages, healthcare, energy, metallurgy, and pharmaceuticals ("Buy").

The primary source of revenue for this project is in fact the large quantity of high purity gaseous nitrogen produced in each of the three different air separation processes. This nitrogen



should be simple enough to sell to whichever industry requires it. There is also an Air Liquide location in Houston, Texas, which can be directly supplied to depending on production rates.

Nitrogen gas can be sold at a rate of around 0.5 cents per liter. Since the density of nitrogen at standard temperature and pressure is 1.25 g/L, this process would generate a revenue of \$400 per kg of nitrogen produced in the concentrated nitrogen stream. The rest of the nitrogen is contained in the enriched oxygen stream at concentrations of either 64, 47, or 5 mol.%.



### 3.1.3 Carbon Dioxide

Although this project does not encapsulate carbon dioxide sequestration, the combustion process produces a large quantity of flue gas which contains mainly  $\text{CO}_2$ , steam, and trace amounts of impurities such as  $\text{NO}_x$ . Since this project aims to reduce  $\text{NO}_x$  emissions, the main source of atmospheric contamination is  $\text{CO}_2$ .

Carbon dioxide has a wide range of industrial uses, ranging from refrigeration and cooling to enhancing the yield of plant products in greenhouses ( $\text{CO}_2$ ). A prime customer for the  $\text{CO}_2$  generated by the combustion process is in the extraction of crude oil from wells. Along the Gulf Coast lies a multitude of oil wells, both onshore and offshore (“Map”). These wells require consistent supplies of carbon dioxide to not only maintain pressure within rock formations drilled into, but also to render the extracted oil less viscous, allowing for simpler withdrawal.



### **3.2 Competitive Analysis**

At the present time, the majority of the world's electricity comes from coal-fired power plants, which provide approximately 39.3% of the total. Natural gas accounts for 22.9% of the world's electricity. (Hanania). There are too many power plants in the US alone to name, so the focus of competition will remain in states along the Gulf Coast. The largest producer of electricity using natural gas is Sabine in Orange County, Texas at a capacity of 2,051 MW. However, this is a commercial-scale plant and uses air to provide the necessary oxygen required for combustion. The process described in this report utilizes a stream of enriched oxygen, either 36, 53, or 95 mol.%, generated from the air separation units and is pilot-scale. At the moment, there are no oxy fuel combustion plants, planned or otherwise, in the United States.

There were a few pilot plants located overseas that examined the feasibility of oxy fuel combustion including the inspiration for this project: Linde's Schwarze Pumpe in Spremberg, Germany. The key difference between this plant and the one proposed in this paper is that the Schwarze Pumpe utilized lignite, a form of coal with low heat content, instead of natural gas. It consisted of one 30 MW-capacity unit. The Schwarze Pumpe was met with a number of roadblocks, including uproar from environmental activists attempting to cordon off coal supply routes and mines. In May of 2014, the plant was decommissioned.

In these times, where CO<sub>2</sub> reduction is not a priority, oxy fuel technology does not appear to be competitive. However, it still remains a viable alternative in carbon capture, and may be economical in the future.



## **Section 4**

# **Preliminary Process Synthesis**

**4.1 Overall Process**

Historically, power plants have used streams of dry air, 21% oxygen by mole, alongside a fuel source to provide the O<sub>2</sub> necessary for combustion. Due to the excess amount of nitrogen in this air stream, the effluent generated by this process contains a large amount of toxic gases such as NO<sub>x</sub> and SO<sub>x</sub>. The Linde Group fashioned a similar process to save energy and increase efficiency while also reducing the amount of nitrous and sulfur oxides. This process is shown in Figure 4.1.

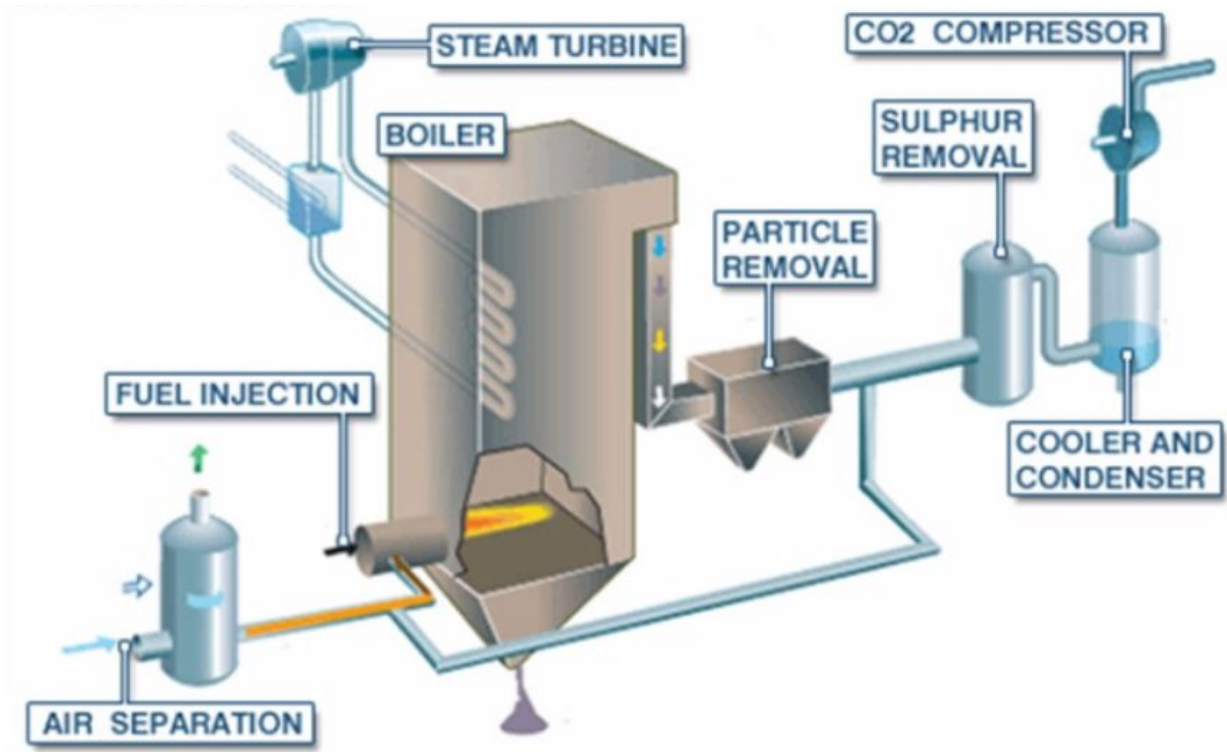


Figure 4.1. Overall process diagram



For the purposes of this project, the combustion will not be rigorously modeled and will be treated as a black box.

The Linde process uses lignite, a form of coal. This project aims to emulate this except in that it will use natural gas instead. The reasoning behind this is that combustion using natural gas reduces CO<sub>2</sub> in the flue gas by up to 60 percent when compared to plants that use coal.

**4.2 Scenarios**

Air Products and Chemicals, Inc. developed multiple patents for cryogenic air separation that produce oxygen-rich streams given a feed of dry air. The first of these patents, shown in Figure 4.2 and invented by Robert M. Thorogood, Thomas M. Roden, and Jeffrey A. Hopkins, details the process to make a 53 mol.% oxygen stream (Thorogood).

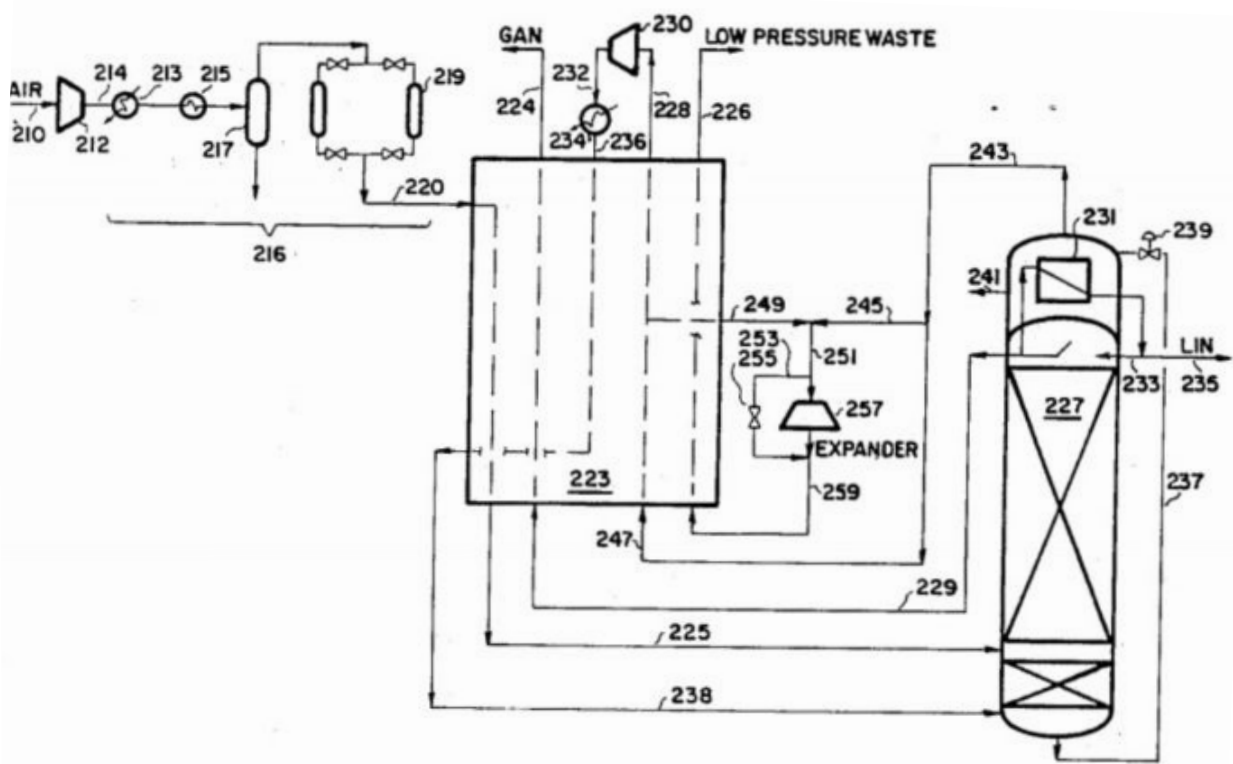


Figure 4.2. Patent for 53% oxygen stream (Low Pressure Waste).

The main products of this process are two enriched nitrogen streams (LIN and GAN on the diagram). The “waste” stream is vented to the atmosphere. However, this project aims to utilize this waste stream and burn an injection of natural gas in a furnace with it. The nitrogen streams are unnecessary and can be sold or vented to the atmosphere.



Another case that will be analyzed is similar to this, except for the fact that the recycle stream that goes through the compressor (230) is removed. This produces an oxygen stream with a concentration of 36 mol.%.

The third and final case that will be covered in this report comes from another Air Products and Chemicals, Inc. patent, shown in Figure 4.3 (Brostow).

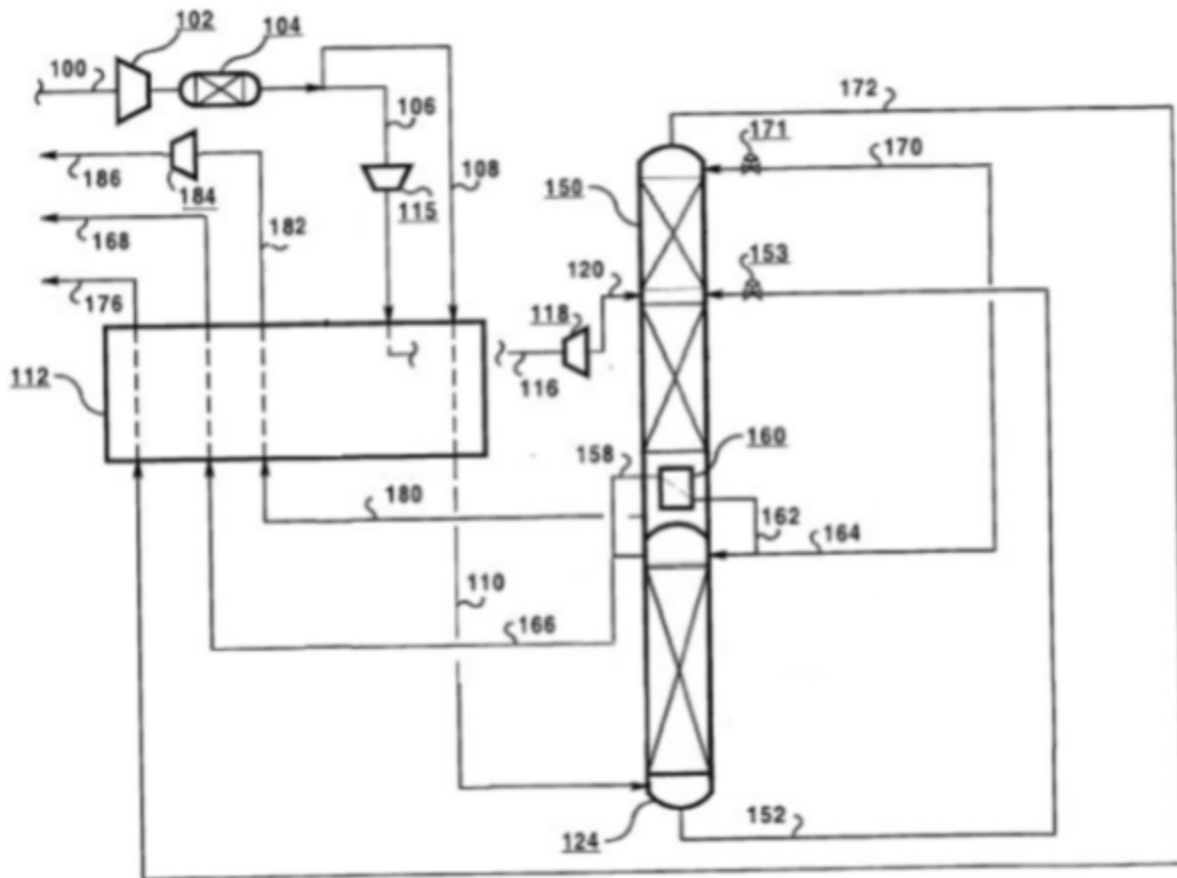


Figure 4.3. Patent for 95% oxygen stream (186)

This patent, invented by Adam Brostow and Donn Herron, utilizes a double-column setup. The lower column is run at a high pressure and sends streams to the low pressure column



above it. Stream 186 is the one that will be used in the combustion process while product streams 168 and 176 are nitrogen-rich and can be sold or vented to the atmosphere.



# **Section 5**

## **Assembly of Database**



**5.1 Thermophysical Property and Price Data**

The primary components of this process are listed in Table 5.1. This includes components in the combustion section, such as methane, carbon dioxide, and water, although the combustion is not modeled rigorously in this report. Methane comprises the largest portion of natural gas at 93.9 mol.% (“Chemical”). The remainder is primarily ethane at 4.2 mol.% with components such as nitrogen, carbon dioxide, propane, and higher order hydrocarbons taking up less than 1% of the total composition of natural gas. The gross heating value of natural gas was discovered to be around 38.7 MJ/m<sup>3</sup>.

*Table 5.1. Thermophysical properties of key components*

Component	Cp (KJ/kg-K)	Boiling Point (K)	Molecular Weight (g/mol)	Price (\$)	$\Delta H_{vap}$ (KJ/kg)	$\Delta H_{combust}$ (KJ/kg)	Density, l (kg/m <sup>3</sup> )	Density, v (kg/m <sup>3</sup> )	Comments
Air	1.006	78.8	28.96	~0	201.9	N/A	870	1.276	Feed stream
Carbon Dioxide	0.849	194.7	44	N/A	379.5	N/A	1101	1.977	In flue gas
Ethane	1.715	184.9	30.1	0.0045/f <sup>3</sup>	N/A	-51,800	546.5	1.36	Secondary component of natural gas
Methane	2.23	111.7	16.04	0.0045/f <sup>3</sup>	N/A	-55,530	422.6	0.656	Primary component of natural gas
Nitrogen	1.04	77.4	28.01	N/A	199	N/A	808.4	1.25	In product stream from air separation
Oxygen	0.92	90.2	32	N/A	213	N/A	1142	1.429	In product stream from air separation
Water	4.184	373.1	18	~0	2030	N/A	1000	0.804	Cooling water, steam in flue gas



### 5.2 Toxicity Data

Kiriishi, et. al analyzed flame temperatures and  $\text{NO}_x$  and  $\text{SO}_x$  production of oxy fuels based on oxygen enrichment. For an air ratio of 1.1, a furnace temperature of 1200 C, and a fuel-gas ratio of  $2 \text{ m}^3 \text{ N}/\text{m}^3 \text{ N-fuel}$ , the  $\text{NO}_x$  emissions are depicted in figure 5.1 (Kiriishi).

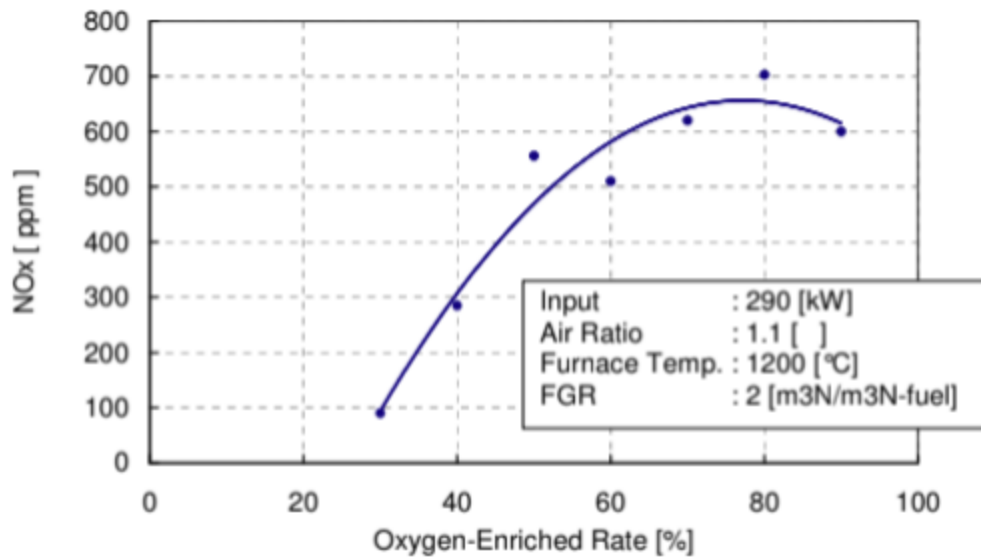


Figure 5.1.  $\text{NO}_x$  emissions data based on oxygen enrichment.

There exists a very clear parabolic shape on the graph, indicating a suboptimal enrichment rate and two optimal enrichment rates. According to Kiriishi, under these conditions, a stream of 70-80% oxygen produces the most  $\text{NO}_x$ , even more than streams with lower oxygen concentrations. The graph comes back down after this peak, indicating that after the threshold,  $\text{NO}_x$  production will decrease with oxygen enrichment.

For this project, the upper and lower limits of oxygen concentration, namely 95% and 36% respectively, Kiriishi indicates that the process will yield positive results in terms of toxin



production while the middle value of 53% oxygen enrichment may or may not produce too much  $\text{NO}_x$ .



## **Section 6**

# **Process Flow Diagram and Material Balance**

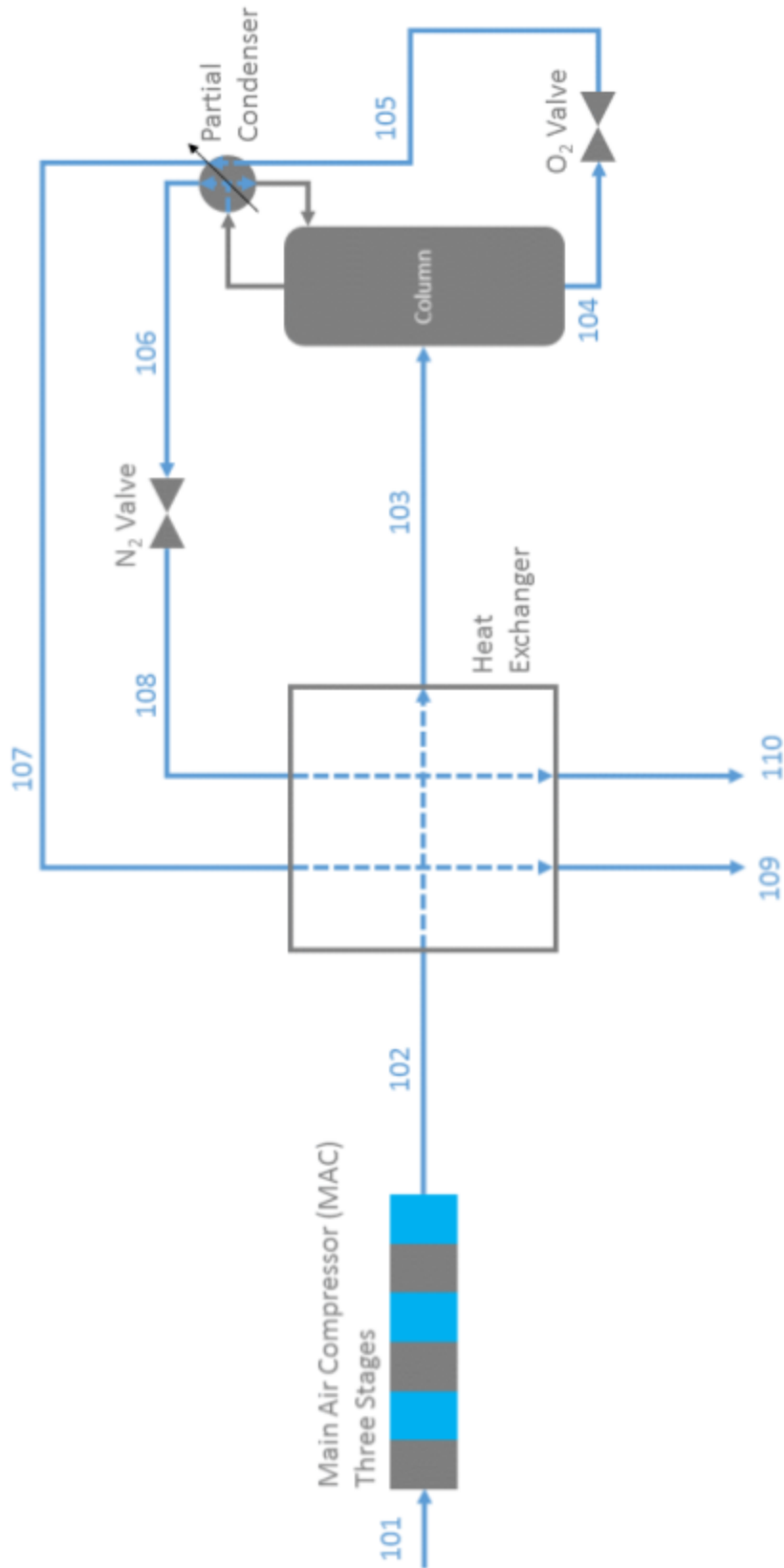


Figure 6.1. Section 100: 36% Product Oxygen Concentration





Table 6.1. Stream table for 36% Oxygen case.

Stream	101	102	103	104	105
Temperature (F)	85	90	-273	-278	-310
Pressure (psig)	0	83.3	78.3	78	4.3
Vapor Fraction	1	1	1	0	0.19
Mass Flow (lb/hr)	30,212	30,212	30,212	178,576	178,576
Mole Flow (lbmol/hr)	10,472	10,472	10,472	6,063	6,063
Volume Flow (cuft/hr)	4,160,000	631,000	196,000	3,580	95,100
Composition (Mol %)					
Oxygen	0.21	0.21	0.21	0.362	0.362
Nitrogen	0.79	0.79	0.79	0.638	0.638
Stream	106	107	108	109	110
Temperature (F)	-285	-278	-301	87.5	88.6
Pressure (psig)	76.3	4.3	4.3	-0.7	-0.7
Vapor Fraction	1	1	1	1	1
Mass Flow (lb/hr)	123,544	178,576	123,544	178,576	123,544
Mole Flow (lbmol/hr)	4,409	6,063	4,409	6,063	4,409
Volume Flow (cuft/hr)	77,200	605,000	381,000	2,540,000	1,850,000
Composition (Mol %)					
Oxygen	0.001	0.362	0.001	0.362	0.001
Nitrogen	0.999	0.638	0.999	0.638	0.999

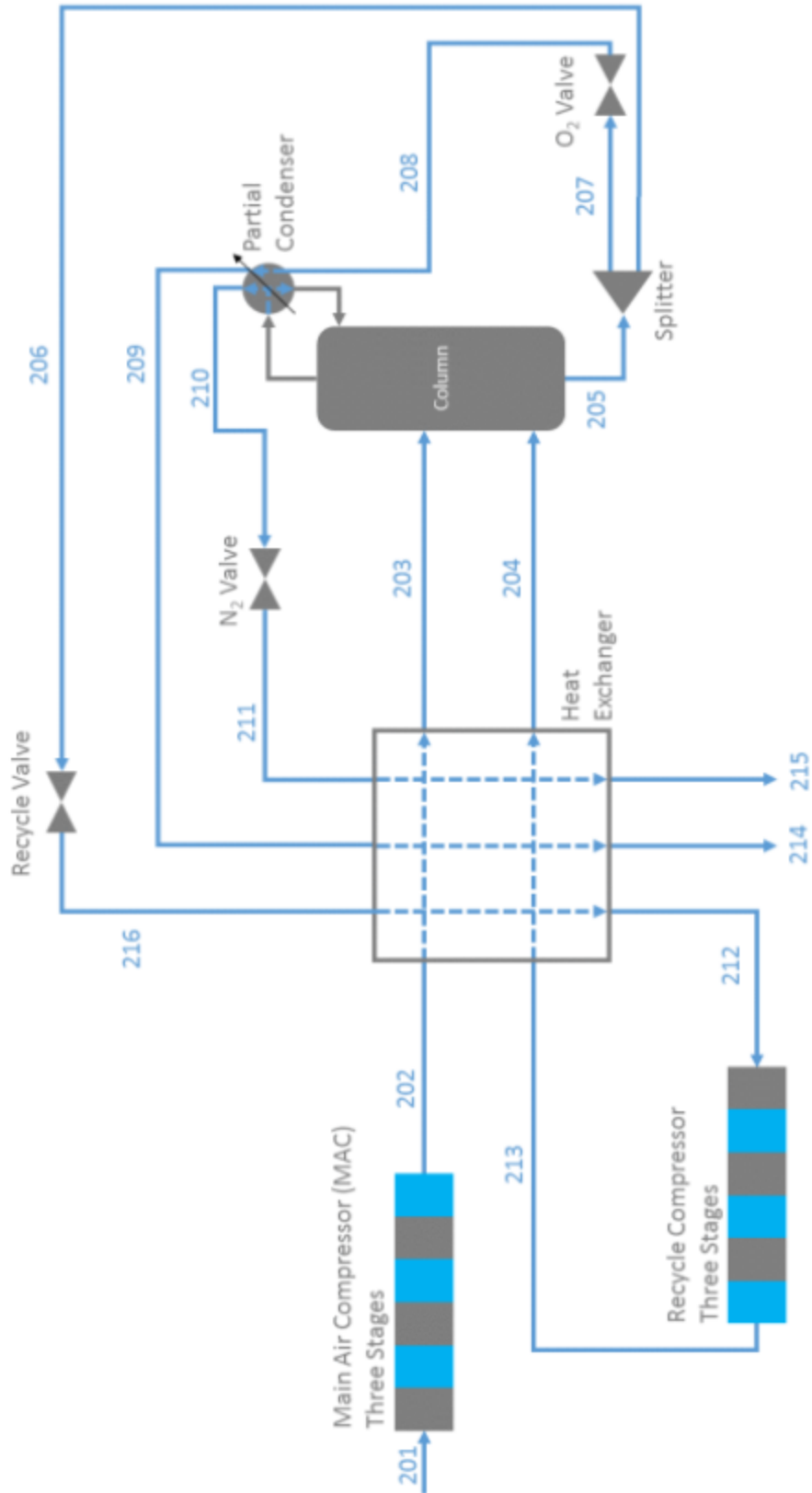


Figure 6.2. Section 200: 53% Product Oxygen Concentration



Table 6.2. Stream table for 53% Oxygen case.

Stream	201	202	203	204	205	206
Temperature (F)	85	90	-269	-256	-265	-265
Pressure (psig)	0	114	112	113	113	113
Vapor Fraction	1	1	0.98	1	0	0
Mass Flow (lb/hr)	362,544	362,544	362,544	149,388	298,776	149,388
Mole Flow (lbmol/hr)	12,566	12,566	12,566	4,960	9,921	4,960
Volume Flow (cuft/hr)	5,000,000	575,000	164,000	72,000	5,870	2,940
Composition (Mol %)						
Oxygen	0.21	0.21	0.21	0.528	0.528	0.528
Nitrogen	0.79	0.79	0.79	0.472	0.472	0.472
Stream	207	208	209	210	211	
Temperature (F)	-265	-306	34.7	-306	-299	
Pressure (psig)	113	5.3	5.3	5.3	5.3	
Vapor Fraction	0	0.232	1	0.232	1	
Mass Flow (lb/hr)	149,388	149,388	149,388	149,388	213,156	
Mole Flow (lbmol/hr)	4,960	4,960	4,960	4,960	7,606	
Volume Flow (cuft/hr)	2,940	92,800	1,320,000	96,900	630,000	
Composition (Mol %)						
Oxygen	0.528	0.528	0.528	0.528	0.003	
Nitrogen	0.472	0.472	0.472	0.472	0.997	
Stream	212	213	214	215	216	
Temperature (F)	88	90	85	88	-306	
Pressure (psig)	3.3	115	3.3	3.3	5.3	
Vapor Fraction	1	1	1	1	0.232	
Mass Flow (lb/hr)	149,388	149,388	149,388	213,156	149,388	
Mole Flow (lbmol/hr)	4,960	4,960	4,960	7,606	4,960	
Volume Flow (cuft/hr)	1,620,000	225,000	1,610,000	2,480,000	92,800	
Composition (Mol %)						
Oxygen	0.528	0.528	0.528	0.003	0.528	
Nitrogen	0.472	0.472	0.472	0.997	0.472	

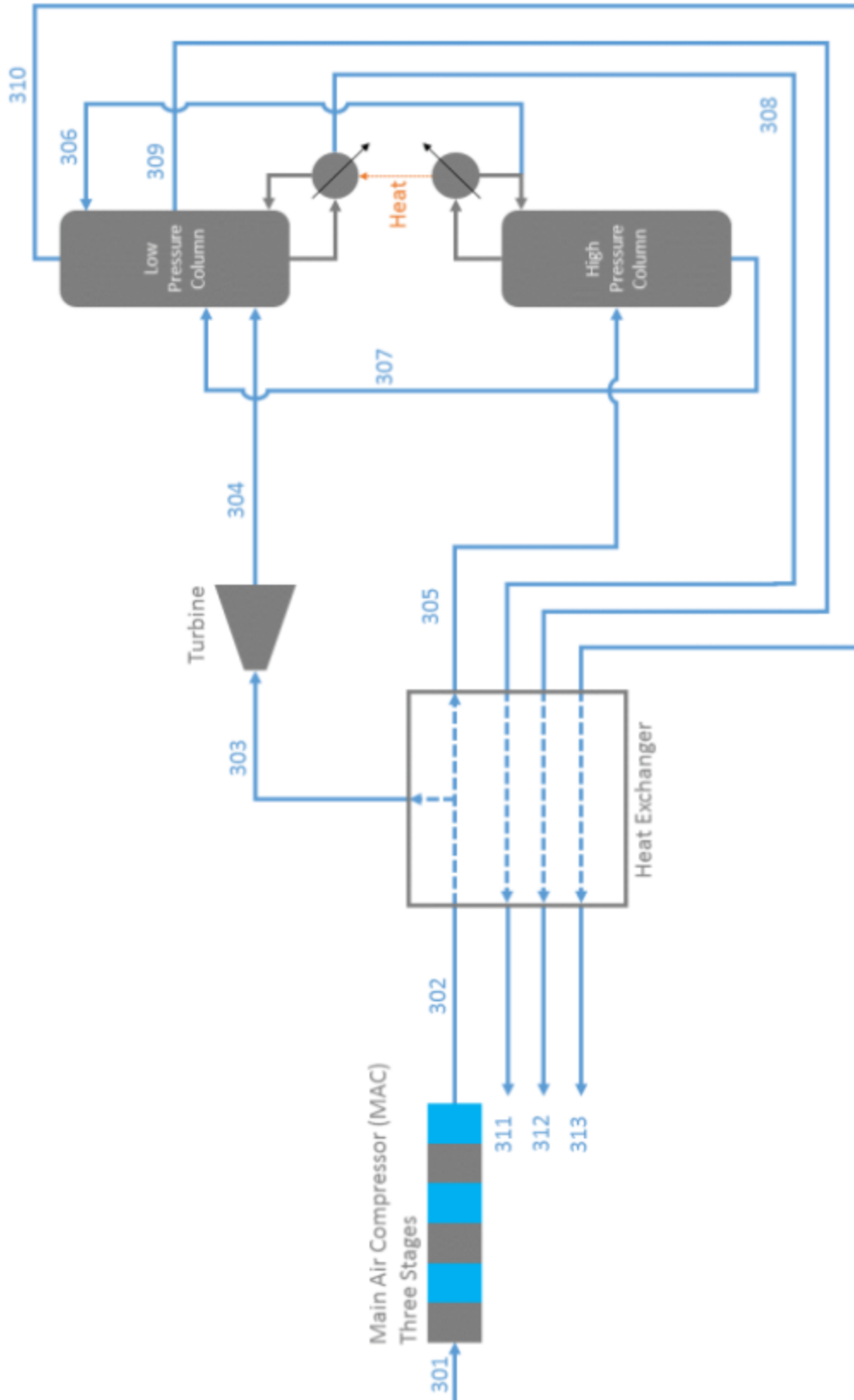


Figure 6.3. Section 300: 95% Product Oxygen Concentration



Table 6.3. Stream table for 95% Oxygen case.

Stream	301	302	303	304	305
Temperature (F)	85	95	-150	-244	-277
Pressure (psig)	0	87.3	87.3	10.3	87.3
Vapor Fraction	1	1	1	1	0.59
Mass Flow (lb/hr)	381,625	381,625	76,325	76,325	305,300
Mole Flow (lbmol/hr)	13,228	13,228	2,646	2,646	10,582
Volume Flow (cuft/hr)	5,260,000	770,000	83,300	239,000	104,000
Composition (Mol %)					
Oxygen	0.21	0.21	0.21	0.21	0.21
Nitrogen	0.79	0.79	0.79	0.79	0.79
Stream	306	307	308	309	
Temperature (F)	-285	-279	-289	-308	
Pressure (psig)	77.3	78.6	12.6	9	
Vapor Fraction	0	0	0	1	
Mass Flow (lb/hr)	82,911	222,389	74,699	128,043	
Mole Flow (lbmol/hr)	2,957	7,625	2,350	4,500	
Volume Flow (cuft/hr)	1,880	4,530	1,100	291,000	
Composition (Mol %)					
Oxygen	0.007	0.29	0.947	0.111	
Nitrogen	0.993	0.71	0.053	0.889	
Stream	310	311	312	313	
Temperature (F)	-312.6	80	80	80	
Pressure (psig)	8.3	8.3	9	8.3	
Vapor Fraction	1	1	1	1	
Mass Flow (lb/hr)	178,884	74,699	128,043	178,884	
Mole Flow (lbmol/hr)	6,378	2,350	4,500	6,378	
Volume Flow (cuft/hr)	413,000	591,000	1,100,000	1,600,000	
Composition (Mol %)					
Oxygen	0.009	0.947	0.111	0.009	
Nitrogen	0.991	0.053	0.889	0.991	



# Section 7

## Process Description



**7.1 Overall Process**

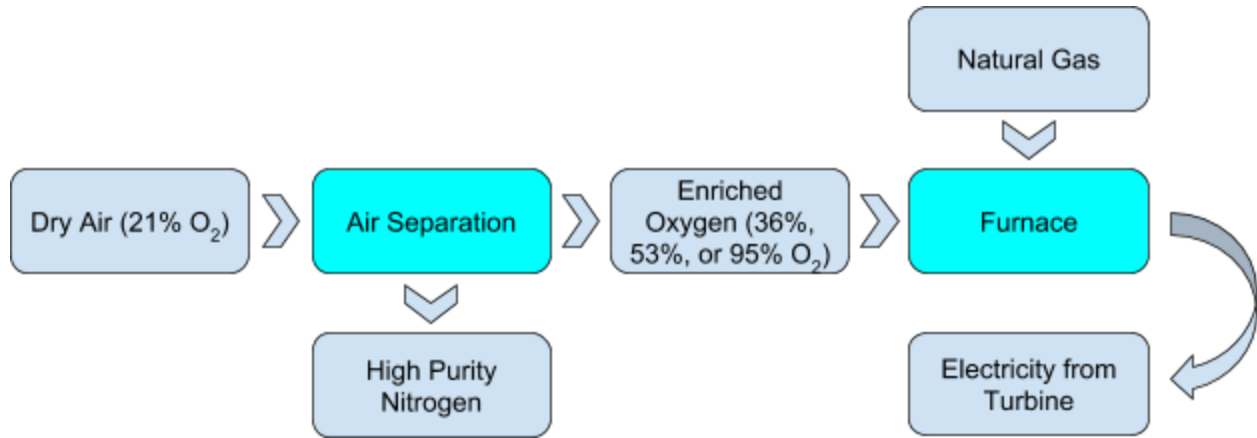


Figure 7.1. Overall process flowchart

The overall process can be broken down into two stages: the air separation and the combustion sections. There are three cases for the air separation. The first involves a single column without a recycle stream, which outputs an enriched oxygen stream of 36 mol.%. The second case adds the recycle stream to this single column process to produce a final oxygen concentration of 53 mol.%. The last case uses two columns: a high pressure and a low pressure one. The oxygen concentration in the enriched stream in this case is 95 mol.%. In all three scenarios, the exiting enriched oxygen stream is fed into a boiler and is burned with natural gas, creating steam and carbon dioxide. This flue gas can be recycled back into the system to reduce the flame temperature. For the purposes of this project, the combustion portion of the process will not be rigorously modeled.



### **7.2 36% Case**

Figure 6.1 details the air separation process for the 36% O<sub>2</sub> case. A stream of air (21 mol.% oxygen and 79 mol.% nitrogen) is fed to a three-stage compressor. This compressor is comprised of three intercoolers which saves energy by allowing cooling between stages. This compressed air stream is then put through a multi-stream heat exchanger, which acts as a medium for various streams throughout the process to exchange heat and reach desired temperatures. Because the required separation cannot occur at ambient temperatures, the heat exchanger lowers the temperature of the compressed air stream to cryogenic temperatures. This cold, compressed air is then fed into the column, which separates the air into two enriched streams. The bottoms product is the stream used in the oxy fuel combustion section and has a composition of 36% oxygen and 64% nitrogen by mole. The distillate contains high purity nitrogen (99.9%) that can be sold for revenue. These streams are then depressurized and fed back into the multi-stream heat exchanger to return their temperatures to ambient conditions.





### **7.3 53% Case**

Figure 6.2 portrays the air separation diagram for the 53% O<sub>2</sub> scenario. Similar to the 36% case, a stream of air is fed to a three-stage compressor and then into the column. However, after the separation, half of the bottoms product, the enriched oxygen stream, is split off from the product stream and recycled back into the column after it is compressed and cooled again. The product stream contains 53% oxygen and 47% nitrogen by mole. This stream enters the combustion section as the enriched oxygen stream. The distillate stream contains high purity nitrogen (99.7%) which can be sold. This air separation process is almost exactly the same as the 36% case with the key difference being the split recycle stream which drives up the final oxygen concentration by about 17 mol.%.



### 7.4 95% Case

The third and final scenario is the case where two columns with different operating pressures are utilized to produce an enriched oxygen stream of 95 mol.%. This process is depicted in Figure 6.3. Again, a stream of dry air is fed into a three-stage compressor and then through the multi-stream heat exchanger, which lowers the temperature of the stream to cryogenic values. After this, 20% of it enters a high pressure column, operating at a pressure of 77.3 psi. The remaining 80% of the initial compressed air stream splits off and enters an expander, recovering some power, and is then fed into the bottom of the low pressure column, which operates at a pressure of 8.3. The distillate from the high pressure column is an enriched nitrogen stream (99.3%) which is recovered and fed to the top of the low pressure column. These two columns are not separate; they are stacked on top of one another with the low pressure one on top. In essence, this means that the duty from the condenser of the high pressure column must equal that of the reboiler of the low pressure column. The bottoms product of the high pressure column is simply a liquid air stream with 21% oxygen. This stream is recovered and fed into the low pressure column at a stage below the enriched nitrogen stream from the high pressure column and above the air stream from the expander. The bottoms product of the low pressure column is the enriched oxygen stream which has an oxygen concentration of about 95%. The distillate contains an enriched nitrogen stream (99.1%) which can be sold. There is another product stream that comes off of the low pressure column which has a composition of 89%. This purity is far too low to sell for revenue, so it will be vented to the atmosphere. These three



streams return to the multi-stream heat exchanger to bring their temperatures to ambient conditions.



# **Section 8**

## **Energy Balance and Utility Requirements**



The cryogenic nature of this process emphasized the importance of minimizing lost heat, minimizing utility costs. The entirety of the input for internal cooling was supplied by the three-stage compressor and its cooling water. Tables 8.1, 8.2, and 8.3 show the overall system energy balances for each oxygen concentration case. Much of the cooling for input streams was done in the heat exchangers for each case, cooling the input streams and heating the outlet streams, as shown in Section 6.

Cooling water had a temperature change of 25 °F. Streams 101, 201, and 301 all entered at ambient temperature, assumed to be 85 °F in the gulf coast. Streams 101 and 201 became 90 °F, while stream 301 became 95 °F. This is a small temperature change; much of the energy was used to compress the streams. Stream 101 was compressed from 0 psig to 83.3 psig. Stream 201 was compressed from 0 psig to 114 psig. Stream 301 was compressed from 0 psig to 87.3 psig. All of this data is shown in Tables 6.1, 6.2, and 6.3. For additional cooling in the 95% oxygen case, an expander was used. This generated about 340 kW of power while cooling stream 303 from -150 °F to -244 °F. The pressure reduced from 87.3 psig to 10.3 psig. Overall, the 36% oxygen case had about 9.8 MW in and out. The 53% oxygen case had about 18.4 MW in and out. The 95% oxygen case had about 14.2 MW in and out. The 53% oxygen case had substantially more because the change in pressure from ambient to column was much higher for this case. In order to achieve the goal of 30 net MW, each case must generate 30 MW + the energy balance of the air separation unit. This energy will be generated in the boiler and steam turbine, which the product streams feed. For startup, liquid nitrogen will be used. The process will be cooled slowly



in order to reduce metal fatigue. Alternatively, the process could start as normal, and the compressor would cool the system. However, this would take much more time and energy.

Tables 8.1, 8.2, and 8.3 show the summarized input and outlet streams for each process as a whole. Streams 101, 102, and 103 are dry air that entered the three-stage compressor. The compressor increased enthalpy by compressing, but its cooling water also decreased the enthalpy by roughly the same amount for all three cases. In Table 8.1, streams 109 and 110 were the product streams exiting the heat exchanger. In Table 8.2, streams 214 and 215 were the product streams for the system exiting the heat exchanger. In Table 8.3, streams 311, 312, and 313 were the product streams exiting the heat exchanger. Streams 110, 215, and 313 were the nitrogen product streams, all with at least 99% purity. Streams 109, 214, and 311 were the oxygen product streams, with purities depending on the case. Stream 312 was the waste stream in the 95% oxygen case. Because the exit temperatures and pressures were similar to the entrance temperatures and pressures, the enthalpies of the product streams were similar to those of the feed streams for the system. Any discrepancies were fully accounted for in the difference in enthalpies between the compressing and cooling in the three-stage compressor.



Table 8.1. Total system energy balance for 36% Oxygen case.

Stream In	Enthalpy Flow (kW)	Stream Out	Enthalpy Flow (kW)
101	163	109	126
		110	101
<b>Total</b>	<b>163</b>	<b>Total</b>	<b>227</b>
Cooling Water	Compressor (kW)	OUT - IN (kW)	
-9,588	kW	9,652	0
1,300,000	lb/hr		

Table 8.2. Total system energy balance for 53% Oxygen case.

Stream In	Enthalpy Flow (kW)	Stream Out	Enthalpy Flow (kW)
201	196	214	76
		215	165
<b>Total</b>	<b>196</b>	<b>Total</b>	<b>241</b>
Cooling Water	Compressor (kW)	OUT - IN (kW)	
-18,187	kW	18,233	0
2,480,000	lb/hr		

Table 8.3. Total system energy balance for 95% Oxygen case.

Stream In	Enthalpy Flow (kW)	Stream Out	Enthalpy Flow (kW)
301	203	311	10
		312	20
		313	29
<b>Total</b>	<b>203</b>	<b>Total</b>	<b>59</b>
Cooling Water	Compressor (kW)	Expander (kW)	OUT - IN (kW)
-13,762	kW	13,958	-340
1,870,000	lb/hr		



## **Section 9**

# **Equipment List and Unit Descriptions**





**Section 9.1 95% Case**

*Main Air Compressor*

Unit ID: Main Air Compressor (MAC)  
Type: Multi-stage Compressor  
Material: Carbon Steel  
Specification Sheet: Page 69  
Costing Data: Page 76

Temperature: 95 °F  
Pressure: 87.3 psig  
Work: 18,700 hp

The multi-stage air compressor was designed with ASPEN. The compressor needed 2 intercoolers in between stages to save work. The compressor had three stages with the 2 intercoolers. The pressure drop from one cooler to the next was 3 psi. The temperature at the outlet of the coolers was set to 95°F to avoid melting the compressor. Air was the feed stream to the compressor. The outlet pressure from the multistage compressor was 87.3 psig. The total work done by the compressor was 18,700 horsepower (13.96MW) and the cooling duty was -13.76MW. There were 13,200 lbmol/hr and 382,000 lb/hr going through the compressor.

*Brazed Aluminum Heat Exchanger*

Unit ID: Heat Exchanger  
Type: Plate-fin  
Material: Brazed Aluminum  
Duty: 12.5 MW  
Specification Sheet: Page 70  
Costing Data: Page 76

LMTD (Duty/UA): 11.5 °F  
Pressure: 8-87 psig  
UA: 3,720,000 Btu/hr-R

Multi-stream heat exchanger was designed with ASPEN. The heat exchanger was a countercurrent plate-fin heat exchanger that used brazed aluminum as the material. The total duty of the heat exchanger was -12.5 MW. The heat exchanger was modeled on ASPEN as two separate heat exchangers as was recommended, but in reality it was one heat exchanger. The UA



was  $3.72 \times 10^6$  BTU/hr-R and the LMTD (log mean temperature difference) is 11.5°F. The heat exchanger was used to bring the feed streams to cryogenic temperatures as they moved towards the distillation columns or the turbine and was also used to bring the product oxygen, nitrogen, and waste streams to ambient conditions. There were 26,500 lbmol/hr and 763,000 lb/hr that go through the heat exchanger. Manufacturers can design the brazed aluminum heat exchangers to have pinches less than 1°C (“Brazed”).

*Turbine*

Unit ID: Turbine	Temperature: -244 °F
Type: Isentropic	Pressure: 10.3 psig
Material: Stainless Steel	Work: -0.48MW
Specification Sheet: Page 72	
Costing Data: Page 76	

The turbine was designed with ASPEN. The turbine was an isentropic turbine with an isentropic efficiency of 0.9. The work required for the turbine was -0.48MW. The outlet temperature from the turbine was 10.3 psig and the outlet temperature was -244°F. The turbine dropped the temperature and the pressure before stream 304 went into the low pressure column. There were 2650 lbmol/hr and 76,300 lb/hr flowing through the turbine.

*Low Pressure Column*

Unit ID: Low Pressure Column	Stages: 38
Type: Distillation Column	Pressure: 8.3 psig
Material: Stainless Steel	Diameter: 11.4 feet
Specification Sheet: Page 73	Tray Spacing: 1 foot
Costing Data: Page 76	



The Low Pressure column was designed with ASPEN. The Condenser (Top Stage) of the column had a temperature of  $-313^{\circ}\text{F}$  and the reflux ratio was set to 0.38 after much trial and error. The Reboiler (bottom stage) had a temperature of  $-289^{\circ}\text{F}$  with a duty of 4.1 MW. The boilup ratio was 2.14. There were 13,200 lbmol/hr and 382,000 lb/hr going through the low pressure column. There were 38 stages for this column with a tray spacing of 1 foot and a diameter of 11.4 feet. The Enriched oxygen stream (Stream 307) was fed on tray 12, the stream from the turbine was fed on tray 18, and the feed from the top of the high pressure column was fed on tray 1. The high oxygen purity product (Stream 308) was a product that comes from tray 38, the high nitrogen purity product (Stream 310) came from tray 1, and the waste stream (Stream 309) came from tray 8. The pressure of the low pressure column was 8.3 psig on stage 1 with a pressure drop of 0.12 psi per tray.

*High Pressure Column*

Unit ID: High Pressure Column  
Type: Distillation Column  
Material: Stainless Steel  
Specification Sheet: Page 74  
Costing Data: Page 76

Stages: 14  
Pressure: 77.3 psig  
Diameter: 9.9 feet  
Tray Spacing: .75 feet  
Reflux Ratio: 1.25

The High Pressure column was designed with ASPEN. The Condenser (Top Stage) of the high pressure column had a temperature of  $-285^{\circ}\text{F}$  with a duty of -3.97 MW and a reflux ratio of 1.25. The Reboiler (bottom stage) had a temperature of  $-279^{\circ}\text{F}$  and a boilup rate of .834. There were 10,600 lbmol/hr and 305,000 lb/hr flowing through the high pressure column. There were 14 trays in the column with a tray spacing of 0.75 feet and a diameter of 9.9 feet. The pressure of the high pressure column was 77.3 psig with a pressure drop of 0.1 psi per stage. The feed from



the heat exchanger (Stream 305) is fed on stage 14. The highly purified nitrogen (Stream 306) came out of the high pressure column on stage 1 and the enriched oxygen stream (Stream 307) came out of the column on stage 14. The high and low pressure columns were designed as two separate columns, but in reality they were really one column separated by an interface between the high and low pressure columns. The reboiler of the low pressure column and the condenser of the high pressure column had the same duty in order for this to work. They were extremely close with a difference of 0.1 MW between them.

**Section 9.2 36% Case**

*Main Air Compressor*

Unit ID: Main Air Compressor (MAC)

Type: Multi-stage Compressor

Material: Carbon Steel

Specification Sheet: Page 57

Costing Data: Page 77

Temperature: 90 °F

Pressure: 83.3 psig

Work: 12,900 hp

The multi-stage air compressor was designed with ASPEN. The compressor needed 2 intercoolers in between stages to save work. The compressor was three stages with the 2 intercoolers. The pressure changed from 12.97 psig to 37.4 psig to 83.3 psig from stage one of the compressor to stage 3. The temperature at the outlet of the coolers was set to 90°F to avoid melting the compressor. Air was the feed stream to the compressor. The outlet pressure from the multistage compressor was 83.3 psig. The total work done by the compressor was 12,900 horsepower (9.62MW) and the cooling duty was -9.6MW. There were 10,500 lbmol/hr and 302,000 lb/hr going through the compressor.



*Brazed Aluminum Heat Exchanger*

Unit ID: Heat Exchanger  
Type: Plate-fin  
Material: Brazed Aluminum  
Duty: 8.09 MW  
Specification Sheet: Page 58  
Costing Data: Page 77

LMTD (Duty/UA): 4.56 °F  
Pressure: 4-83 psig  
UA: 6,060,000 Btu/hr-R

Multi-stream heat exchanger was designed with ASPEN. The heat exchanger was a countercurrent plate-fin heat exchanger that used brazed aluminum as the material. The total duty of the heat exchanger was 8.09 MW. The UA was  $6.06 \times 10^6$  BTU/hr-R and the LMTD was 4.56°F. The heat exchanger was used to bring the feed streams to cryogenic temperatures as they moved towards the distillation columns and was also used to bring the product oxygen and nitrogen to ambient conditions. There were 20,900 lbmol/hr and 604,000 lb/hr went through the heat exchanger. Manufacturers can design the brazed aluminum heat exchangers to have pinches less than 1°C (“Brazed”).

*Column*

Unit ID: Column  
Type: Distillation Column  
Material: Stainless Steel  
Specification Sheet: Page 60  
Costing Data: Page 77

Stages: 15  
Pressure: 76.3 psig  
Diameter: 8.74 feet  
Tray Spacing: 1 foot

The distillation column was designed with ASPEN. The Condenser (Top Stage) of the column had a temperature of -285°F and the reflux ratio was set to 1.59 after much trial and error. The duty of the condenser was -4.16 MW. The Reboiler (bottom stage) had a temperature of -278°F and a boilup ratio of 1.77. There were 10,500 lbmol/hr and 302,000 lb/hr going



through the distillation column. There were 25 stages for this column with a tray spacing of 1 foot and a diameter of 8.74 feet. The feed came from the heat exchanger (Stream 103) and was fed on stage 15. The high oxygen purity product (Stream 104) was a product that came from tray 15 and the high nitrogen purity product (Stream 106) came from tray 1. The pressure of the column was 76.3 psig on stage 1 with a pressure drop of 0.12 psi per tray.

*Oxygen Valve*

Unit ID: O<sub>2</sub> valve

Type: Valve

Material: Stainless Steel

Specification Sheet: Page 62

Costing Data: Page 77

Temperature: -310 °F

Pressure: 4.3 psig

Vapor Fraction: 0.19

Oxygen valve was designed with ASPEN. The outlet pressure of the oxygen valve was 4.3 psig with a pressure drop of 73.7 psi. The outlet temperature was -310°F with a vapor fraction of 0.19. There were 6060 lbmol/hr and 179,000 lb/hr going through the oxygen valve.

*Nitrogen Valve*

Unit ID: N<sub>2</sub> valve

Type: Valve

Material: Stainless Steel

Specification Sheet: Page 62

Costing Data: Page 77

Temperature: -301 °F

Pressure: 4.3 psig

Vapor Fraction: 1

Nitrogen valve was designed with ASPEN. The outlet pressure of the nitrogen valve was 4.3 psig with a pressure drop of 72 psi. The outlet temperature was -301°F with a vapor fraction of 1. There were 4410 lbmol/hr and 124,000 lb/hr going through the nitrogen valve.



**Section 9.3 53% Case**

*Main Air Compressor*

Unit ID: Main Air Compressor (MAC)  
Type: Multi-stage Compressor  
Material: Carbon Steel  
Specification Sheet: Page 63  
Costing Data: Page 77

Temperature: 90 °F  
Pressure: 114 psig  
Work: 18,000 hp

The multi-stage air compressor was designed with ASPEN. The compressor needed 2 intercoolers in between stages to save work. The compressor was three stages with the 2 intercoolers. The pressure changed from 15.6 psig to 47.8 psig to 114.3 psig from stage one of the compressor to stage 3. The temperature at the outlet of the coolers was set to 90°F to avoid melting the compressor. Air was the feed stream to the compressor. The outlet pressure from the multistage compressor was 114.3 psig. The total work done by the compressor was 18,000 horsepower (13.4MW) and the cooling duty was -13.4MW. There was 5700 lbmol/hr and 164,000 lb/hr going through the compressor.

*Recycle Multistage Compressor*

Unit ID: Recycle Compressor Three Stages  
Type: Multi-stage compressor  
Material: Carbon Steel  
Specification Sheet: Page 63  
Costing Data: Page 77

Temperature: 89.3 °F  
Pressure: 115 psig  
Work: 6420 hp

The multi-stage recycle compressor was designed with Aspen. The compressor needed 2 intercoolers in between stages to save work. The compressor was three stages with the 2 intercoolers. The pressure changed from 20.1 psig to 52.6 psig to 115.3 psig from stage one of



the compressor to stage 3. The temperature at the outlet of the coolers was set to 90°F to avoid melting the compressor. Air was the feed stream to the compressor. The outlet pressure from the multistage compressor was 115.3 psig. The total work done by the compressor was 6420 horsepower (4.79MW) and the cooling duty was -4.8MW. There were 2250 lbmol/hr and 67,800 lb/hr going through the compressor.

*Brazed Aluminum Heat Exchanger*

Unit ID: Heat Exchanger  
Type: Plate-fin  
Material: Brazed Aluminum  
Duty: 13.6 MW  
Specification Sheet: Page 64  
Costing Data: Page 77

LMTD (Duty/UA): 14.7 °F  
Pressure: 5-115 psig  
UA: 3,160,000 Btu/hr-R

Multi-stream heat exchanger was designed with ASPEN. The heat exchanger was a countercurrent plate-fin heat exchanger that used brazed aluminum as the material. The total duty of the heat exchanger was 13.6 MW. The UA was  $3.16 \times 10^6$  BTU/hr-R and the LMTD was 14.7°F. The heat exchanger was used to bring the feed streams to cryogenic temperatures as they moved towards the distillation columns and was also used to bring the product oxygen and nitrogen to ambient conditions. 35,100 lbmol/hr and 1,020,000 lb/hr went through the heat exchanger. Manufacturers can design the brazed aluminum heat exchangers to have pinches less than 1°C (“Brazed”).

*Column*

Unit ID: Column  
Type: Distillation Column  
Material: Stainless Steel  
Specification Sheet: Page 66  
Costing Data: Page 77

Stages: 25  
Pressure: 8.3 psig  
Diameter 1: 10.9 feet  
Diameter 2: 6.49 feet  
Tray Spacing: 1 foot





The distillation column was designed with ASPEN. The Condenser (Top Stage) of the column has a temperature of  $-277^{\circ}\text{F}$  and the reflux ratio was set to 1.52 after much trial and error. The duty of the condenser was  $-6.5$  MW. The Reboiler (bottom stage) had a temperature of  $-265^{\circ}\text{F}$  and a boilup ratio of 0.535. There were 17,500 lbmol/hr and 512,000 lb/hr going through the distillation column. There were 25 stages for this column with a tray spacing of 1 foot and a diameter 1 of 10.9 feet and a diameter 2 of 6.49 feet. The different diameters were due to the different feeds to the column. The feeds came from the heat exchanger stream 203 which was fed on stage 21 and stream 204 which was fed on stage 26. The high oxygen purity product (Stream 205) was a product that came from tray 25 and the high nitrogen purity product (Stream 210) that came from tray 1. The pressure of the column was 110.3 psig on stage 1 with a pressure drop of 0.12 psi per tray.

*Oxygen Valve*

Unit ID: O<sub>2</sub> valve

Type: Valve

Material: Stainless Steel

Specification Sheet: Page 68

Costing Data: Page 77

Temperature:  $-306^{\circ}\text{F}$

Pressure: 5.3 psig

Vapor Fraction: 0.23

Oxygen valve was designed with ASPEN. The outlet pressure of the oxygen valve was 5.3 psig with a pressure drop of 108 psi. The outlet temperature was  $-306^{\circ}\text{F}$  with a vapor fraction of 0.23. There were 4960 lbmol/hr and 149,000 lb/hr going through the oxygen valve.



*Nitrogen Valve*

Unit ID: N<sub>2</sub> valve

Type: Valve

Material: Stainless Steel

Specification Sheet: Page 68

Costing Data: Page 77

Temperature: -299 °F

Pressure: 5.3 psig

Vapor Fraction: 1

Nitrogen valve was designed with ASPEN. The outlet pressure of the oxygen valve was 5.3 psig with a pressure drop of 105 psi. The outlet temperature was -299°F with a vapor fraction of 1. There were 7610 lbmol/hr and 213,000 lb/hr going through the nitrogen valve.

*Recycle Valve*

Unit ID: Recycle valve

Type: Valve

Material: Stainless Steel

Specification Sheet: Page 68

Costing Data: Page 77

Temperature: -306 °F

Pressure: 5.3 psig

Vapor Fraction: .23

Recycle valve was designed with ASPEN. The outlet pressure of the oxygen valve was 5.3 psig with a pressure drop of 108 psi. The outlet temperature was -306°F with a vapor fraction of 0.23. There were 4960 lbmol/hr and 149,000 lb/hr going through the recycle valve.



# Section 10

## Specification Sheets



**10.1 36% Case:**

<b>Main Air Compressor</b>		
<b>Identification:</b>	Date: April 17, 2018	
	Item	Compressor
	Item No.	MAC
	No. Required	1
<b>Function:</b>	Increases pressure and lowers volume of inlet stream	
<b>Operation:</b>	Continuous	
Streams:	101	102
Inlet/Outlet:	In	Out
<b>Temperature (°F)</b>	85	90
<b>Pressure (psia)</b>	14.7	98
<b>Vapor Fraction</b>	1	1
<b>Mass Flow (lb/hr)</b>	302,000	302,000
<b>Component Mass Flow (lb/hr)</b>		
<i>Nitrogen</i>	232,000	232,000
<i>Oxygen</i>	70,400	70,400
<b>Component Molar Composition</b>		
<i>Nitrogen</i>	0.79	0.79
<i>Oxygen</i>	0.21	0.21
<b>Molar Flow (lbmol/hr)</b>	10,500	10,500
<b>Operating Volume Flow (cuft/hr)</b>	4,160,000	631,000
<b>Design Data:</b>		
Outlet Pressure (psia)	98	
Total Work (MW)	9.65	
Total Cooling Duty (MW)	-9.59	
Net Work Required (MW)	9.65	
Net Cooling Duty (MW)	-9.59	
<b>Utilities:</b>	Requires 9.65 MW of power	
<b>Comments and drawings:</b>		



<b>Brazed Aluminum Heat Exchanger</b>						
		Date: April 17, 2018				
<b>Identification:</b>	Item No.	Heat Exchanger				
	No. Required				1	
<b>Function:</b>	Heats and cools streams accordingly					
<b>Operation:</b>	Continuous					
<b>Streams:</b>	102	103	107	109	108	110
<b>Inlet/Outlet:</b>	In	Out	In	Out	In	Out
<b>Temperature (°F)</b>	90	-273	-278	87.5	-301	89
<b>Pressure (psia)</b>	98	93	19	14	19	14
<b>Vapor Fraction</b>	1	1	1	1	1	1
<b>Mass Flow (lb/hr)</b>	302,000	302,000	179,000	179,000	124,000	124,000
<b>Component Mass Flow (lb/hr)</b>						
<i>Nitrogen</i>	232,000	232,000	108,000	108,000	123,000	123,000
<i>Oxygen</i>	70,400	70,400	70,200	70,200	206	206
<b>Component Molar Composition</b>						
<i>Nitrogen</i>	0.79	0.79	0.64	1	0.999	0.999
<i>Oxygen</i>	0.21	0.21	0.36	0	0.001	0.001
<b>Molar Flow (lbmol/hr)</b>	10,500	10,500	6,050	6,050	4,400	4,400
<b>Operating Volume Flow (cuft/hr)</b>	631,000	196,000	605,000	2,540,000	381,000	1,850,000
<b>Design Data:</b>						
Duty (MW)	8.1					
<b>Utilities:</b>	Requires 8.1 MW of power					
<b>Comments and drawings:</b>	Brazed Aluminum, Plate-fin					



<b>Coldbox</b>	
<b>Identification:</b>	Item Coldbox Date: April 17, 2018 No. Required 1
<b>Function:</b>	Keep at Cryogenic temperatures.
<b>Operation:</b>	Continuous
<b>Streams:</b>	N/A
<b>Temperature (°F)</b>	N/A
<b>Pressure (psia)</b>	N/A
<b>Vapor Fraction</b>	N/A
<b>Mass Flow (lb/hr)</b>	N/A
<b>Component Mass Flow (lb/hr)</b>	N/A
<i>Nitrogen</i>	N/A
<i>Oxygen</i>	N/A
<i>Carbon Dioxide</i>	N/A
<i>Water</i>	N/A
<i>Methane</i>	N/A
<b>Molar Flow (lbmol/hr)</b>	N/A
<b>Operating Volume Flow (cuft/hr)</b>	N/A
<b>Design Data:</b>	Diameter: Excess 4 feet Height: Excess 10 feet to make space for heat exchanger
<b>Utilities:</b>	N/A
<b>Comments and drawings:</b>	surrounds heat exchanger to keep at cryogenic temperatures



<b>Column</b>	Date: April 17, 2018			
<b>Identification:</b>	Item		Column	
	Item No.			
	No. Required		1	
<b>Function:</b>	Separates inlet air stream into enriched streams			
<b>Operation:</b>	Continuous			
<b>Streams:</b>	103	104	106	
<b>Inlet/Outlet:</b>	In	Out	Out	
<b>Temperature (°F)</b>	-273	-278	-285	
<b>Pressure (psia)</b>	93	93	91	
<b>Vapor Fraction</b>	1	0	1	
<b>Mass Flow (lb/hr)</b>	302,000	179,000	124,000	
<b>Component Mass Flow (lb/hr)</b>				
<i>Nitrogen</i>	232,000	108,000	123,000	
<i>Oxygen</i>	70,400	70,200	206	
<b>Component Molar Composition</b>				
<i>Nitrogen</i>	0.79	0.36	0.999	
<i>Oxygen</i>	0.21	0.64	0.001	
<b>Molar Flow (lbmol/hr)</b>	4750	2750	2000	
<b>Operating Volume Flow (cuft/hr)</b>	196,000	3,580	77,200	
<b>Design Data:</b>		Condenser	Reboiler	
Temperature (°F)		-285	-278	
Heat Duty (MW)		-4.16	0	
Boilup Ratio			1.77	
Reflux Ratio		1.59		
<b>Utilities:</b>	Produces 4.16 MW of power			
<b>Comments and drawings:</b>				



<b>Heater</b>		
<b>Identification:</b>	Date: April 17, 2018	
	Item	Heater
	Item No.	
	No. Required	1
<b>Function:</b>	Increases temperature of oxygen stream before heat exchanger	
<b>Operation:</b>	Continuous	
<b>Streams:</b>	105	107
<b>Inlet/Outlet:</b>	In	Out
<b>Temperature (°F)</b>	-310	-278
<b>Pressure (psia)</b>	19	19
<b>Vapor Fraction</b>	0.19	1
<b>Mass Flow (lb/hr)</b>	179,000	179,000
<b>Component Mass Flow (lb/hr)</b>		
<i>Nitrogen</i>	108,000	108,000
<i>Oxygen</i>	70,200	70,200
<b>Component Molar Composition</b>		
<i>Nitrogen</i>	0.64	0.64
<i>Oxygen</i>	0.36	0.36
<b>Molar Flow (lbmol/hr)</b>	6,050	6,050
<b>Operating Volume Flow (cuft/hr)</b>	95,100	605,000
<b>Design Data:</b>		
Outlet Temperature (°F)	-278	
Outlet Pressure (psia)	19	
Vapor Fraction	1	
Heat Duty (MW)	4.16	
<b>Utilities:</b>	Requires 4.16 MW of power	
<b>Comments and drawings:</b>		





<b>Valve</b>				
Date: April 17, 2018				
<b>Identification:</b>	Item	Valve		
	Item No.			
	No. Required	2		
<b>Function:</b>	Lowers pressure of and partially vaporizes inlet stream			
<b>Operation:</b>	Continuous			
<b>Streams:</b>	104	105	106	108
<b>Inlet/Outlet:</b>	In	Out	In	Out
<b>Temperature (°F)</b>	-278	-310	-285	-301
<b>Pressure (psia)</b>	93	19	91	19
<b>Vapor Fraction</b>	0	0.19	1	1
<b>Mass Flow (lb/hr)</b>	179,000	179,000	124,000	124,000
<b>Component Mass Flow (lb/hr)</b>				
<i>Nitrogen</i>	108,000	108,000	123,000	123,000
<i>Oxygen</i>	70,200	70,200	206	206
<b>Component Molar Composition</b>				
<i>Nitrogen</i>	0.64	0.64	0.999	1
<i>Oxygen</i>	0.36	0.36	0.001	0
<b>Molar Flow (lbmol/hr)</b>	6,050	6,050	4,400	4,400
<b>Operating Volume Flow (cuft/hr)</b>	3,580	95,100	77,200	381,000
<b>Design Data:</b>	Valve 1	Valve 2		
Pressure Drop (psia)	74	72		
Outlet Temperature (°F)	-310	-301		
Outlet Pressure (psia)	19	19		
Outlet Vapor Fraction	0.19	1		
<b>Utilities:</b>				
<b>Comments and drawings:</b>				



**10.2 53% Case**

<b>Main Air Compressor</b>				
<b>Identification:</b>	Date: April 17, 2018			
	Item	Compressor		
	Item No.	MAC		
	No. Required	2		
<b>Function:</b>	Increases pressure and lowers volume of inlet stream			
<b>Operation:</b>	Continuous			
Streams:	201	202	212	213
Inlet/Outlet:	In	Out	In	Out
<b>Temperature (°F)</b>	85	90	88	90
<b>Pressure (psia)</b>	14.7	129	18	130
<b>Vapor Fraction</b>	1	1	1	1
<b>Mass Flow (lb/hr)</b>	363,000	363,000	149,000	149,000
<b>Component Mass Flow (lb/hr)</b>				
<i>Nitrogen</i>	278,000	278,000	65,600	65,600
<i>Oxygen</i>	84,400	84,400	83,700	83,700
<b>Component Molar Composition</b>				
<i>Nitrogen</i>	0.79	0.79	0.47	0.47
<i>Oxygen</i>	0.21	0.21	0.53	0.53
<b>Molar Flow (lbmol/hr)</b>	12,500	12,500	4,950	4,950
<b>Operating Volume Flow (cuft/hr)</b>	5,000,000	575,000	1,620,000	225,000
<b>Design Data:</b>	Feed Air	Recycle		
Outlet Pressure (psia)	129	130		
Total Work (MW)	13.4	4.79		
Total Cooling Duty (MW)	-13.4	-4.8		
Net Work Required (MW)	13.4	4.79		
Net Cooling Duty (MW)	-13.4	-4.8		
<b>Utilities:</b>	Require 18.2 MW of power together			
<b>Comments and drawings:</b>	Streams 201 and 202 for one compressor and Streams 212 and 213 for the other			



<b>Brazed Aluminum Heat Exchanger</b>		Date: April 17, 2018									
<b>Identification:</b>	Item Item No. No. Required	Heat Exchanger  1									
<b>Function:</b>	Heats and cools streams accordingly										
<b>Operation:</b>	Continuous										
<b>Streams:</b>	202	203	209	214	211	215	213	204	216	212	
<b>Inlet/Outlet:</b>	In	Out	In	Out	In	Out	In	Out	In	Out	
<b>Temperature (°F)</b>	90	-269	35	85	-299	88	90	-256	-306	88	
<b>Pressure (psia)</b>	129	127	20	18	20	18	130	128	20	18	
<b>Vapor Fraction</b>	1	0.98	1	1	1	1	1	1	0.23	1	
<b>Mass Flow (lb/hr)</b>	363,000	363,000	149,000	149,000	213,000	213,000	149,000	149,000	149,000	149,000	
<b>Component Mass Flow (lb/hr)</b>											
<i>Nitrogen</i>	278,000	278,000	65,600	65,600	212,000	212,000	65,600	65,600	65,600	65,600	
<i>Oxygen</i>	84,400	84,400	83,700	83,700	700	700	84,700	84,700	84,700	84,700	
<b>Component Molar Composition</b>											
<i>Nitrogen</i>	0.79	0.79	0.47	0.47	0.997	0.997	0.47	0.47	0.47	0.47	
<i>Oxygen</i>	0.21	0.21	0.53	0.53	0.003	0.003	0.53	0.53	0.53	0.53	
<b>Molar Flow (lbmol/hr)</b>	12,500	12,500	4,950	4,950	7,590	7,590	4,950	4,950	4,950	4,950	
<b>Operating Volume Flow (cuft/hr)</b>	575,000	164,000	1,320,000	1,610,000	630,000	2,480,000	225,000	72,000	92,800	1,620,000	
<b>Design Data:</b>											
Duty (MW)	13.6										
UA (BTU/hr-F)	3,160,000										
Hot End Temperature Approach (°F)	1.95										
Cold End Temperature Approach (°F)	36.6										
Hot NTU	24.4										
Cold NTU	26.8										
<b>Utilities:</b>	Requires 13.6 MW of power										
<b>Comments and drawings:</b>	Brazed Aluminum, Plate-fin										



<b>Coldbox</b>	
<b>Identification:</b>	Item Coldbox Date: April 17, 2018
	No. Required 1
<b>Function:</b>	Keep at Cryogenic temperatures.
<b>Operation:</b>	Continuous
<b>Streams:</b>	N/A
<b>Temperature (°F)</b>	N/A
<b>Pressure (psia)</b>	N/A
<b>Vapor Fraction</b>	N/A
<b>Mass Flow (lb/hr)</b>	N/A
<b>Component Mass Flow (lb/hr)</b>	N/A
<i>Nitrogen</i>	N/A
<i>Oxygen</i>	N/A
<i>Carbon Dioxide</i>	N/A
<i>Water</i>	N/A
<i>Methane</i>	N/A
<b>Molar Flow (lbmol/hr)</b>	N/A
<b>Operating Volume Flow (cuft/hr)</b>	N/A
<b>Design Data:</b>	
	Diameter: Excess 4 feet
	Height: Excess 10 feet to make space for heat exchanger
<b>Utilities:</b>	N/A
<b>Comments and drawings:</b>	surrounds heat exchanger to keep at cryogenic temperatures



<b>Column</b>	April 17, 2018			
<b>Identification:</b>	Item	Column		
	Item No.			
	No. Required	1		
<b>Function:</b>	Separates air stream into enriched streams			
<b>Operation:</b>	Continuous			
Streams:	203	204	205	210
Inlet/Outlet:	In	In	Out	Out
Temperature (°F)	-269	-256	-265	-277
Pressure (psia)	127	128	128	125
Vapor Fraction	0.98	1	0	1
Mass Flow (lb/hr)	363,000	149,000	299,000	213,000
<b>Component Mass Flow (lb/hr)</b>				
<i>Nitrogen</i>	278,000	65,600	131,000	212,000
<i>Oxygen</i>	84,400	83,700	167,000	700
<b>Component Molar Composition</b>				
<i>Nitrogen</i>	0.79	0.47	0.47	0.997
<i>Oxygen</i>	0.21	0.53	0.53	0.003
Molar Flow (lbmol/hr)	12,500	4,950	9,900	7,590
Operating Volume Flow (cuft/hr)	164,000	72,000	5,870	96,900
<b>Design Data:</b>	Condenser Reboiler			
Heat Duty (MW)	-6.5	0		
Outlet Temperature (°F)	-277	-265		
Outlet Pressure (psia)	125	128		
Boilup Ratio		0.53		
Reflux Ratio	1.52			
<b>Utilities:</b>	Produces 6.5 MW of power			
<b>Comments and drawings:</b>				



<b>Heater</b>		
Date: April 17, 2018		
<b>Identification:</b>	Item	Heater
	Item No.	
	No. Required	1
<b>Function:</b>	Raises temperature of oxygen stream before entering heat exchanger.	
<b>Operation:</b>	Continuous	
<b>Streams:</b>	208	209
<b>Inlet/Outlet:</b>	In	Out
<b>Temperature (°F)</b>	-306	34.7
<b>Pressure (psia)</b>	20	20
<b>Vapor Fraction</b>	0.23	1
<b>Mass Flow (lb/hr)</b>	149,000	149,000
<b>Component Mass Flow (lb/hr)</b>		
<i>Nitrogen</i>	65,600	65,600
<i>Oxygen</i>	83,700	83,700
<b>Component Molar Composition</b>		
<i>Nitrogen</i>	0.47	0.47
<i>Oxygen</i>	0.53	0.53
<b>Molar Flow (lbmol/hr)</b>	4,950	4,950
<b>Operating Volume Flow (cuft/hr)</b>	92,800	1.32E+06
<b>Design Data:</b>		
Heat Duty (MW)	6.5	
Outlet Temperature (°F)	34.7	
Outlet Pressure (psia)	20	
<b>Utilities:</b>	Requires 6.5 MW of power	
<b>Comments and drawings:</b>		



<b>Valve</b>	Date: April 17, 2018					
<b>Identification:</b>	Item	Valve				
	Item No.					
	No. Required	3				
<b>Function:</b>	Lowers pressure of and partially vaporizes inlet stream					
<b>Operation:</b>	Continuous					
<b>Streams:</b>	207	208	210	211	206	209
<b>Inlet/Outlet:</b>	In	Out	In	Out	In	Out
<b>Temperature (°F)</b>	-265	-306	-277	-299	-265	-306
<b>Pressure (psia)</b>	128	20	125	20	128	20
<b>Vapor Fraction</b>	0	0.23	1	1	0	0.23
<b>Mass Flow (lb/hr)</b>	149,000	149,000	213,000	213,000	149,000	149,000
<b>Component Mass Flow (lb/hr)</b>						
<i>Nitrogen</i>	65,600	65,600	212,000	212,000	65,600	65,600
<i>Oxygen</i>	83,700	83,700	700	700	83,700	83,700
<b>Component Molar Composition</b>						
<i>Nitrogen</i>	0.47	0.47	0.997	0.997	0.47	0.47
<i>Oxygen</i>	0.53	0.53	0.003	0.003	0.53	0.53
<b>Molar Flow (lbmol/hr)</b>	4,950	4,950	7,590	7,590	4,950	4,950
<b>Operating Volume Flow (cuft/hr)</b>	2,940	92,800	96,900	630,000	2,940	92,800
<b>Design Data:</b>	Valve 1	Valve 2	Valve 3			
Pressure Drop (psia)	108	105	108			
Outlet Temperature (°F)	-306	-299	-306			
Outlet Pressure (psia)	20	20	20			
Outlet Vapor Fraction	0.23	1	0.23			
<b>Utilities:</b>						
<b>Comments and drawings:</b>	Stream 210 and 211 one valve, Streams 206 and 209 one valve, and Streams 207 and 208 one valve					



**10.3 95% Case:**

<b>Main Air Compressor</b>			
<b>Identification:</b>	Item	Compressor	Date: April 17,2018
	Item No.	MAC	
	No. Required	1	
<hr/>			
<b>Function:</b>	Compress inlet stream of air		
<b>Operation:</b>	Continuous		
<hr/>			
<b>Streams:</b>	301	302	
<b>Inlet/Outlet:</b>	In	Out	
<b>Temperature (°F)</b>	85	95	
<b>Pressure (psig)</b>	0	87.3	
<b>Vapor Fraction</b>	1	1	
<b>Mass Flow (lb/hr)</b>	382,000	382,000	
<b>Component Mass Flow (lb/hr)</b>			
<i>Nitrogen</i>	293,000	293,000	
<i>Oxygen</i>	88,900	88,900	
<b>Component Molar Compositon</b>			
<i>Nitrogen</i>	0.79	0.79	
<i>Oxygen</i>	0.21	0.21	
<b>Molar Flow (lbmol/hr)</b>	13,200	13,200	
<b>Operating Volume Flow (cuft/hr)</b>	5.26E+06	770,000	
<hr/>			
<b>Design Data:</b>	Outlet Pressure: 87.3 psia Total Work: 13.96 MW Total Cooling Duty: -13.76 MW Carbon Steel		
<b>Utilities:</b>	13.96 MWh of Electricity		
<b>Comments and drawings:</b>	Intercoolers between stages allows cooling in between the stages, saving work.		





**Brazed Aluminum Plate-Fin  
Heat Exchanger**

Date: April 17, 2018

**Identification:**  
Item Heat Exchanger  
Item No.  
No. Required 1

**Function:** Cool stream from compressor to cryogenic temperatures and warm the product streams.

**Operation:** Continuous

<b>Streams:</b>	302	303	305	308	309	310	311	312	313
<b>Inlet/Outlet</b>	In	Out	Out	In	In	In	Out	Out	Out
<b>Temperature (°F)</b>	95	-150	-277	-289	-308	-313	80	80	80
<b>Pressure (psia)</b>	87.3	87.3	87.3	12.6	9	8.3	8.3	9	8.3
<b>Vapor Fraction</b>	1	1	0.59	0	1	1	1	1	1
<b>Mass Flow (lb/hr)</b>	382,000	76,300	305,000	222,000	128,000	179,000	74,700	128,000	179,000
<b>Component Mass Flow (lb/hr)</b>									
<i>Nitrogen</i>	293,000	17,800	71,100	3,505	112,000	177,000	3505	112,000	177,000
<i>Oxygen</i>	88,900	58,500	234,000	71,200	15,900	1780	71,200	15,900	1780
<b>Component Molar Composition</b>									
<i>Nitrogen</i>	0.79	0.79	0.79	0.053	0.889	0.991	0.053	0.889	0.991
<i>Oxygen</i>	0.21	0.21	0.21	0.947	0.111	0.009	0.947	0.111	0.009
<b>Molar Flow (lbmol/hr)</b>	13,200	2,650	10,600	2350	4500	6380	2350	4500	6380
<b>Operating Volume Flow (cuft/hr)</b>	770,000	83,300	104,000	1100	291,000	413,000	591,000	1.10E+06	1.6E+06

**Design Data:**  
Duty: -12.5 MW

**Utilities:**

**Comments and drawings:** Brazed Aluminum, Plate-Fin



<b>Coldbox</b>	
<b>Identification:</b>	Item Coldbox Date: April 17, 2018
	No. Required 1
<b>Function:</b>	Keep at Cryogenic temperatures.
<b>Operation:</b>	Continuous
<b>Streams:</b>	N/A
<b>Temperature (°F)</b>	N/A
<b>Pressure (psia)</b>	N/A
<b>Vapor Fraction</b>	N/A
<b>Mass Flow (lb/hr)</b>	N/A
<b>Component Mass Flow (lb/hr)</b>	N/A
<i>Nitrogen</i>	N/A
<i>Oxygen</i>	N/A
<i>Carbon Dioxide</i>	N/A
<i>Water</i>	N/A
<i>Methane</i>	N/A
<b>Molar Flow (lbmol/hr)</b>	N/A
<b>Operating Volume Flow (cuft/hr)</b>	N/A
<b>Design Data:</b>	
	Diameter: Excess 4 feet
	Height: Excess 10 feet to make space for heat exchanger
<b>Utilities:</b>	N/A
<b>Comments and drawings:</b>	surrounds heat exchanger to keep at cryogenic temperatures



<b>Turbine</b>		Date: April 17, 2018
<b>Identification:</b>	Item	Turbine
	No. Required	1
<b>Function:</b>	Reduce Temperature and Pressure of Stream 303.	
<b>Operation:</b>	Continuous	
<b>Streams:</b>	303	304
<b>Inlet/Outlet:</b>	In	Out
<b>Temperature (°F)</b>	-150	-244
<b>Pressure (psia)</b>	87.3	10.3
<b>Vapor Fraction</b>	1	1
<b>Mass Flow (lb/hr)</b>	76,300	76,300
<b>Component Mass Flow (lb/hr)</b>		
<i>Nitrogen</i>	17,800	17,800
<i>Oxygen</i>	58,500	58,500
<b>Molar Composition</b>		
<i>Nitrogen</i>	0.79	0.79
<i>Oxygen</i>	0.21	0.21
<b>Molar Flow (lbmol/hr)</b>	2,650	2650
<b>Operating Volume Flow (cuft/hr)</b>	83,300	239,000
<b>Design Data:</b>	Net work required: -0.48 MW Efficiency: 0.9 Outlet pressure: 10.3 psig Outlet temperature: -244 (°F) Isentropic outlet temperature: -254 (°F)	
<b>Utilities:</b>	Produces 0.48 MW of electricity	
<b>Comments and drawings:</b>		



<b>Low Pressure Column</b>							
<b>Identification:</b>		Item	Date: April 17, 2018				
		Item No.	Dist Column				
		No.					
		Required	1				
<b>Function:</b>							
<b>Operation:</b>		Continuous					
<b>Streams:</b>							
		304	306	307	308	309	310
<b>Inlet/Outlet:</b>		In	In	In	Out	Out	Out
<b>Temperature (°F)</b>		-244	-285	-279	-289	-308	-313
<b>Pressure (psia)</b>		10.3	77.3	78.6	12.6	9	8.3
<b>Vapor Fraction</b>		1	0	0	0	1	1
<b>Mass Flow (lb/hr)</b>		76,300	83,000	222,000	222,000	128,000	179,000
<b>Component Mass Flow (lb/hr)</b>							
	<i>Nitrogen</i>	17,800	82,200	152,000	3,505	112,000	177,000
	<i>Oxygen</i>	58,500	671	70,440	71,200	15,900	1780
<b>Component Molar Composition</b>							
	<i>Nitrogen</i>	0.79	0.993	0.71	0.053	0.889	0.991
	<i>Oxygen</i>	0.21	0.007	0.29	0.947	0.111	0.009
<b>Molar Flow (lbmol/hr)</b>		2650	2960	7630	2350	4500	6380
<b>Operating Volume Flow (cuft/hr)</b>		239,000	1880	4530	1100	291,000	413,000
<b>Design Data:</b>							
Heat Duty: 4.1MW							
Reflux Ratio: 0.38							
Stages:38							
Feed Stream 304 on Tray 18							
Feed Stream 307 on Tray 12							
Feed Stream 306 on Tray 1							
Pressure Stage 1: 8.3 psig							
Pressure Drop per Stage: .12							
Tray Spacing: 1 foot							
Diameter: 11.4 feet							
Carbon Steel							
<b>Utilities:</b> 4.1 MW electricity							
<b>Comments and drawings:</b>							



<b>High Pressure Column</b>			
<b>Identification:</b>	Item Item No. No. Required	Dist Column   1	
<b>Function:</b>			
<b>Operation:</b>	Continuous		
Streams:	305	306	307
Inlet/Outlet:	In	Out	Out
<b>Temperature (°F)</b>	-277	-285	-279
<b>Pressure (psia)</b>	87.3	77.3	78.6
<b>Vapor Fraction</b>	0.59	0	0
<b>Mass Flow (lb/hr)</b>	305,000	83,000	222,000
<b>Component Mass Flow (lb/hr)</b>			
<i>Nitrogen</i>	234,000	82,200	152,000
<i>Oxygen</i>	71,100	\	70,440
<b>Component Molar Composition</b>			
<i>Nitrogen</i>	0.79	0.993	0.71
<i>Oxygen</i>	0.21	0.007	0.29
<b>Molar Flow (lbmol/hr)</b>	10,600	2960	7630
<b>Operating Volume Flow (cuft/hr)</b>	104,000	1880	4530
<b>Design Data:</b>			
Heat Duty: -3.97			
Reflux Ratio: 1.25			
Feed Stream 305 on Tray 14			
Trays: 14			
Pressure Stage 1: 77.3 psig			
Pressure Drop per Stage: .1 psig			
Tray Spacing: .75 feet			
Diameter: 9.87 feet			
Carbon Steel			
<b>Utilities:</b> Generates 3.97 MW			
<b>Comments and drawings:</b>			



# Section 11

## Equipment Cost Summary



All equipment costs, except for the BAHXs, were estimated using correlations from Product and Process Design Principles: Synthesis, Analysis, and Design by Seider et al. The CE index was projected to be 595 in December 2018 - a 4% increase from December 2017. The cost of the BAHXs was estimated using correlations provided by our project author, Adam Brostow, and additional data from a previous senior design project that used a brazed aluminum heat exchanger (Rodrigues). To estimate the cost of the “black box” natural gas power generation plant, US Environmental Protection Agency data regarding the cost of a natural gas small scale combined heat and power system, which revealed the total installed cost to be about \$650/kw of capacity (Darrow). The largest share of the equipment costs was made up by the compressors and the power plant since it was calculated as one line item. The following three tables show the equipment costs for each of our three oxygen enrichment scenarios.

Table 11.1. Equipment costs and bare module factors for 95% purity oxygen plant and power plant

Equipment Description	Purchase Cost	Bare Module Factor	Bare Module Cost
<b>Name</b>		(default 3.21 if blank)	
Expander	\$120,000	3.21	\$385,200
MAC	\$4,880,000	2.15	\$10,492,000
Cold Box	\$240,000	4.16	\$998,400
High Pressure Column	\$275,000	4.16	\$1,144,000
Low Pressure Column	\$447,000	4.16	\$1,860,000
BAHX	\$750,000	3	\$2,250,000
Power plant	\$27,300,000	1	\$27,300,000
<b>Total</b>			<b>\$44,430,000</b>



Table 11.2. Equipment costs and bare module factors for 53% purity oxygen plant and power plant

Equipment Description	Purchase Cost	Bare Module Factor	Bare Module Cost
<b>Name</b>		(default 3.21 if blank)	
MAC	\$4,750,000	2.15	\$10,200,000
Recycle Compressor	\$2,500,000	2.15	\$5,400,000
Cryogenic Column	\$450,000	4.16	\$1,880,000
Cold box	\$170,000	4.16	\$710,000
BAHX	\$810,000	3	\$2,430,000
Power Plant	\$27,300,000	1	\$27,300,000
<b>Total</b>			<b>\$47,920,000</b>

Table 11.3. Equipment costs and bare module factors for 36% purity oxygen plant and power plant

Equipment Description	Purchase Cost	Bare Module Factor	Bare Module Cost
<b>Name</b>		(default 3.21 if blank)	
MAC	\$3,870,000	2.15	\$8,320,000
Cryogenic Column	\$200,000	4.16	\$832,000
Cold Box	\$113,000	4.16	\$470,000
BAHX	\$475,000	3	\$1,425,000
Power Plant	\$26,000,000	1	\$26,000,000
<b>Total</b>			<b>\$37,000,000</b>





## **Section 12**

# **Fixed-Capital Investment Summary**



The fixed capital investment summary includes the equipment expenditures shown in section 11 of this report, land expenses, site preparation and contingencies, contractor fees, and plant start-up. The following tables show the factors used to calculate the fixed-capital investment. The assumptions were discussed with industrial consultants and advisors for the project, further, they were consistent with the assumptions given in Seider et al.

Table 12.1. Assumptions and methods used to calculate the total permanent investment

Total Permanent Investment		
Year:	% of Total Permanent Investment	
2019	100%	(default is first year of Construction, otherwise over-ride this year)
2020	0%	
2021	0%	
2022	0%	
	Cost of Site Preparations:	5.00% of Total Bare Module Costs
	Cost of Service Facilities:	5.00% of Total Bare Module Costs
	Allocated Costs for utility plants and related facilities:	\$0
	Cost of Contingencies and Contractor Fees:	18.00% of Direct Permanent Investment
	Cost of Land:	2.00% of Total Depreciable Capital
	Cost of Royalties:	\$0
	Cost of Plant Start-Up:	10.00% of Total Depreciable Capital

The total permanent investments for each oxygen purity were calculated following the same rules. It is likely that this project would be undertaken by a regulated utility or a competitive electricity generator so a discount rate of 9% was used. This is a reasonable assumption according to the European Union’s PRIME model (Capros). The following tables show the total permanent investments for the three oxygen purity levels including the cost of the power generation. The capital cost would be incurred in 2018 for each scenario.



Table 12.2. Total permanent investment cost for 95% oxygen and power generation.

<b>Investment Summary</b>			
<b><u>Total Bare Module Costs:</u></b>			
Fabricated Equipment	\$	6,250,859	
Process Machinery	\$	38,176,166	
<b><u>Total Bare Module Costs:</u></b>			<b>\$ 44,427,025</b>
<b><u>Direct Permanent Investment</u></b>			
Cost of Site Preparations:	\$	2,221,351	
Cost of Service Facilities:	\$	2,221,351	
Allocated Costs for utility plants and related facilities:	\$	-	
<b><u>Direct Permanent Investment</u></b>			<b>\$ 48,869,727</b>
<b><u>Total Depreciable Capital</u></b>			
Cost of Contingencies & Contractor Fees	\$	8,796,551	
<b><u>Total Depreciable Capital</u></b>			<b>\$ 57,666,278</b>
<b><u>Total Permanent Investment</u></b>			
Cost of Land:	\$	1,153,326	
Cost of Royalties:	\$	-	
Cost of Plant Start-Up:	\$	5,766,628	
<b>Total Permanent Investment - Unadjusted</b>			<b>\$ 64,586,232</b>
Site Factor			1.00
<b><u>Total Permanent Investment</u></b>			<b>\$ 64,586,232</b>



Table 12.3. Total permanent investment cost for 53% oxygen and power generation.

<b>Investment Summary</b>		
<b>Total Bare Module Costs:</b>		
Fabricated Equipment	\$	5,020,000
Process Machinery	\$	42,912,500
<b>Total Bare Module Costs:</b>	<b>\$</b>	<b>47,932,500</b>
<b>Direct Permanent Investment</b>		
Cost of Site Preparations:	\$	2,396,625
Cost of Service Facilities:	\$	2,396,625
Allocated Costs for utility plants and related facilities:	\$	-
<b>Direct Permanent Investment</b>	<b>\$</b>	<b>52,725,750</b>
<b>Total Depreciable Capital</b>		
Cost of Contingencies & Contractor Fees	\$	9,490,635
<b>Total Depreciable Capital</b>	<b>\$</b>	<b>62,216,385</b>
<b>Total Permanent Investment</b>		
Cost of Land:	\$	1,244,328
Cost of Royalties:	\$	-
Cost of Plant Start-Up:	\$	6,221,639
<b>Total Permanent Investment - Unadjusted</b>	<b>\$</b>	<b>69,682,351</b>
Site Factor		1.00
<b>Total Permanent Investment</b>	<b>\$</b>	<b>69,682,351</b>



Table 12.4. Total permanent investment cost for 36% oxygen and power generation.

<b>Investment Summary</b>			
<b>Total Bare Module Costs:</b>			
Fabricated Equipment	\$	2,727,080	
Process Machinery	\$	34,320,500	
<b>Total Bare Module Costs:</b>			<b>\$ 37,047,580</b>
<b>Direct Permanent Investment</b>			
Cost of Site Preparations:	\$	1,852,379	
Cost of Service Facilities:	\$	1,852,379	
Allocated Costs for utility plants and related facilities:	\$	-	
<b>Direct Permanent Investment</b>			<b>\$ 40,752,338</b>
<b>Total Depreciable Capital</b>			
Cost of Contingencies & Contractor Fees	\$	7,335,421	
<b>Total Depreciable Capital</b>			<b>\$ 48,087,759</b>
<b>Total Permanent Investment</b>			
Cost of Land:	\$	961,755	
Cost of Royalties:	\$	-	
Cost of Plant Start-Up:	\$	4,808,776	
<b>Total Permanent Investment - Unadjusted</b>			<b>\$ 53,858,290</b>
Site Factor			1.00
<b>Total Permanent Investment</b>			<b>\$ 53,858,290</b>



# Section 13

## Operating and Variable Costs



In this section, the operating and variable costs will be tabulated. This includes the maintenance, operations, wages, utilities, raw materials, etc. First, the variable costs will be shown. These have been modeled treating the plant like a nitrogen plant, since nitrogen is the largest revenue generator, and calculating the relative production rate of electricity and relative consumption of natural gas. For each scenario, a power purchase agreement (PPA) was imagined where \$35/MWh of electricity is received, which is competitive in the electricity generation sector. Natural gas was priced at \$3.10/MCF which is a typical price an electricity generator would pay in Texas (“Natural Gas Prices”). The remaining variable costs relevant here were calculated according to the rules in table 13.1.

Table 13.1. Rules for calculating general variable expenses

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

Given the rules in table 13.1, and the known operating parameters of the plant (330 days per year and 100% of designed capacity) the variable costs could be accounted. The total output of nitrogen was known from ASPEN simulations for each scenario, then the power output and amount of natural gas required could be calculated using the oxygen flow rate. Using that information the ratios of electricity produced and natural gas required per pound of nitrogen could be formulated. Tables 13.2 through 13.4 show these results for each oxygen purity. For the 95% oxygen, and 53% oxygen case, the variable costs of power production (shown as raw materials) were larger than the revenue generated (shown as byproducts).



Table 13.2. Variable cost summary for 95% oxygen plant including power generation.

<b>Variable Costs at 100% Capacity:</b>		
<b>General Expenses</b>		
Selling / Transfer Expenses:	\$	424,977
Direct Research:	\$	679,963
Allocated Research:	\$	70,829
Administrative Expense:	\$	283,318
Management Incentive Compensation:	\$	177,074
<b>Total General Expenses</b>	<b>\$</b>	<b>1,636,161</b>
<b>Raw Materials</b>	\$0.005785 per lb of nitrogen	\$8,194,404
<b>Byproducts</b>	\$0.005576 per lb of nitrogen	(\$7,899,242)
<b>Utilities</b>	\$0.000128 per lb of nitrogen	\$181,202
<b>Total Variable Costs</b>	<b>\$</b>	<b>2,112,524</b>

Table 13.3. Variable cost summary for 53% oxygen plant including power generation.

<b>Variable Costs at 100% Capacity:</b>		
<b>General Expenses</b>		
Selling / Transfer Expenses:	\$	506,397
Direct Research:	\$	810,236
Allocated Research:	\$	84,400
Administrative Expense:	\$	337,598
Management Incentive Compensation:	\$	210,999
<b>Total General Expenses</b>	<b>\$</b>	<b>1,949,629</b>
<b>Raw Materials</b>	\$0.004945 per lb of nitrogen	\$8,346,271
<b>Byproducts</b>	\$0.004926 per lb of nitrogen	(\$8,314,992)
<b>Utilities</b>	\$0.000141 per lb of nitrogen	\$238,318
<b>Total Variable Costs</b>	<b>\$</b>	<b>2,219,227</b>





Table 13.4. Variable cost summary for 36% oxygen plant including power generation.

<b>Variable Costs at 100% Capacity:</b>		
<b>General Expenses</b>		
Selling / Transfer Expenses:	\$	293,400
Direct Research:	\$	469,441
Allocated Research:	\$	48,900
Administrative Expense:	\$	195,600
Management Incentive Compensation:	\$	122,250
<b>Total General Expenses</b>	<b>\$</b>	<b>1,129,592</b>
<b>Raw Materials</b>	\$0.008122 per lb of nitrogen	\$7,943,328
<b>Byproducts</b>	\$0.008470 per lb of nitrogen	(\$8,283,672)
<b>Utilities</b>	\$0.000127 per lb of nitrogen	\$124,454
<b>Total Variable Costs</b>	<b>\$</b>	<b>913,701</b>

For the day to day operations of the plant, one engineer was assumed to be splitting their time between the air separation and power production for \$200,000/yr including benefits with the help of one control assistant for \$500,000/yr including benefits. A single operator per shift was accounted for at \$40/hr along with a few percent of the direct wages and benefits going towards supplies etc. The other fixed costs associated with operating the plant at 100% capacity were calculated according to the rules shown in table 13.5, which were discussed and verified with our consultants and Seider et al.



Table 13.5. Rules for calculating costs of operating the plant.

<b><u>Maintenance</u></b>		
Wages and Benefits:	4.50%	of Total Depreciable Capital
Salaries and Benefits:	25.00%	of Maintenance Wages and Benefits
Materials and Services:	100.00%	of Maintenance Wages and Benefits
Maintenance Overhead:	5.00%	of Maintenance Wages and Benefits
<b><u>Operating Overhead</u></b>		
General Plant Overhead:	7.10%	of Maintenance and Operations Wages and Benefits
Mechanical Department Services:	2.40%	of Maintenance and Operations Wages and Benefits
Employee Relations Department	5.90%	of Maintenance and Operations Wages and Benefits
Business Services	7.40%	of Maintenance and Operations Wages and Benefits
<b><u>Property Taxes and Insurance</u></b>		
Property Taxes and Insurance:	2.00%	of Total Depreciable Capital
<b><u>Straight Line Depreciation</u></b>		
Direct Plant:	8.00%	of Total Depreciable Capital, less 1.18 times the Allocated Costs for Utility Plants and Related Facilities
Allocated Plant:	6.00%	of 1.18 times the Allocated Costs for Utility Plants and Related Facilities
<b><u>Other Annual Expenses</u></b>		
Rental Fees (Office and Laboratory Space):		\$0
Licensing Fees:		\$0
Miscellaneous:		\$0
<b><u>Depletion Allowance</u></b>		
Annual Depletion Allowance:		\$0

The metrics in table 13.5 combined with the labor costs as described above were used to calculate the fixed operating costs of the plant at 100% capacity.

Table 13.6. Total fixed costs for operating the plant at 100% of it's capacity.

Purity (%)	Total Fixed Costs
95	\$8,683,842
54	\$9,304,136
36	\$4,270,379



# **Section 14**

## **Important Considerations**



### **14.1 Plant Location**

Several factors are critical to give the highest chance of success. The key factors are a nearby nitrogen customer, cheap and easily accessible natural gas, a reliable electricity market and ideally oil and gas drilling customer interested in CO<sub>2</sub>. The vast natural gas pipeline network and industrial processes involving nitrogen in the gulf coast made the area best suited for this plant. The plant would partner with a nearby firm and build a nitrogen pipe that can feed a steady flow of nitrogen. Additionally, the industrial area would be able to make quick use of the 30 MW of electricity. There are certainly other areas of the US with similar characteristics, but the drilling industry in the gulf coast set it apart. While modeling and analysis of carbon capture were outside the scope of our project, in reality it would be necessary for an oxy fuel plant to take advantage of the increased concentration of CO<sub>2</sub> in it's flue gas.

### **14.2 Environmental Issues**

There are well documented environmental issues associated with burning fossil fuels. Carbon dioxide emissions, NO<sub>x</sub> and SO<sub>x</sub>, and other pollutants are a concern especially in the gulf coast where many counties are non attainment zones for one or more pollutants. The emissions control systems involved in the power plant are outside the scope of this project. Since carbon capture was not included in our design, this plant would actually emit more CO<sub>2</sub> per MWh sold than a traditional natural gas plant because of the extra power required to run the ASU. However, this plant lays the groundwork for a potential part of the climate change solution. This could be mitigated by switching the design to combined cycle or doing the additional work to capture the CO<sub>2</sub> from the flue gas. The oxy fuel increases the proportion of



the flue gas that is  $\text{CO}_2$  so it would be easier to capture than in a traditional natural gas power plant.

The plant would also show reduced  $\text{NO}_x$  emissions since a large portion of the nitrogen that would otherwise enter the boiler is separated out before combustion. oxy fuel boilers often produce high concentrations of  $\text{NO}_x$  due to increased flame temperature, but the total flow rate would be lower (Bensakhria). Natural gas, in general, has very low sulfur, particulate, and heavy metal concentrations, so those pollutants pose little environmental risk for this project. Natural gas has high combustion efficiency so little carbon monoxide or volatile organic compounds (VOCs) are produced (“Natural Gas Combustion”). However, drilling is not without environmental consequences. Air emissions and water usage at the drilling site are a significant environmental concern for experts in this field (Raimi).

### **14.3 Safety**

The operation of an oxy fuel power plant has unique safety considerations. The most concerning of which is boiler explosions. The temperature of the boiler will need to be regulated very carefully by recycling the flue gas. An additional emergency air intake should be included on the boiler in case the flue gas recycle fails. The natural gas should not be in contact with extremely high purity oxygen at any point which mitigates much of the risk.

Air separation plants also have four main hazards: rapid oxidation, embrittlement, pressure excursions due to vaporizing liquids, and oxygen enriched or deficient atmospheres (Schmidt). We recommend following the procedure provided by Air Products in their white paper written by Schmidt et. al. cited directly above. The plant should undergo a formal Design



Hazard Review (DHR) and a Quantitative Risk Assessment (QRA). After the completion of the DHR and QRA there should be an Operation Readiness Inspection (ORI) to ensure that the problems identified in the DHR and QRA were addressed.

Many of the risks have been addressed by assumption of dry air that is composed of oxygen and nitrogen, which was given in the problem statement. Other impurities in the air can solidify at the cryogenic temperatures, but that is not a concern for this project. Regular cleaning and maintenance of the main air compressor is necessary and a requiring workers to keep a safe distance is also good practice. Columns should be equipped with emergency pressure relief valves, and the materials of construction must be able to withstand cryogenic temperatures and should never be cold shocked to avoid damage.

#### **14.4 Plant Startup**

Plant start up should be done gradually and carefully using either liquid nitrogen or just with air. Air can be used along with the Joule-Thompson cooling to slowly bring the plant to steady state cryogenic temperatures. Alternatively, liquid nitrogen can be used to achieve these temperatures at the fastest rate possible. Prior to operation of the main air compressor, all equipment should be cleaned and thoroughly dried to avoid any frozen solids in the system.



# **Section 15**

## **Profitability Analysis**



The analysis of each plant design showed a negative net present value (NPV) in 2018. The 95% and 53% actually showed negative net earnings during the third production year, which is the first year at 100% production capacity. The 36% oxygen purity scenario is the closest to having a positive NPV and actually does have a slightly positive IRR. In these calculations, the nitrogen product was sold for \$0.01/lb, which is reasonable, especially because the plant requires a customer who will agree to buy it whenever it is produced. The price was sacrificed for a guaranteed buyer that is located nearby. However, the profitability was very sensitive to the price of nitrogen. The profitability measures shown in the following tables are for, what we considered, the most realistic case, which is where the price of nitrogen is \$0.01/lb.

Table 15.1. Profitability measures for the 95% oxygen scenario including power generation.

<b>The Internal Rate of Return (IRR) for this project is</b>	<b>-4.19%</b>
<b>The Net Present Value (NPV) of this project in 2018 is</b>	<b>\$(36,741,500)</b>
<b>ROI Analysis (Third Production Year)</b>	
Annual Sales	14,165,896
Annual Costs	(10,796,366)
Depreciation	(5,166,899)
Income Tax	431,369
Net Earnings	<u>(1,366,001)</u>
Total Capital Investment	<u>65,990,923</u>
ROI	<b>-2.07%</b>





Table 15.2. Profitability measures for the 53% oxygen scenario including power generation.

<b>The Internal Rate of Return (IRR) for this project is</b>		-0.37%
<b>The Net Present Value (NPV) of this project in 2018 is</b>		\$(30,850,600)
<b>ROI Analysis (Third Production Year)</b>		
Annual Sales	16,879,909	
Annual Costs	(11,523,363)	
Depreciation	(5,574,588)	
Income Tax	52,330	
Net Earnings	<u>(165,712)</u>	
Total Capital Investment	<u>71,379,188</u>	
ROI		-0.23%

Table 15.3. Profitability measures for the 36% oxygen scenario including power generation.

<b>The Internal Rate of Return (IRR) for this project is</b>		1.18%
<b>The Net Present Value (NPV) of this project in 2018 is</b>		\$(19,730,800)
<b>ROI Analysis (Third Production Year)</b>		
Annual Sales	9,780,014	
Annual Costs	(5,184,080)	
Depreciation	(4,308,663)	
Income Tax	(68,945)	
Net Earnings	<u>218,326</u>	
Total Capital Investment	<u>54,510,944</u>	
ROI		0.40%

The profitability measures changed greatly with increases in the price of nitrogen. In two of the ASPEN simulations, >99.5% nitrogen was produced, therefore doing sensitivity analysis up to \$0.02/lb was reasonable. At prices greater than \$0.015/lb, all three cases have a positive IRR, and only the 95% case had a small negative NPV. At \$0.02/lb the three scenarios were



profitable with IRR's greater than 15% and NPV's greater than \$24,000,000. Figure 15.1 shows these results at the three nitrogen prices discussed above for each oxygen purity. Similar results could be achieved by doubling the price of electricity. However, negotiating a PPA for any price greater than \$35-\$40/MWh would not be competitive with other generation sources, so it is not worthwhile to investigate these prices. Another potential consideration would be participate in the wholesale electricity markets and collect the locational marginal price (LMP) for the electricity. The biggest issue with this strategy would be facing the swings in the market. It would be beneficial during peak loads when the LMP is very high, sometimes well over \$100/MWh, but there are many hours throughout the day when the LMP is below \$25/MWh, or, worse yet, below \$0/MWh if variable sources are over producing during a time of low demand. Given the price volatility, a stable PPA seems like the most sensible choice for a pilot scale plant.

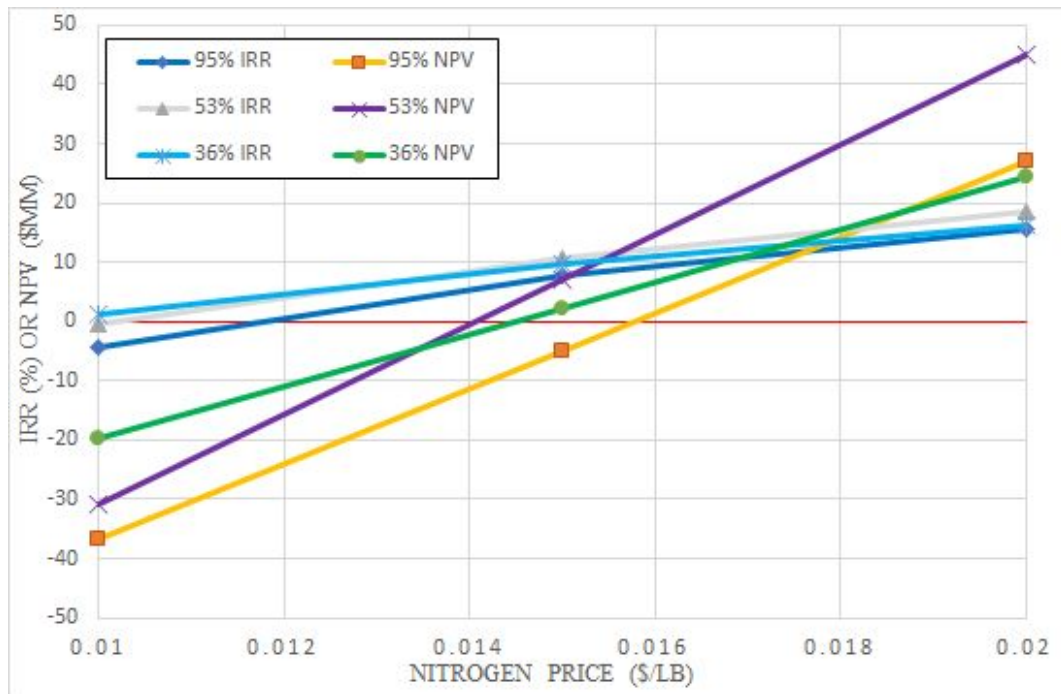


Figure 15.1. Profitability metrics' sensitivity to nitrogen price for each oxygen purity.



The real issue with the proposition of oxy fuel is that the air separation plant was far more profitable without the addition of the power plant. To model the 95% oxygen purity case, the oxygen was sold for \$0.02/lb, electricity was purchased at \$0.05/kWh (reasonable for the gulf coast according to EIA data), and the capital cost of the power plant was set to zero. In the 36% and 53% cases, the oxygen enriched stream was vented to the atmosphere and assigned zero value, electricity to run the compressor was purchased at \$0.05/kWh, and the capital cost of the power plant was neglected. All three cases were profitable while selling the nitrogen for \$0.01/lb. This analysis did neglect the cost of storage tanks for oxygen in the 95% case, but it is notable that the easiest way to make the plant profitable was to get rid of the power generation. The improved profitability metrics for each case of oxygen purity are shown in table 15.4. Each value was calculated using \$0.01/lb for nitrogen, which was not profitable for any of the cases when power generation was included.

Table 15.4. IRR and NPV for the ASU's if power generation is not done.

Case	IRR	NPV
95%	36.00%	\$ 54,338,000
54%	10.12%	\$ 2,056,700
36%	10.31%	\$ 1,270,500

The next question is what would make the oxy fuel power generation a worthwhile investment. A logical test is carbon pricing for the 95% purity model. Given the extremely high purity oxygen, there would be almost no nitrogen in the flue gas. Assuming near complete combustion of natural gas, the flue gas will consist of  $\frac{1}{3}$  CO<sub>2</sub> and  $\frac{2}{3}$  H<sub>2</sub>O by mole. This means that carbon capture could be as simple as cooling the flue gas below 100 °C to condense the



water - note this would not lend itself to sequestration since the purified CO<sub>2</sub> stream would be gaseous. Given the simplicity of generating a high purity CO<sub>2</sub> stream, the costs of doing carbon capture would be low relative to the rest of the process. Therefore, it is reasonable to do an order of magnitude estimation of the profitability assuming no changes in plant costs, and adding in a CO<sub>2</sub> product. By stoichiometry and known production rates from ASPEN simulations, the ratio of carbon captured to nitrogen produced on a mass basis was calculated. Then, using a reasonable \$40/ton price on carbon, the profitability of the 95% oxygen purity case was calculated. The IRR and NPV were 11.24 and \$8,500,000 respectively. Despite the inefficiencies of our 95% model, this case was still profitable. These numbers are certainly handwavy - considering no additional capital or power was modeled and a new product was produced. However, rigorous modeling of carbon capture was outside the scope of this project, and it is nonetheless interesting to note that simplified estimates showed carbon capture to be profitable.



# **Section 16**

## **Conclusion and Recommendations**



The most reasonable pricing for our products and materials yielded results that were not profitable for each oxygen purity that was tested. However, the profitability was extremely sensitive to the price of nitrogen and each case was profitable if the price of nitrogen doubled, which is not extremely likely. Doubling the price of electricity also yielded profitable results, but that is even less likely than the nitrogen price doubling. The plants were all much more profitable if the power generation was not included and the oxygen was vented for lower purities or sold for high purity. The choice of oxygen purity had little bearing on the profitability in our analysis, but could greatly affect the cost of carbon capture.

This process utilized a steam cycle and boiler to generate electricity, which seems wasteful. Most natural gas generation built today uses a combined cycle, which could increase the efficiency from about 35% to 60%, thus nearly doubling the fuel efficiency of our plant. Getting more electricity per unit of fuel would significantly increase the chances of being profitable.

Future work should rigorously model a natural gas combined cycle plant with a >95% oxygen purity stream. The back-of-the-envelope calculations described in Section 15 showed that this could be profitable with a carbon price of \$40/ton. Increasing the efficiency of the ASU and rigorously modeling all of the benefits of 95% oxy fuel in a combined cycle plant with carbon capture, rather than investigating different oxygen concentrations, could be very interesting. We believe the key benefits of oxy fuel were not examined in our project due to the structure. Therefore, rigorous modeling of the oxy fuel combustion and carbon capture at a single oxygen concentration would yield more interesting and informative results. Separately, modeling



the power plant as a peaker, or a plant that only operates for a few hours a day during times with sufficiently high LMP's, and sells oxygen during the other times of the day would be a very interesting future project.



# Section 17

## Acknowledgements





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# Section 18

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# Section 19

## Appendices

**Appendix A: Sample Calculations**

*Cooling water requirements:*

Cooling water requirements for compressor intercoolers.

Inlet: 85°F

Outlet: 110°F

c = specific heat of water = 1 BTU/(lb °F)

Q (ASPEN) = 32,740,000 BTU/hr

$$Q = mc\Delta T$$

$$\Delta T = 110^\circ\text{F} - 85^\circ\text{F} = 25^\circ\text{F}$$

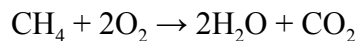
$$m = \frac{Q}{c\Delta T} = \frac{32,740,000 \text{ BTU/hr}}{1(\text{BTU/lb}^\circ\text{F}) \times 25(^\circ\text{F})} = 1,309,600 \text{ lb/hr of cooling water}$$

*Natural gas feed requirements:*

For this example, the amount of gas required to generate 30 MW of electricity using a steam turbine will be calculated.

Lower heating value of natural gas: 0.0149 MWh/kg

Rankine cycle thermal efficiency: 35%



$$m = \frac{30 \text{ MWh}}{0.0149(\text{MWh/kg}) \times 0.35} = 5753 \text{ kg natural gas to produce 30 MWh}$$
$$\frac{5753 \text{ kg}}{1 \text{ hr}} = 5753 \text{ kg/hr natural gas, which will produce 30 MW}$$

*Net Power calculation:*

Given an oxygen flow rate, calculating net power.

O<sub>2</sub> flow rate (ASPEN) = 1000 kmol/hr

Molecular weight of natural gas = 16 kg/kmol

$$\frac{1 \text{ kmol gas}}{2 \text{ kmol oxygen}} \times 1000 \text{ kmol oxygen} = 500 \text{ kmol/hr of natural gas}$$

$$500 \text{ kmol} \times \frac{16 \text{ kg}}{\text{kmol}} = 8000 \text{ kg/hr of natural gas}$$

From above,

$$\text{Power} = 8000(\text{kg/hr}) \times 0.0149(\text{MWh/kg}) \times .35 = 41.7 \text{ MW}$$

Compressor work (ASPEN) = 12 MW

$$\text{Net power} = 41.7 \text{ MW} - 12 \text{ MW} = 29.7 \text{ MW}$$



**Appendix B: EPA New Source Requirements**

The following information was obtained from the EPA’s New Source Performance Standards (NSPS) for electric utility steam generating units. These rules apply to units with a potential electrical output of 25 MW or greater. The full text of the regulation (40 CFR part 60 subpart Da) can be found at the following web address:

<https://www.gpo.gov/fdsys/pkg/CFR-2015-title40-vol7/pdf/CFR-2015-title40-vol7-part60-subpartDa.pdf>

Table A.1. NO<sub>x</sub> emission standards for new sources per unit heat input.

Fuel type	Emission limit for heat input	
	ng/J	lb/MMBtu
<b>Gaseous fuels:</b>		
Coal-derived fuels .....	210	0.50
All other fuels .....	86	0.20
<b>Liquid fuels:</b>		
Coal-derived fuels .....	210	0.50
Shale oil .....	210	0.50
All other fuels .....	130	0.30
<b>Solid fuels:</b>		
Coal-derived fuels .....	210	0.50
Any fuel containing more than 25%, by weight, coal refuse .....	( <sup>1</sup> )	( <sup>1</sup> )
Any fuel containing more than 25%, by weight, lignite if the lignite is mined in North Dakota, South Dakota, or Montana, and is combusted in a slag tap furnace <sup>2</sup> .....	340	0.80
Any fuel containing more than 25%, by weight, lignite not subject to the 340 ng/J heat input emission limit <sup>2</sup> .....	260	0.60
Subbituminous coal .....	210	0.50
Bituminous coal .....	260	0.60
Anthracite coal .....	260	0.60
All other fuels .....	260	0.60

<sup>1</sup> Exempt from NO<sub>x</sub> standards and NO<sub>x</sub> monitoring requirements.  
<sup>2</sup> Any fuel containing less than 25%, by weight, lignite is not prorated but its percentage is added to the percentage of the predominant fuel.

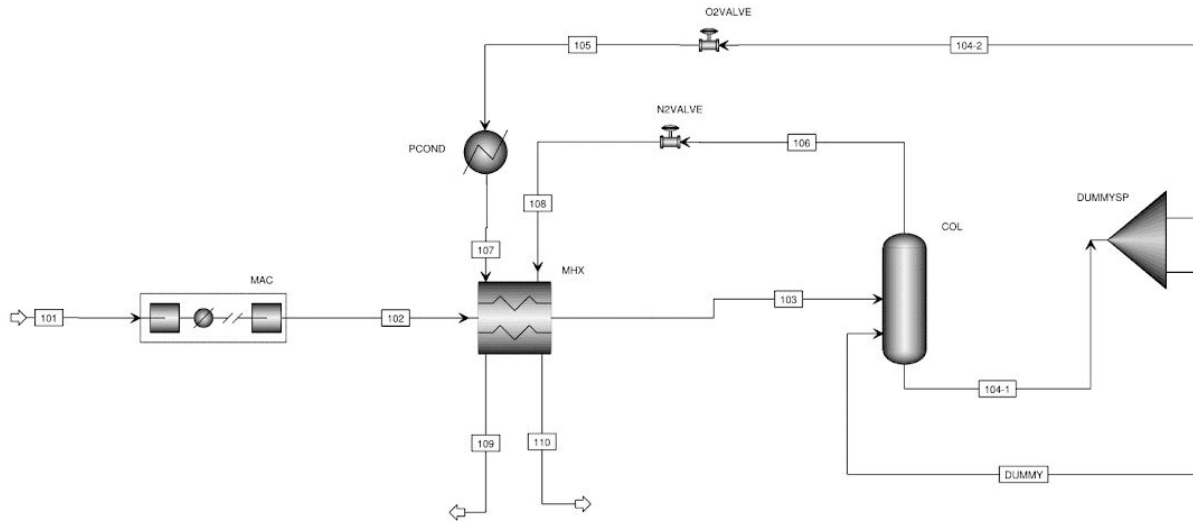




**Appendix C: ASPEN Block and Stream reports**

**36% Oxygen**

Flowsheet



Block Report

BLOCK: MHX      MODEL: MHEATX

-----

HOT SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	102	103
COLD SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	108	110
	107	109

PROPERTIES FOR STREAM 102  
 PROPERTY OPTION SET: PSRK      RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 107  
 PROPERTY OPTION SET: PSRK      RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 108  
 PROPERTY OPTION SET: PSRK      RKS-MHV1 EQUATION OF STATE

	***	MASS AND ENERGY BALANCE	***	
		IN	OUT	RELATIVE DIFF.
TOTAL BALANCE				
MOLE (LBMOL/HR)		20943.9	20943.9	0.00000



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```

MASS (LB/HR )           604240.      604240.      0.00000
ENTHALPY (BTU/HR )     -0.260736E+08  -0.260736E+08  0.00000
  
```

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

```

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

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM 102 :

```

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE      F          -273.000
PRESSURE DROP              PSI          5.00000
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM 107 :

```

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE      F          87.5000
PRESSURE DROP              PSI          5.00000
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM 108 :

```

TWO PHASE FLASH
PRESSURE DROP              PSI          5.00000
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
102	-0.27621E+08	-273.00	93.000	1.0000
107	0.15564E+08	87.50	14.000	1.0000
108	0.12057E+08	88.58	14.000	1.0000

```

-----
|
| 102 |
|----->| 10472.  LBMOL/HR |----->| 103
| 90.00 | | -273.00 |
|
| 109 |
|<-----| 6062.7  LBMOL/HR |<-----| 107
| 87.50 | | -278.26 |
|
| 110 |
|<-----| 4409.2  LBMOL/HR |<-----| 108
| 88.58 | | -300.79 |
|
|-----
  
```



BLOCK: MHX MODEL: MHEATX

-----

HOT SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	102	103
COLD SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	108	110
	107	109

PROPERTIES FOR STREAM 102  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 107  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 108  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

	***	MASS AND ENERGY BALANCE	***	
		IN	OUT	RELATIVE DIFF.
TOTAL BALANCE				
MOLE (LBMOL/HR)		20943.9	20943.9	0.00000
MASS (LB/HR )		604240.	604240.	0.00000
ENTHALPY (BTU/HR )		-0.260736E+08	-0.260736E+08	0.00000

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

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM 102 :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	-273.000
PRESSURE DROP	PSI	5.00000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM 107 :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	87.5000
PRESSURE DROP	PSI	5.00000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM 108 :

TWO PHASE FLASH		
PRESSURE DROP	PSI	5.00000
MAXIMUM NO. ITERATIONS		30



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CONVERGENCE TOLERANCE

0.000100000

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
102	-0.27621E+08	-273.00	93.000	1.0000
107	0.15564E+08	87.50	14.000	1.0000
108	0.12057E+08	88.58	14.000	1.0000

```

-----
102 | | | 103
----->| | 10472. | LBMOL/HR |----->
 90.00 | | | | | -273.00
 | | | | | |
109 | | | 107
<-----| | 6062.7 | LBMOL/HR |<-----
 87.50 | | | | | -278.26
 | | | | | |
110 | | | 108
<-----| | 4409.2 | LBMOL/HR |<-----
 88.58 | | | | | -300.79
 | | | | | |
-----

```

BLOCK: MHX MODEL: MHEATX

```

-----
HOT SIDE:  INLET STREAM  OUTLET STREAM
           -----
           102           103

COLD SIDE:  INLET STREAM  OUTLET STREAM
           -----
           108           110
           107           109

```

PROPERTIES FOR STREAM 102  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 107  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 108  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (LBMOL/HR)	20943.9	20943.9	0.00000
MASS (LB/HR )	604240.	604240.	0.00000
ENTHALPY (BTU/HR )	-0.260736E+08	-0.260736E+08	0.00000



\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*

```

SPECIFICATIONS FOR STREAM 102      :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE              F          -273.000
PRESSURE DROP                      PSI          5.00000
MAXIMUM NO. ITERATIONS              30
CONVERGENCE TOLERANCE              0.000100000
    
```

```

SPECIFICATIONS FOR STREAM 107      :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE              F          87.5000
PRESSURE DROP                      PSI          5.00000
MAXIMUM NO. ITERATIONS              30
CONVERGENCE TOLERANCE              0.000100000
    
```

```

SPECIFICATIONS FOR STREAM 108      :
TWO PHASE FLASH
PRESSURE DROP                      PSI          5.00000
MAXIMUM NO. ITERATIONS              30
CONVERGENCE TOLERANCE              0.000100000
    
```

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
102	-0.27621E+08	-273.00	93.000	1.0000
107	0.15564E+08	87.50	14.000	1.0000
108	0.12057E+08	88.58	14.000	1.0000

```

-----
|
| 102 |
|----->|          10472.   LBMOL/HR |----->| 103
| 90.00 |
|
| 109 |
|----->|          6062.7   LBMOL/HR |----->| 107
| 87.50 |
|
| 110 |
|----->|          4409.2   LBMOL/HR |----->| 108
| 88.58 |
|
|----->|
|
|----->|
    
```



# Oxy Fuel for Clean Energy Generation

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BLOCK: COL MODEL: RADFRAC

```

-----
INLETS   - 103      STAGE 15
          DUMMY     STAGE  1
OUTLETS  - 106      STAGE  1
          104-1     STAGE 15

```

PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (LBMOL/HR)	10472.0	10472.0	0.00000
MASS (LB/HR )	302120.	302120.	0.192664E-15
ENTHALPY (BTU/HR )	-0.268473E+08	-0.410453E+08	0.345910

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\*\*\*  
 \*\*\*\* INPUT DATA \*\*\*\*  
 \*\*\*\*\*

\*\*\*\* INPUT PARAMETERS \*\*\*\*

NUMBER OF STAGES	15
ALGORITHM OPTION	STANDARD
ABSORBER OPTION	NO
INITIALIZATION OPTION	STANDARD
HYDRAULIC PARAMETER CALCULATIONS	NO
INSIDE LOOP CONVERGENCE METHOD	BROYDEN
DESIGN SPECIFICATION METHOD	NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS	25
MAXIMUM NO. OF INSIDE LOOP ITERATIONS	10
MAXIMUM NUMBER OF FLASH ITERATIONS	30
FLASH TOLERANCE	0.000100000
OUTSIDE LOOP CONVERGENCE TOLERANCE	0.000100000

\*\*\*\* COL-SPECS \*\*\*\*

MOLAR VAPOR DIST / TOTAL DIST	1.00000
MOLAR DISTILLATE RATE	LBMOL/HR 4,409.25
REBOILER DUTY	BTU/HR 0.0

\*\*\*\* PROFILES \*\*\*\*

P-SPEC	STAGE 1	PRES, PSIA	91.0000
--------	---------	------------	---------

\*\*\*\*\*  
 \*\*\*\* RESULTS \*\*\*\*  
 \*\*\*\*\*

\*\*\* COMPONENT SPLIT FRACTIONS \*\*\*



COMPONENT:	OUTLET STREAMS	
	106	104-1
OXYGEN	.29239E-02	.99708
NITROGEN	.53220	.46780

\*\*\* SUMMARY OF KEY RESULTS \*\*\*

TOP STAGE TEMPERATURE	F	-285.026
BOTTOM STAGE TEMPERATURE	F	-277.764
TOP STAGE LIQUID FLOW	LBMOL/HR	6,988.72
BOTTOM STAGE LIQUID FLOW	LBMOL/HR	6,062.71
TOP STAGE VAPOR FLOW	LBMOL/HR	4,409.25
BOILUP VAPOR FLOW	LBMOL/HR	10,706.5
MOLAR REFLUX RATIO		1.58501
CONDENSER DUTY (W/O SUBCOOL)	BTU/HR	-0.141980+08
REBOILER DUTY	BTU/HR	0.0

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

DEW POINT	0.62477E-11	STAGE= 12
BUBBLE POINT	0.19593E-11	STAGE= 14
COMPONENT MASS BALANCE	0.20530E-10	STAGE= 10 COMP=OXYGEN
ENERGY BALANCE	0.30102E-12	STAGE= 15

\*\*\*\* PROFILES \*\*\*\*

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

STAGE	TEMPERATURE F	PRESSURE PSIA	ENTHALPY BTU/LBMOL		HEAT DUTY BTU/HR
			LIQUID	VAPOR	
1	-285.03	91.000	-4687.1	-2656.2	-.14198+08
2	-284.95	91.120	-4687.8	-2655.8	
3	-284.85	91.240	-4689.0	-2655.2	
14	-278.81	92.560	-4818.7	-2609.9	
15	-277.76	92.680	-4838.4	-2602.0	

STAGE	FLOW RATE LBMOL/HR		FEED RATE LBMOL/HR			PRODUCT RATE LBMOL/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	6989.	4409.					4409.2452
2	6983.	0.1140E+05					
3	6974.	0.1139E+05					
14	6297.	0.1081E+05					
15	6063.	0.1071E+05			.10472+05	6062.7122	

\*\*\*\* MASS FLOW PROFILES \*\*\*\*

STAGE	FLOW RATE LB/HR		FEED RATE LB/HR			PRODUCT RATE LB/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.1959E+06	0.1235E+06					.12354+06



```
2 0.1958E+06 0.3194E+06
3 0.1957E+06 0.3193E+06
14 0.1843E+06 0.3095E+06
15 0.1786E+06 0.3078E+06                .30212+06  .17858+06
```

```
**** MOLE-X-PROFILE ****
STAGE  OXYGEN  NITROGEN
  1    0.33759E-02  0.99662
  2    0.60907E-02  0.99391
  3    0.99228E-02  0.99008
 14    0.31423      0.68577
 15    0.36167      0.63833
```

```
**** MOLE-Y-PROFILE ****
STAGE  OXYGEN  NITROGEN
  1    0.14583E-02  0.99854
  2    0.26341E-02  0.99737
  3    0.42978E-02  0.99570
 14    0.15635      0.84365
 15    0.18542      0.81458
```

```
**** K-VALUES ****
STAGE  OXYGEN  NITROGEN
  1    0.43197      1.0019
  2    0.43248      1.0035
  3    0.43312      1.0057
 14    0.49757      1.2302
 15    0.51268      1.2761
```

```
**** MASS-X-PROFILE ****
STAGE  OXYGEN  NITROGEN
  1    0.38543E-02  0.99615
  2    0.69512E-02  0.99305
  3    0.11318E-01  0.98868
 14    0.34357      0.65643
 15    0.39290      0.60710
```

```
**** MASS-Y-PROFILE ****
STAGE  OXYGEN  NITROGEN
  1    0.16654E-02  0.99833
  2    0.30077E-02  0.99699
  3    0.49062E-02  0.99509
 14    0.17471      0.82529
 15    0.20636      0.79364
```

```
*****
***** HYDRAULIC PARAMETERS *****
*****
```

\*\*\* DEFINITIONS \*\*\*

```
MARANGONI INDEX = SIGMA - SIGMATO
FLOW PARAM = (ML/MV) * SQRT (RHOV/RHOL)
QR = QV * SQRT (RHOV / (RHOL - RHOV))
F FACTOR = QV * SQRT (RHOV)
```





WHERE:

SIGMA IS THE SURFACE TENSION OF LIQUID FROM THE STAGE  
 SIGMATO IS THE SURFACE TENSION OF LIQUID TO THE STAGE  
 ML IS THE MASS FLOW OF LIQUID FROM THE STAGE  
 MV IS THE MASS FLOW OF VAPOR TO THE STAGE  
 RHOL IS THE MASS DENSITY OF LIQUID FROM THE STAGE  
 RHOV IS THE MASS DENSITY OF VAPOR TO THE STAGE  
 QV IS THE VOLUMETRIC FLOW RATE OF VAPOR TO THE STAGE

TEMPERATURE  
 F

STAGE	LIQUID FROM	VAPOR TO
1	-285.03	-284.95
2	-284.95	-284.85
3	-284.85	-284.73
14	-278.81	-277.76
15	-277.76	-273.06

STAGE	MASS FLOW LB/HR		VOLUME FLOW CUFT/HR		MOLECULAR WEIGHT	
	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO
1	0.19587E+06	0.31942E+06	4532.8	0.19948E+06	28.027	28.024
2	0.19579E+06	0.31933E+06	4526.6	0.19922E+06	28.038	28.031
3	0.19565E+06	0.31920E+06	4517.1	0.19896E+06	28.053	28.040
14	0.18429E+06	0.30784E+06	3765.9	0.19417E+06	29.266	28.752
15	0.17858E+06	0.30212E+06	3582.1	0.19709E+06	29.455	28.850

STAGE	DENSITY LB/CUFT		VISCOSITY CP		SURFACE TENSION DYNE/CM
	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM
1	43.212	1.6013	0.75176E-01	0.66472E-02	4.7018
2	43.253	1.6029	0.75235E-01	0.66522E-02	4.7117
3	43.314	1.6043	0.75333E-01	0.66585E-02	4.7270
14	48.937	1.5854	0.86063E-01	0.70358E-02	6.0990
15	49.852	1.5329	0.87829E-01	0.72277E-02	6.2943

STAGE	MARANGONI INDEX DYNE/CM	FLOW PARAM	QR	REDUCED F-FACTOR (LB-CUFT) **.5/HR
			CUFT/HR	
1		0.11805	39131.	0.25242E+06
2	0.98736E-02	0.11803	39082.	0.25223E+06
3	0.15380E-01	0.11797	39021.	0.25201E+06
14	0.21838	0.10776	35529.	0.24448E+06
15	0.19538	0.10365	35105.	0.24402E+06

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

\*\*\*\*\*  
 \*\*\* SECTION 1 \*\*\*  
 \*\*\*\*\*



STARTING STAGE NUMBER 2  
 ENDING STAGE NUMBER 15  
 FLOODING CALCULATION METHOD GLITSCH6

DESIGN PARAMETERS

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

TRAY SPECIFICATIONS

-----  
 TRAY TYPE SIEVE  
 NUMBER OF PASSES 4  
 TRAY SPACING FT 1.00000

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

STAGE WITH MAXIMUM DIAMETER 2  
 COLUMN DIAMETER FT 8.74233  
 DC AREA/COLUMN AREA 0.093750  
 SIDE DOWNCOMER VELOCITY FT/SEC 0.22344  
 FLOW PATH LENGTH FT 1.64054  
 SIDE DOWNCOMER WIDTH FT 0.53180  
 SIDE WEIR LENGTH FT 4.17916  
 CENTER DOWNCOMER WIDTH FT 0.34340  
 CENTER WEIR LENGTH FT 8.73558  
 OFF-CENTER DOWNCOMER WIDTH FT 0.38658  
 OFF-CENTER SHORT WEIR LENGTH FT 7.55573  
 OFF-CENTER LONG WEIR LENGTH FT 7.95559  
 TRAY CENTER TO OCDC CENTER FT 2.00553

\*\*\*\* SIZING PROFILES \*\*\*\*

STAGE	DIAMETER	TOTAL AREA	ACTIVE AREA	SIDE DC AREA
	FT	SQFT	PER PANEL	PER PANEL
			SQFT	SQFT
2	8.7423	60.027	12.005	1.4069
3	8.7423	60.027	12.005	1.4069
4	8.7423	60.027	12.005	1.4069
5	8.7423	60.027	12.005	1.4069
6	8.7423	60.027	12.005	1.4069
7	8.7423	60.027	12.005	1.4069
8	8.7423	60.027	12.005	1.4069
9	8.7423	60.027	12.005	1.4069
10	8.7423	60.027	12.005	1.4069
11	8.7423	60.027	12.005	1.4069
12	8.7423	60.027	12.005	1.4069
13	8.7423	60.027	12.005	1.4069
14	8.7423	60.027	12.005	1.4069
15	8.7423	60.027	12.005	1.4069



\*\*\*\* ADDITIONAL SIZING PROFILES \*\*\*\*

STAGE	FLOODING FACTOR	PRES. DROP PSI	DC BACKUP FT	DC BACKUP/ (TSFC+WHT)
2	80.00	0.7238E-01	0.5273	48.67
3	79.87	0.7235E-01	0.5262	48.57
4	79.71	0.7232E-01	0.5247	48.43
5	79.48	0.7229E-01	0.5226	48.24
6	79.18	0.7226E-01	0.5197	47.97
7	78.78	0.7223E-01	0.5159	47.62
8	78.25	0.7220E-01	0.5108	47.15
9	77.57	0.7218E-01	0.5044	46.56
10	76.73	0.7217E-01	0.4965	45.83
11	75.72	0.7217E-01	0.4872	44.97
12	74.58	0.7220E-01	0.4771	44.04
13	73.39	0.7226E-01	0.4668	43.09
14	72.25	0.7235E-01	0.4572	42.20
15	71.11	0.7210E-01	0.4452	41.09

STAGE	HEIGHT OVER WEIR FT	DC REL FROTH DENS	TR LIQ REL FROTH DENS	FRA APPR TO SYS LIMIT
2	0.1508	0.6039	0.2279	54.61
3	0.1505	0.6040	0.2280	54.50
4	0.1501	0.6040	0.2282	54.34
5	0.1496	0.6042	0.2284	54.13
6	0.1489	0.6043	0.2286	53.84
7	0.1479	0.6045	0.2289	53.46
8	0.1465	0.6048	0.2292	52.96
9	0.1448	0.6051	0.2297	52.31
10	0.1427	0.6055	0.2302	51.52
11	0.1401	0.6060	0.2308	50.60
12	0.1372	0.6064	0.2315	49.58
13	0.1342	0.6067	0.2322	48.55
14	0.1314	0.6070	0.2329	47.58
15	0.1269	0.6073	0.2332	46.72

BLOCK: DUMMYS MODEL: FSPLIT

-----

INLET STREAM: 104-1  
 OUTLET STREAMS: 104-2 DUMMY  
 PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (LBMOL/HR)	6062.71	6062.71	0.00000
MASS (LB/HR )	178576.	178576.	0.00000
ENTHALPY (BTU/HR )	-0.293336E+08	-0.293336E+08	0.00000

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*



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```

FRACTION OF FLOW          STRM=104-2    FRAC=          1.00000

*** RESULTS ***

STREAM= 104-2             SPLIT=          1.00000    KEY=  0    STREAM-ORDER=  1
  DUMMY                   0.0                0        0                2
  
```

BLOCK: MAC      MODEL: MCOMPR

```

-----
INLET STREAMS:   101          TO STAGE   1
OUTLET STREAMS:  102          FROM STAGE  3
PROPERTY OPTION SET: PSRK      RKS-MHV1 EQUATION OF STATE
  
```

```

*** MASS AND ENERGY BALANCE ***

TOTAL BALANCE
MOLE (LBMOL/HR)          10472.0          10472.0          0.00000
MASS (LB/HR )             302120.          302120.          0.00000
ENTHALPY (BTU/HR )       556542.          773629.         -0.280609
  
```

```

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

\*\*\* INPUT DATA \*\*\*

```

ISENTROPIC CENTRIFUGAL COMPRESSOR
NUMBER OF STAGES                3
FINAL PRESSURE, PSIA            98.0000
DISTRIBUTION AMONG STAGES       EQUAL P-RATIO
  
```

### COMPRESSOR SPECIFICATIONS PER STAGE

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

### COOLER SPECIFICATIONS PER STAGE

STAGE NUMBER	PRESSURE DROP PSI	TEMPERATURE F
1	0.000	90.00
2	0.000	90.00
3	0.000	90.00

\*\*\* RESULTS \*\*\*

```

FINAL PRESSURE, PSIA                98.0000
TOTAL WORK REQUIRED, HP                12,943.0
TOTAL COOLING DUTY , BTU/HR         -0.327156+08
  
```



\*\*\* PROFILE \*\*\*

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE PSIA	PRESSURE RATIO	OUTLET TEMPERATURE F
1	27.67	1.882	233.9
2	52.07	1.882	240.2
3	98.00	1.882	240.1

STAGE NUMBER	INDICATED HORSEPOWER HP	BRAKE HORSEPOWER HP
1	4286.	4286.
2	4327.	4327.
3	4330.	4330.

STAGE NUMBER	HEAD DEVELOPED FT-LBF/LB	VOLUMETRIC FLOW CUFT/HR	ISENTROPIC EFFICIENCY
1	0.2022E+05	0.4164E+07	0.7200
2	0.2042E+05	0.2233E+07	0.7200
3	0.2043E+05	0.1187E+07	0.7200

COOLER PROFILE

STAGE NUMBER	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	COOLING LOAD BTU/HR	VAPOR FRACTION
1	90.00	27.67	-.1056E+08	1.000
2	90.00	52.07	-.1105E+08	1.000
3	90.00	98.00	-.1110E+08	1.000

BLOCK: N2VALVE MODEL: VALVE

INLET STREAM: 106  
 OUTLET STREAM: 108  
 PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
--	----	-----	----------------

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (LBMOL/HR)	4409.25	4409.25	0.00000
MASS (LB/HR )	123544.	123544.	0.00000
ENTHALPY (BTU/HR )	-0.117118E+08	-0.117118E+08	0.00000

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*





\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*

TWO PHASE PQ FLASH		
PRESSURE DROP	PSI	0.0
SPECIFIED HEAT DUTY	BTU/HR	0.141981+08
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

\*\*\* RESULTS \*\*\*

OUTLET TEMPERATURE	F	-278.26
OUTLET PRESSURE	PSIA	19.000
OUTLET VAPOR FRACTION		1.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
OXYGEN	0.36167	0.68986	0.36167	2.0415
NITROGEN	0.63833	0.31014	0.63833	5.6302

Stream Report

101 102 103 104-1 104-2  
-----

STREAM ID	101	102	103	104-1	104-2
FROM :	----	MAC	MHX	COL	DUMMYSP
TO :	MAC	MHX	COL	DUMMYSP	O2VALVE

SUBSTREAM: MIXED

PHASE:	VAPOR	VAPOR	VAPOR	LIQUID	LIQUID
COMPONENTS: LBMOL/HR					
OXYGEN	2199.1111	2199.1111	2199.1111	2192.6811	2192.6811
NITROGEN	8272.8464	8272.8464	8272.8464	3870.0312	3870.0312
TOTAL FLOW:					
LBMOL/HR	1.0472+04	1.0472+04	1.0472+04	6062.7122	6062.7122
LB/HR	3.0212+05	3.0212+05	3.0212+05	1.7858+05	1.7858+05
CUFT/HR	4.1644+06	6.3093+05	1.9640+05	3582.1109	3582.1109
STATE VARIABLES:					
TEMP F	85.0000	90.0000	-273.0000	-277.7637	-277.7637
PRES PSIA	14.7000	98.0000	93.0000	92.6800	92.6800
VFRAC	1.0000	1.0000	1.0000	0.0	0.0
LFRAC	0.0	0.0	0.0	1.0000	1.0000
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	53.1459	73.8763	-2563.7371	-4838.3560	-4838.3560
BTU/LB	1.8421	2.5607	-88.8631	-164.2635	-164.2635



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BTU/HR	5.5654+05	7.7363+05	-2.6847+07	-2.9334+07	-2.9334+07
ENTROPY:					
BTU/LBMOL-R	1.1182	-2.6127	-10.4386	-22.4763	-22.4763
BTU/LB-R	3.8759-02	-9.0562-02	-0.3618	-0.7631	-0.7631
DENSITY:					
LBMOL/CUFT	2.5147-03	1.6598-02	5.3321-02	1.6925	1.6925
LB/CUFT	7.2549-02	0.4788	1.5383	49.8522	49.8522
AVG MW	28.8504	28.8504	28.8504	29.4548	29.4548

105 106 107 108 109

-----

STREAM ID	105	106	107	108	109
FROM :	O2VALVE	COL	PCOND	N2VALVE	MHX
TO :	PCOND	N2VALVE	MHX	MHX	----
SUBSTREAM: MIXED					
PHASE:	MIXED	VAPOR	VAPOR	VAPOR	VAPOR
COMPONENTS: LBMOL/HR					
OXYGEN	2192.6811	6.4300	2192.6811	6.4300	2192.6811
NITROGEN	3870.0312	4402.8152	3870.0312	4402.8152	3870.0312
TOTAL FLOW:					
LBMOL/HR	6062.7122	4409.2452	6062.7122	4409.2452	6062.7122
LB/HR	1.7858+05	1.2354+05	1.7858+05	1.2354+05	1.7858+05
CUFT/HR	9.5148+04	7.7238+04	6.0463+05	3.8134+05	2.5429+06
STATE VARIABLES:					
TEMP F	-310.4517	-285.0259	-278.2571	-300.7938	87.5000
PRES PSIA	19.0000	91.0000	19.0000	19.0000	14.0000
VFRAC	0.1896	1.0000	1.0000	1.0000	1.0000
LFRAC	0.8104	0.0	0.0	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-4838.3560	-2656.1875	-2496.4815	-2656.1875	70.6464
BTU/LB	-164.2635	-94.7985	-84.7562	-94.7985	2.3985
BTU/HR	-2.9334+07	-1.1712+07	-1.5135+07	-1.1712+07	4.2831+05
ENTROPY:					
BTU/LBMOL-R	-22.1234	-11.9239	-6.8406	-9.0663	1.5262
BTU/LB-R	-0.7511	-0.4256	-0.2322	-0.3236	5.1814-02
DENSITY:					
LBMOL/CUFT	6.3719-02	5.7087-02	1.0027-02	1.1562-02	2.3842-03
LB/CUFT	1.8768	1.5995	0.2953	0.3240	7.0225-02
AVG MW	29.4548	28.0193	29.4548	28.0193	29.4548

110 DUMMY

-----

STREAM ID	110	DUMMY
FROM :	MHX	DUMMYSP
TO :	----	COL
SUBSTREAM: MIXED		
PHASE:	VAPOR	MISSING
COMPONENTS: LBMOL/HR		
OXYGEN	6.4300	0.0
NITROGEN	4402.8152	0.0
TOTAL FLOW:		
LBMOL/HR	4409.2452	0.0
LB/HR	1.2354+05	0.0
CUFT/HR	1.8534+06	0.0







# Oxy Fuel for Clean Energy Generation

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```

COLD SIDE:   INLET STREAM   OUTLET STREAM
             -----
             211             215
             209             214
             216             212
    
```

```

PROPERTIES FOR STREAM 202
PROPERTY OPTION SET:  PSRK           RKS-MHV1 EQUATION OF STATE
    
```

```

PROPERTIES FOR STREAM 209
PROPERTY OPTION SET:  PSRK           RKS-MHV1 EQUATION OF STATE
    
```

```

PROPERTIES FOR STREAM 213
PROPERTY OPTION SET:  PSRK           RKS-MHV1 EQUATION OF STATE
    
```

```

PROPERTIES FOR STREAM 211
PROPERTY OPTION SET:  PSRK           RKS-MHV1 EQUATION OF STATE
    
```

```

PROPERTIES FOR STREAM 216
PROPERTY OPTION SET:  PSRK           RKS-MHV1 EQUATION OF STATE
    
```

```

***  MASS AND ENERGY BALANCE  ***
                                     IN           OUT           RELATIVE DIFF.
TOTAL BALANCE
MOLE (KMOL/HR )                    15900.0        15900.0        0.00000
MASS (KG/HR )                       464417.        464417.        0.00000
ENTHALPY (CAL/SEC )                 -0.308761E+07  -0.308761E+07  0.245209E-06
    
```

```

***  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 \*\*\*

```

MAXIMUM NO. ITERATIONS                30
CONVERGENCE TOLERANCE                 0.000100000
    
```

```

SPECIFICATIONS FOR STREAM 202  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE              K           105.928
PRESSURE DROP                       ATM          0.13609
MAXIMUM NO. ITERATIONS              30
CONVERGENCE TOLERANCE               0.000100000
    
```

```

SPECIFICATIONS FOR STREAM 209  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE              K           302.594
PRESSURE DROP                       ATM          0.13609
MAXIMUM NO. ITERATIONS              30
CONVERGENCE TOLERANCE               0.000100000
    
```

```

SPECIFICATIONS FOR STREAM 213  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE              K           113.150
PRESSURE DROP                       ATM          0.13609
MAXIMUM NO. ITERATIONS              30
    
```



# Oxy Fuel for Clean Energy Generation

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CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 211 :  
 TWO PHASE FLASH  
 PRESSURE DROP ATM 0.13609  
 MAXIMUM NO. ITERATIONS 30  
 CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM 216 :  
 TWO PHASE FLASH  
 PRESSURE DROP ATM 0.13609  
 MAXIMUM NO. ITERATIONS 30  
 CONVERGENCE TOLERANCE 0.000100000

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY CAL/SEC	OUTLET TEMPERATURE K	OUTLET PRESSURE ATM	OUTLET VAPOR FRAC
202	-0.23689E+07	105.93	8.6418	0.9820
209	0.12237E+06	302.59	1.2248	1.0000
213	-0.88492E+06	113.15	8.7099	1.0000
211	0.14488E+07	304.29	1.2248	1.0000
216	0.16826E+07	304.29	1.2248	1.0000

```

-----
| 202 | | 203 | |
|----->| 5700.0 | KMOL/HR |----->|
| 305.37 | | 105.93 |
|----->| 213 | | 204 |
|----->| 2250.0 | KMOL/HR |----->|
| 305.37 | | 113.15 |
|----->| 214 | | 209 |
|----->| 2250.0 | KMOL/HR |----->|
| 302.59 | | 274.66 |
|----->| 215 | | 211 |
|----->| 3450.0 | KMOL/HR |----->|
| 304.29 | | 89.07 |
|----->| 212 | | 216 |
|----->| 2250.0 | KMOL/HR |----->|
| 304.29 | | 85.57 |
-----

```

\*\*\* INTERNAL ANALYSIS \*\*\*

FLOW IS COUNTERCURRENT.  
 DUTY 0.32538E+07 CAL/SEC  
 UA 0.39831E+06 CAL/SEC-K  
 AVERAGE LMTD (DUTY/UA) 8.1691 K



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MIN TEMP APPROACH		1.0845	K					
HOT-SIDE TEMP APPROACH		1.0845	K					
COLD-SIDE TEMP APPROACH		20.354	K					
HOT-SIDE NTU		24.415						
COLD-SIDE NTU		26.773						
DUTY	T HOT	T COLD	DELTA T	LMTD	UA ZONE	Q ZONE	UA	
PINCH	STREAM	IN/OUT/DEW/						
POINT	BUBBLE POINT							
CAL/SEC	K	K	K	K	CAL/SEC-K	CAL/SEC		
CAL/SEC-K								
0.000	105.93	85.57	20.35					
0.3435E+05	105.99	85.72	20.27	20.31	1691.	0.3435E+05	1691.	
LOC DP 202								
0.1317E+06	113.15	86.15	27.00	23.47	4146.	0.9731E+05	5837.	
OUT 213								
0.4067E+06	128.53	87.33	41.20	33.60	8187.	0.2751E+06		
0.1402E+05								
0.7343E+06	147.72	88.42	59.31	49.70	6591.	0.3276E+06		
0.2062E+05	DP 216							
0.7373E+06	147.91	89.07	58.83	59.07	50.33	2973.		
0.2067E+05	IN 211							
0.8135E+06	152.48	95.75	56.73	57.78	1318.	0.7616E+05		
0.2198E+05								
0.1220E+07	177.21	131.89	45.33	50.82	8004.	0.4067E+06		
0.2999E+05								
0.1627E+07	202.42	168.39	34.03	39.41	0.1032E+05	0.4067E+06		
0.4031E+05								
0.2034E+07	227.92	205.05	22.87	28.08	0.1448E+05	0.4067E+06		
0.5479E+05								
0.2440E+07	253.62	241.80	11.82	16.74	0.2429E+05	0.4067E+06		
0.7909E+05								
0.2804E+07	276.70	274.66	2.04	5.57	0.6528E+05	0.3634E+06		
0.1444E+06	IN 209							
0.2847E+07	279.46	277.47	1.99	2.01	0.2151E+05	0.4332E+05		
0.1659E+06								
0.3235E+07	304.18	302.59	1.58	1.78	0.2182E+06	0.3880E+06		
0.3841E+06	OUT 209							
0.3254E+07	305.37	304.29	1.08	1.32	0.1422E+05	0.1874E+05		
0.3983E+06	GBL							

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

BLOCK: MHX      MODEL: MHEATX

HOT SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	202	203
	213	204

COLD SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	211	215
	209	214



```

                216                212

PROPERTIES FOR STREAM 202
PROPERTY OPTION SET:  PSRK          RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 209
PROPERTY OPTION SET:  PSRK          RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 213
PROPERTY OPTION SET:  PSRK          RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 211
PROPERTY OPTION SET:  PSRK          RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 216
PROPERTY OPTION SET:  PSRK          RKS-MHV1 EQUATION OF STATE

***  MASS AND ENERGY BALANCE  ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (KMOL/HR )                15900.0      15900.0          0.00000
MASS (KG/HR )                   464417.      464417.          0.00000
ENTHALPY (CAL/SEC )             -0.308761E+07  -0.308761E+07  0.245209E-06

***  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  ***

MAXIMUM NO. ITERATIONS                30
CONVERGENCE TOLERANCE                 0.000100000

SPECIFICATIONS FOR STREAM 202  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE                K                105.928
PRESSURE DROP                         ATM              0.13609
MAXIMUM NO. ITERATIONS                30
CONVERGENCE TOLERANCE                 0.000100000

SPECIFICATIONS FOR STREAM 209  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE                K                302.594
PRESSURE DROP                         ATM              0.13609
MAXIMUM NO. ITERATIONS                30
CONVERGENCE TOLERANCE                 0.000100000

SPECIFICATIONS FOR STREAM 213  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE                K                113.150
PRESSURE DROP                         ATM              0.13609
MAXIMUM NO. ITERATIONS                30
CONVERGENCE TOLERANCE                 0.000100000

SPECIFICATIONS FOR STREAM 211  :
TWO PHASE FLASH

```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

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PRESSURE DROP                ATM                0.13609
MAXIMUM NO. ITERATIONS      30
CONVERGENCE TOLERANCE      0.000100000
  
```

```

SPECIFICATIONS FOR STREAM 216 :
TWO PHASE FLASH
PRESSURE DROP                ATM                0.13609
MAXIMUM NO. ITERATIONS      30
CONVERGENCE TOLERANCE      0.000100000
  
```

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY CAL/SEC	OUTLET TEMPERATURE K	OUTLET PRESSURE ATM	OUTLET VAPOR FRAC
202	-0.23689E+07	105.93	8.6418	0.9820
209	0.12237E+06	302.59	1.2248	1.0000
213	-0.88492E+06	113.15	8.7099	1.0000
211	0.14488E+07	304.29	1.2248	1.0000
216	0.16826E+07	304.29	1.2248	1.0000

```

-----
|
| 202 |
|----->|          5700.0    KMOL/HR          |----->| 203 |
| 305.37 | |          |          |          |          | 105.93 |
|
| 213 |
|----->|          2250.0    KMOL/HR          |----->| 204 |
| 305.37 | |          |          |          |          | 113.15 |
|
| 214 |
|<-----|          2250.0    KMOL/HR          |<-----| 209 |
| 302.59 | |          |          |          |          | 274.66 |
|
| 215 |
|<-----|          3450.0    KMOL/HR          |<-----| 211 |
| 304.29 | |          |          |          |          | 89.07 |
|
| 212 |
|<-----|          2250.0    KMOL/HR          |<-----| 216 |
| 304.29 | |          |          |          |          | 85.57 |
|
|-----
  
```

\*\*\* INTERNAL ANALYSIS \*\*\*

```

FLOW IS COUNTERCURRENT.
DUTY                0.32538E+07 CAL/SEC
UA                0.39831E+06 CAL/SEC-K
AVERAGE LMTD (DUTY/UA) 8.1691 K
MIN TEMP APPROACH  1.0845 K
HOT-SIDE TEMP APPROACH 1.0845 K
COLD-SIDE TEMP APPROACH 20.354 K
HOT-SIDE NTU       24.415
  
```



# Oxy Fuel for Clean Energy Generation

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COLD-SIDE NTU		26.773						
DUTY PINCH	T HOT STREAM IN/OUT/DEW/ POINT BUBBLE POINT CAL/SEC K	T COLD K	DELTA T K	LMTD K	UA ZONE CAL/SEC-K	Q ZONE CAL/SEC	UA	
0.000	105.93	85.57	20.35					
0.3435E+05	105.99	85.72	20.27	20.31	1691.	0.3435E+05	1691.	
LOC DP 202								
0.1317E+06	113.15	86.15	27.00	23.47	4146.	0.9731E+05	5837.	
OUT 213								
0.4067E+06	128.53	87.33	41.20	33.60	8187.	0.2751E+06		
0.1402E+05								
0.7343E+06	147.72	88.42	59.31	49.70	6591.	0.3276E+06		
0.2062E+05	DP 216							
0.7373E+06	147.91	89.07	58.83	59.07	50.33	2973.		
0.2067E+05	IN 211							
0.8135E+06	152.48	95.75	56.73	57.78	1318.	0.7616E+05		
0.2198E+05								
0.1220E+07	177.21	131.89	45.33	50.82	8004.	0.4067E+06		
0.2999E+05								
0.1627E+07	202.42	168.39	34.03	39.41	0.1032E+05	0.4067E+06		
0.4031E+05								
0.2034E+07	227.92	205.05	22.87	28.08	0.1448E+05	0.4067E+06		
0.5479E+05								
0.2440E+07	253.62	241.80	11.82	16.74	0.2429E+05	0.4067E+06		
0.7909E+05								
0.2804E+07	276.70	274.66	2.04	5.57	0.6528E+05	0.3634E+06		
0.1444E+06	IN 209							
0.2847E+07	279.46	277.47	1.99	2.01	0.2151E+05	0.4332E+05		
0.1659E+06								
0.3235E+07	304.18	302.59	1.58	1.78	0.2182E+06	0.3880E+06		
0.3841E+06	OUT 209							
0.3254E+07	305.37	304.29	1.08	1.32	0.1422E+05	0.1874E+05		
0.3983E+06	GBL							

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

BLOCK: MHX      MODEL: MHEATX

HOT SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	202	203
	213	204

COLD SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	211	215
	209	214
	216	212

PROPERTIES FOR STREAM 202  
PROPERTY OPTION SET: PSRK      RKS-MHV1 EQUATION OF STATE



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

PROPERTIES FOR STREAM 209  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 213  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 211  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 216  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***			
	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (KMOL/HR )	15900.0	15900.0	0.00000
MASS (KG/HR )	464417.	464417.	0.00000
ENTHALPY (CAL/SEC )	-0.308761E+07	-0.308761E+07	0.245209E-06

*** 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 \*\*\*

MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 202 :		
TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	K	105.928
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 209 :		
TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	K	302.594
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 213 :		
TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	K	113.150
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 211 :		
TWO PHASE FLASH		
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000





Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

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SPECIFICATIONS FOR STREAM 216      :
TWO PHASE FLASH
PRESSURE DROP                       ATM           0.13609
MAXIMUM NO. ITERATIONS              30
CONVERGENCE TOLERANCE               0.000100000
    
```

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY CAL/SEC	OUTLET TEMPERATURE K	OUTLET PRESSURE ATM	OUTLET VAPOR FRAC
202	-0.23689E+07	105.93	8.6418	0.9820
209	0.12237E+06	302.59	1.2248	1.0000
213	-0.88492E+06	113.15	8.7099	1.0000
211	0.14488E+07	304.29	1.2248	1.0000
216	0.16826E+07	304.29	1.2248	1.0000

```

-----
|
| 202 | | 203 | | |
|----->| 5700.0 | KMOL/HR | |----->|
| 305.37 | | 105.93 |
|
| 213 | | 204 | | |
|----->| 2250.0 | KMOL/HR | |----->|
| 305.37 | | 113.15 |
|
| 214 | | 209 | | |
|<-----| 2250.0 | KMOL/HR | |<-----|
| 302.59 | | 274.66 |
|
| 215 | | 211 | | |
|<-----| 3450.0 | KMOL/HR | |<-----|
| 304.29 | | 89.07 |
|
| 212 | | 216 | | |
|<-----| 2250.0 | KMOL/HR | |<-----|
| 304.29 | | 85.57 |
|
|-----
    
```

\*\*\* INTERNAL ANALYSIS \*\*\*

```

FLOW IS COUNTERCURRENT.
DUTY                0.32538E+07 CAL/SEC
UA                  0.39831E+06 CAL/SEC-K
AVERAGE LMTD (DUTY/UA) 8.1691 K
MIN TEMP APPROACH  1.0845 K
HOT-SIDE TEMP APPROACH 1.0845 K
COLD-SIDE TEMP APPROACH 20.354 K
HOT-SIDE NTU       24.415
COLD-SIDE NTU      26.773
    
```

```

DUTY      T HOT      T COLD      DELTA T      LMTD      UA ZONE      Q ZONE      UA
PINCH  STREAM IN/OUT/DEW/
    
```



# Oxy Fuel for Clean Energy Generation

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POINT	BUBBLE POINT							
CAL/SEC	K	K	K	K	CAL/SEC-K	CAL/SEC		
CAL/SEC-K								
0.000	105.93	85.57	20.35					
0.3435E+05	105.99	85.72	20.27	20.31	1691.	0.3435E+05	1691.	
LOC DP 202								
0.1317E+06	113.15	86.15	27.00	23.47	4146.	0.9731E+05	5837.	
OUT 213								
0.4067E+06	128.53	87.33	41.20	33.60	8187.	0.2751E+06		
0.1402E+05								
0.7343E+06	147.72	88.42	59.31	49.70	6591.	0.3276E+06		
0.2062E+05	DP 216							
0.7373E+06	147.91	89.07	58.83	59.07	50.33	2973.		
0.2067E+05	IN 211							
0.8135E+06	152.48	95.75	56.73	57.78	1318.	0.7616E+05		
0.2198E+05								
0.1220E+07	177.21	131.89	45.33	50.82	8004.	0.4067E+06		
0.2999E+05								
0.1627E+07	202.42	168.39	34.03	39.41	0.1032E+05	0.4067E+06		
0.4031E+05								
0.2034E+07	227.92	205.05	22.87	28.08	0.1448E+05	0.4067E+06		
0.5479E+05								
0.2440E+07	253.62	241.80	11.82	16.74	0.2429E+05	0.4067E+06		
0.7909E+05								
0.2804E+07	276.70	274.66	2.04	5.57	0.6528E+05	0.3634E+06		
0.1444E+06	IN 209							
0.2847E+07	279.46	277.47	1.99	2.01	0.2151E+05	0.4332E+05		
0.1659E+06								
0.3235E+07	304.18	302.59	1.58	1.78	0.2182E+06	0.3880E+06		
0.3841E+06	OUT 209							
0.3254E+07	305.37	304.29	1.08	1.32	0.1422E+05	0.1874E+05		
0.3983E+06	GBL							

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

BLOCK: MHX      MODEL: MHEATX

HOT SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	202	203
	213	204

COLD SIDE:	INLET STREAM	OUTLET STREAM
	-----	-----
	211	215
	209	214
	216	212

PROPERTIES FOR STREAM 202  
PROPERTY OPTION SET: PSRK      RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 209  
PROPERTY OPTION SET: PSRK      RKS-MHV1 EQUATION OF STATE



## Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

PROPERTIES FOR STREAM 213

PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 211

PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

PROPERTIES FOR STREAM 216

PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (KMOL/HR )	15900.0	15900.0	0.00000
MASS (KG/HR )	464417.	464417.	0.00000
ENTHALPY (CAL/SEC )	-0.308761E+07	-0.308761E+07	0.245209E-06

\*\*\* 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 \*\*\*

MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 202	:	
TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	K	105.928
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 209	:	
TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	K	302.594
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 213	:	
TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	K	113.150
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 211	:	
TWO PHASE FLASH		
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000
SPECIFICATIONS FOR STREAM 216	:	
TWO PHASE FLASH		
PRESSURE DROP	ATM	0.13609
MAXIMUM NO. ITERATIONS		30



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

CONVERGENCE TOLERANCE

0.000100000

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY CAL/SEC	OUTLET TEMPERATURE K	OUTLET PRESSURE ATM	OUTLET VAPOR FRAC
202	-0.23689E+07	105.93	8.6418	0.9820
209	0.12237E+06	302.59	1.2248	1.0000
213	-0.88492E+06	113.15	8.7099	1.0000
211	0.14488E+07	304.29	1.2248	1.0000
216	0.16826E+07	304.29	1.2248	1.0000

```

-----
|
| 202 |
|----->|          5700.0    KMOL/HR |
| 305.37 |
|
| 213 |
|----->|          2250.0    KMOL/HR |
| 305.37 |
|
| 214 |
|-----<|          2250.0    KMOL/HR |
| 302.59 |
|
| 215 |
|-----<|          3450.0    KMOL/HR |
| 304.29 |
|
| 212 |
|-----<|          2250.0    KMOL/HR |
| 304.29 |
|
|-----
|
| 203 |
|----->|          105.93
|
| 204 |
|----->|          113.15
|
| 209 |
|-----<|          274.66
|
| 211 |
|-----<|          89.07
|
| 216 |
|-----<|          85.57
|
|-----

```

\*\*\* INTERNAL ANALYSIS \*\*\*

FLOW IS COUNTERCURRENT.

DUTY	0.32538E+07	CAL/SEC
UA	0.39831E+06	CAL/SEC-K
AVERAGE LMTD (DUTY/UA)	8.1691	K
MIN TEMP APPROACH	1.0845	K
HOT-SIDE TEMP APPROACH	1.0845	K
COLD-SIDE TEMP APPROACH	20.354	K
HOT-SIDE NTU	24.415	
COLD-SIDE NTU	26.773	

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



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

0.000	105.93	85.57	20.35				
0.3435E+05	105.99	85.72	20.27	20.31	1691.	0.3435E+05	1691.
LOC DP 202							
0.1317E+06	113.15	86.15	27.00	23.47	4146.	0.9731E+05	5837.
OUT 213							
0.4067E+06	128.53	87.33	41.20	33.60	8187.	0.2751E+06	
0.1402E+05							
0.7343E+06	147.72	88.42	59.31	49.70	6591.	0.3276E+06	
0.2062E+05	DP 216						
0.7373E+06	147.91	89.07	58.83	59.07	50.33	2973.	
0.2067E+05	IN 211						
0.8135E+06	152.48	95.75	56.73	57.78	1318.	0.7616E+05	
0.2198E+05							
0.1220E+07	177.21	131.89	45.33	50.82	8004.	0.4067E+06	
0.2999E+05							
0.1627E+07	202.42	168.39	34.03	39.41	0.1032E+05	0.4067E+06	
0.4031E+05							
0.2034E+07	227.92	205.05	22.87	28.08	0.1448E+05	0.4067E+06	
0.5479E+05							
0.2440E+07	253.62	241.80	11.82	16.74	0.2429E+05	0.4067E+06	
0.7909E+05							
0.2804E+07	276.70	274.66	2.04	5.57	0.6528E+05	0.3634E+06	
0.1444E+06	IN 209						
0.2847E+07	279.46	277.47	1.99	2.01	0.2151E+05	0.4332E+05	
0.1659E+06							
0.3235E+07	304.18	302.59	1.58	1.78	0.2182E+06	0.3880E+06	
0.3841E+06	OUT 209						
0.3254E+07	305.37	304.29	1.08	1.32	0.1422E+05	0.1874E+05	
0.3983E+06	GBL						

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

BLOCK: COL      MODEL: RADFRAC

```

-----
INLETS  - 203      STAGE  21
          204      STAGE  25
          DUMMY    STAGE   1
OUTLETS  - 210      STAGE   1
          205      STAGE  25
          DUMMY2   STAGE   2
  
```

PROPERTY OPTION SET:    PSRK      RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (KMOL/HR )	7950.00	7950.00	-0.114402E-15
MASS (KG/HR )	232208.	232208.	0.406286E-11
ENTHALPY (CAL/SEC )	-0.317073E+07	-0.472359E+07	0.328746

\*\*\* 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 ****
*****

**** INPUT PARAMETERS ****

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

**** COL-SPECS ****

MOLAR VAPOR DIST / TOTAL DIST  1.00000
MOLAR DISTILLATE RATE          KMOL/HR 3,450.00
REBOILER DUTY                  CAL/SEC 0.0

**** PROFILES ****

P-SPEC      STAGE 1 PRES, ATM      8.50575

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

*** COMPONENT SPLIT FRACTIONS ***

                                OUTLET STREAMS
                                -----
                                210      205      DUMMY2
COMPONENT:
OXYGEN      .41640E-02   .99584   0.0000
NITROGEN    .61806     .38194   0.0000

*** SUMMARY OF KEY RESULTS ***

TOP STAGE TEMPERATURE          K      101.556
BOTTOM STAGE TEMPERATURE      K      108.199
TOP STAGE LIQUID FLOW          KMOL/HR 5,255.67
BOTTOM STAGE LIQUID FLOW      KMOL/HR 4,500.00
TOP STAGE VAPOR FLOW           KMOL/HR 3,450.00
BOILUP VAPOR FLOW             KMOL/HR 2,405.75
MOLAR REFLUX RATIO            1.52338
MOLAR BOILUP RATIO            0.97906
CONDENSER DUTY (W/O SUBCOOL)  CAL/SEC -1,552,860.
REBOILER DUTY                  CAL/SEC 0.0
```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

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

DEW POINT	0.56569E-08	STAGE= 15
BUBBLE POINT	0.43439E-08	STAGE= 25
COMPONENT MASS BALANCE	0.93720E-08	STAGE= 10 COMP=OXYGEN
ENERGY BALANCE	0.56203E-09	STAGE= 25

\*\*\*\* PROFILES \*\*\*\*

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

STAGE	TEMPERATURE K	PRESSURE ATM	ENTHALPY CAL/MOL		HEAT DUTY CAL/SEC
			LIQUID	VAPOR	
1	101.56	8.5057	-2533.8	-1470.7	-.15529+07
2	101.61	8.5139	-2534.6	-1470.4	
3	101.68	8.5221	-2535.6	-1469.9	
19	105.50	8.6527	-2610.5	-1440.4	
20	105.72	8.6609	-2614.2	-1438.7	
21	105.77	8.6691	-2614.6	-1438.4	
22	105.87	8.6772	-2615.9	-1437.7	
24	106.71	8.6936	-2629.4	-1431.1	
25	108.20	8.7017	-2651.3	-1419.4	

STAGE	FLOW RATE KMOL/HR		FEED RATE KMOL/HR			PRODUCT RATE KMOL/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	5256.	3450.					3450.0000
2	5248.	8706.					
3	5239.	8698.					
19	4676.	8156.					
20	4652.	8126.		5597.3758			
21	4752.	2505.	102.6241				
22	4743.	2502.					
24	4656.	2468.					
25	4500.	2406.		2250.0014		4500.0014	

\*\*\*\* MASS FLOW PROFILES \*\*\*\*

STAGE	FLOW RATE KG/HR		FEED RATE KG/HR			PRODUCT RATE KG/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.1474E+06	0.9669E+05					.96686+05
2	0.1472E+06	0.2440E+06					
3	0.1471E+06	0.2439E+06					
19	0.1373E+06	0.2345E+06					
20	0.1369E+06	0.2339E+06		.16142+06			
21	0.1398E+06	0.7212E+05	3026.7052				
22	0.1397E+06	0.7209E+05					
24	0.1383E+06	0.7154E+05					
25	0.1355E+06	0.7053E+05		.67761+05		.13552+06	

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

STAGE	OXYGEN	NITROGEN
1	0.60508E-02	0.99395
2	0.10066E-01	0.98993



3	0.15127E-01	0.98487
19	0.33600	0.66400
20	0.35277	0.64723
21	0.35558	0.64442
22	0.36210	0.63790
24	0.42389	0.57611
25	0.52759	0.47241

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

STAGE	OXYGEN	NITROGEN
1	0.28775E-02	0.99712
2	0.47933E-02	0.99521
3	0.72148E-02	0.99279
19	0.18353	0.81647
20	0.19457	0.80543
21	0.19649	0.80351
22	0.20089	0.79911
24	0.24435	0.75565
25	0.32691	0.67309

\*\*\*\* K-VALUES \*\*\*\*

STAGE	OXYGEN	NITROGEN
1	0.47555	1.0032
2	0.47618	1.0053
3	0.47695	1.0080
19	0.54622	1.2296
20	0.55156	1.2444
21	0.55258	1.2469
22	0.55480	1.2527
24	0.57645	1.3116
25	0.61964	1.4248

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

STAGE	OXYGEN	NITROGEN
1	0.69057E-02	0.99309
2	0.11482E-01	0.98852
3	0.17242E-01	0.98276
19	0.36629	0.63371
20	0.38370	0.61630
21	0.38661	0.61339
22	0.39335	0.60665
24	0.45666	0.54334
25	0.56057	0.43943

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

STAGE	OXYGEN	NITROGEN
1	0.32855E-02	0.99671
2	0.54714E-02	0.99453
3	0.82328E-02	0.99177
19	0.20431	0.79569
20	0.21627	0.78373
21	0.21834	0.78166
22	0.22309	0.77691
24	0.26974	0.73026
25	0.35683	0.64317

BLOCK: MAC MODEL: MCOMPR

-----  
INLET STREAMS: 201 TO STAGE 1





# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

OUTLET STREAMS: 202 FROM STAGE 3  
 PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (KMOL/HR )	5700.00	5700.00	0.00000
MASS (KG/HR )	164447.	164447.	0.00000
ENTHALPY (CAL/SEC )	46748.7	60395.2	-0.225954

\*\*\* 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  
 NUMBER OF STAGES 3  
 FINAL PRESSURE, ATM 8.77793  
 DISTRIBUTION AMONG STAGES EQUAL P-RATIO

### COMPRESSOR SPECIFICATIONS PER STAGE

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

### COOLER SPECIFICATIONS PER STAGE

STAGE NUMBER	PRESSURE DROP ATM	TEMPERATURE K
1	0.000	305.4
2	0.000	305.4
3	0.000	305.4

\*\*\* RESULTS \*\*\*

FINAL PRESSURE, ATM 8.77793  
 TOTAL WORK REQUIRED, KW 13,443.1  
 TOTAL COOLING DUTY , CAL/SEC -3,197,180.

\*\*\* PROFILE \*\*\*

### COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE ATM	PRESSURE RATIO	OUTLET TEMPERATURE K
1	2.063	2.063	398.5
2	4.256	2.063	402.1





BLOCK: O2VALVE MODEL: VALVE

```

-----
INLET STREAM:          207
OUTLET STREAM:         208
PROPERTY OPTION SET:  PSRK      RKS-MHV1 EQUATION OF STATE

```

```

***  MASS AND ENERGY BALANCE  ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (KMOL/HR )              2250.00      2250.00          0.00000
MASS (KG/HR )                 67761.2      67761.2          0.00000
ENTHALPY (CAL/SEC )          -0.165708E+07  -0.165708E+07  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  ***
VALVE OUTLET PRESSURE      ATM                      1.36092
VALVE FLOW COEF CALC.      NO

```

```

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

```

```

***  RESULTS  ***
VALVE PRESSURE DROP        ATM                      7.34080

```

BLOCK: PCOND MODEL: HEATER

```

-----
INLET STREAM:          208
OUTLET STREAM:         209
PROPERTY OPTION SET:  PSRK      RKS-MHV1 EQUATION OF STATE

```

```

***  MASS AND ENERGY BALANCE  ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (KMOL/HR )              2250.00      2250.00          0.00000
MASS (KG/HR )                 67761.2      67761.2          0.00000
ENTHALPY (CAL/SEC )          -0.165708E+07  -104223.          -0.937105

```

```

***  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 PQ FLASH
PRESSURE DROP              ATM                      0.0
SPECIFIED HEAT DUTY        CAL/SEC          1,552,860.

```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

MAXIMUM NO. ITERATIONS 30  
CONVERGENCE TOLERANCE 0.000100000

\*\*\* RESULTS \*\*\*

OUTLET TEMPERATURE K 274.66  
OUTLET PRESSURE ATM 1.3609  
OUTLET VAPOR FRACTION 1.0000

V-L PHASE EQUILIBRIUM :

COMP	F(I)	X(I)	Y(I)	K(I)
OXYGEN	0.52759	0.52759	0.52759	MISSING
NITROGEN	0.47241	0.47241	0.47241	MISSING

BLOCK: RECCOMP MODEL: MCOMPR

-----  
INLET STREAMS: 212 TO STAGE 1  
OUTLET STREAMS: 213 FROM STAGE 3  
PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (KMOL/HR )	2250.00	2250.00	-0.311160E-06
MASS (KG/HR )	67761.2	67761.2	-0.288809E-06
ENTHALPY (CAL/SEC )	25557.0	22721.8	0.110936

\*\*\* 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  
NUMBER OF STAGES 3  
FINAL PRESSURE, ATM 8.84598  
DISTRIBUTION AMONG STAGES EQUAL P-RATIO

COMPRESSOR SPECIFICATIONS PER STAGE

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

COOLER SPECIFICATIONS PER STAGE

STAGE NUMBER	PRESSURE DROP ATM	TEMPERATURE K
--------------	-------------------	---------------



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

1	0.000	305.4
2	0.000	305.4
3	0.000	305.4

\*\*\* RESULTS \*\*\*

FINAL PRESSURE, ATM	8.84598
TOTAL WORK REQUIRED, KW	4,789.49
TOTAL COOLING DUTY , CAL/SEC	-1,146,780.

\*\*\* PROFILE \*\*\*

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE ATM	PRESSURE RATIO	OUTLET TEMPERATURE K
1	2.368	1.933	390.8
2	4.576	1.933	392.1
3	8.846	1.933	392.1

STAGE NUMBER	INDICATED HORSEPOWER KW	BRAKE HORSEPOWER KW
1	1592.	1592.
2	1598.	1598.
3	1599.	1599.

STAGE NUMBER	HEAD DEVELOPED M-KGF/KG	VOLUMETRIC FLOW L/MIN	ISENTROPIC EFFICIENCY
1	6210.	0.7644E+06	0.7200
2	6234.	0.3969E+06	0.7200
3	6238.	0.2053E+06	0.7200

COOLER PROFILE

STAGE NUMBER	OUTLET TEMPERATURE K	OUTLET PRESSURE ATM	COOLING LOAD CAL/SEC	VAPOR FRACTION
1	305.4	2.368	-.3766E+06	1.000
2	305.4	4.576	-.3839E+06	1.000
3	305.4	8.846	-.3862E+06	1.000

BLOCK: REVALVE MODEL: VALVE

-----  
 INLET STREAM: 206  
 OUTLET STREAM: 216  
 PROPERTY OPTION SET: PSRK RKS-MHV1 EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (KMOL/HR )	2250.00	2250.00	0.00000
MASS (KG/HR )	67761.2	67761.2	0.00000
ENTHALPY (CAL/SEC )	-0.165708E+07	-0.165708E+07	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 ***

VALVE OUTLET PRESSURE      ATM          1.36092
VALVE FLOW COEF CALC.     NO

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

*** RESULTS ***

VALVE PRESSURE DROP        ATM          7.34080

BLOCK:  SPLIT      MODEL: FSPLIT
-----
INLET STREAM:            205
OUTLET STREAMS:         207          206
PROPERTY OPTION SET:    PSRK          RKS-MHV1 EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (KMOL/HR )           4500.00          4500.00          0.00000
MASS (KG/HR )              135522.          135522.          0.00000
ENTHALPY (CAL/SEC )        -0.331417E+07    -0.331417E+07    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 ***

FRACTION OF FLOW          STRM=206    FRAC=          0.50000

*** RESULTS ***

STREAM= 207              SPLIT=          0.50000    KEY= 0    STREAM-ORDER= 2
      206                0.50000          0          0          1

```

Stream Report

201 202 203 204 205  
-----



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

STREAM ID	201	202	203	204	205
FROM :	----	MAC	MHX	MHX	COL
TO :	MAC	MHX	COL	COL	SPLIT
CONV. MAX. REL. ERR:	0.0	0.0	0.0	-1.2341-06	0.0
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	MIXED	VAPOR	LIQUID
COMPONENTS: KMOL/HR					
OXYGEN	1197.0000	1197.0000	1197.0000	1187.0727	2374.1454
NITROGEN	4503.0000	4503.0000	4503.0000	1062.9287	2125.8560
WATER	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
KMOL/HR	5700.0000	5700.0000	5700.0000	2250.0014	4500.0014
KG/HR	1.6445+05	1.6445+05	1.6445+05	6.7761+04	1.3552+05
L/MIN	2.3584+06	2.7154+05	7.7617+04	3.3962+04	2770.3376
STATE VARIABLES:					
TEMP K	302.5944	305.3722	105.9278	113.1500	108.1990
PRES ATM	1.0003	8.7779	8.6418	8.7099	8.7017
VFRAC	1.0000	1.0000	0.9820	1.0000	0.0
LFRAC	0.0	0.0	1.7970-02	0.0	1.0000
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
CAL/MOL	29.5255	38.1444	-1458.0212	-1379.5128	-2651.3329
CAL/GM	1.0234	1.3221	-50.5373	-45.8065	-88.0371
CAL/SEC	4.6749+04	6.0395+04	-2.3085+06	-8.6220+05	-3.3142+06
ENTROPY:					
CAL/MOL-K	1.1182	-3.1687	-11.2838	-10.2008	-21.7754
CAL/GM-K	3.8759-02	-0.1098	-0.3911	-0.3387	-0.7230
DENSITY:					
MOL/CC	4.0281-05	3.4985-04	1.2240-03	1.1042-03	2.7073-02
GM/CC	1.1621-03	1.0093-02	3.5312-02	3.3253-02	0.8153
AVG MW	28.8504	28.8504	28.8504	30.1161	30.1161

206 207 208 209 210

-----

STREAM ID	206	207	208	209	210
FROM :	SPLIT	SPLIT	O2VALVE	PCOND	COL
TO :	REVALVE	O2VALVE	PCOND	MHX	N2VALVE
SUBSTREAM: MIXED					
PHASE:	LIQUID	LIQUID	MIXED	VAPOR	VAPOR
COMPONENTS: KMOL/HR					
OXYGEN	1187.0727	1187.0727	1187.0727	1187.0727	9.9273
NITROGEN	1062.9280	1062.9280	1062.9280	1062.9280	3440.0727
WATER	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
KMOL/HR	2250.0007	2250.0007	2250.0007	2250.0007	3450.0000
KG/HR	6.7761+04	6.7761+04	6.7761+04	6.7761+04	9.6686+04
L/MIN	1385.1688	1385.1688	4.3778+04	6.2070+05	4.5746+04
STATE VARIABLES:					
TEMP K	108.1990	108.1990	85.5742	274.6615	101.5561
PRES ATM	8.7017	8.7017	1.3609	1.3609	8.5057
VFRAC	0.0	0.0	0.2316	1.0000	1.0000
LFRAC	1.0000	1.0000	0.7684	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
CAL/MOL	-2651.3329	-2651.3329	-2651.3329	-166.7567	-1470.7015



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

CAL/GM	-88.0371	-88.0371	-88.0371	-5.5371	-52.4783
CAL/SEC	-1.6571+06	-1.6571+06	-1.6571+06	-1.0422+05	-1.4094+06
ENTROPY:					
CAL/MOL-K	-21.7754	-21.7754	-21.2655	0.1796	-12.3808
CAL/GM-K	-0.7230	-0.7230	-0.7061	5.9625-03	-0.4418
DENSITY:					
MOL/CC	2.7073-02	2.7073-02	8.5659-04	6.0416-05	1.2569-03
GM/CC	0.8153	0.8153	2.5797-02	1.8195-03	3.5226-02
AVG MW	30.1161	30.1161	30.1161	30.1161	28.0249

211 212 213 214 215

-----

STREAM ID	211	212	213	214	215
FROM :	N2VALVE	MHX	RECCOMP	MHX	MHX
TO :	MHX	RECCOMP	MHX	----	----
CONV. MAX. REL. ERR:	0.0	2.1179-05	0.0	0.0	0.0
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
COMPONENTS: KMOL/HR					
OXYGEN	9.9273	1187.0727	1187.0727	1187.0727	9.9273
NITROGEN	3440.0727	1062.9280	1062.9287	1062.9280	3440.0727
WATER	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
KMOL/HR	3450.0000	2250.0007	2250.0014	2250.0007	3450.0000
KG/HR	9.6686+04	6.7761+04	6.7761+04	6.7761+04	9.6686+04
L/MIN	2.9731+05	7.6440+05	1.0620+05	7.6014+05	1.1725+06
STATE VARIABLES:					
TEMP K	89.0749	304.2877	305.3722	302.5944	304.2877
PRES ATM	1.3609	1.2248	8.8460	1.2248	1.2248
VFRAC	1.0000	1.0000	1.0000	1.0000	1.0000
LFRAC	0.0	0.0	0.0	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
CAL/MOL	-1470.7015	40.8911	36.3548	29.0284	41.1312
CAL/GM	-52.4783	1.3578	1.2072	0.9639	1.4677
CAL/SEC	-1.4094+06	2.5557+04	2.2722+04	1.8143+04	3.9417+04
ENTROPY:					
CAL/MOL-K	-9.0912	1.1067	-2.8339	1.0676	-0.2276
CAL/GM-K	-0.3244	3.6747-02	-9.4099-02	3.5449-02	-8.1203-03
DENSITY:					
MOL/CC	1.9340-04	4.9058-05	3.5312-04	4.9333-05	4.9040-05
GM/CC	5.4200-03	1.4774-03	1.0635-02	1.4857-03	1.3743-03
AVG MW	28.0249	30.1161	30.1161	30.1161	28.0249

216 DUMMY DUMMY2

-----

STREAM ID	216	DUMMY	DUMMY2
FROM :	REVALVE	----	COL
TO :	MHX	COL	----
SUBSTREAM: MIXED			
PHASE:	MIXED	MISSING	MISSING
COMPONENTS: KMOL/HR			
OXYGEN	1187.0727	0.0	0.0
NITROGEN	1062.9280	0.0	0.0

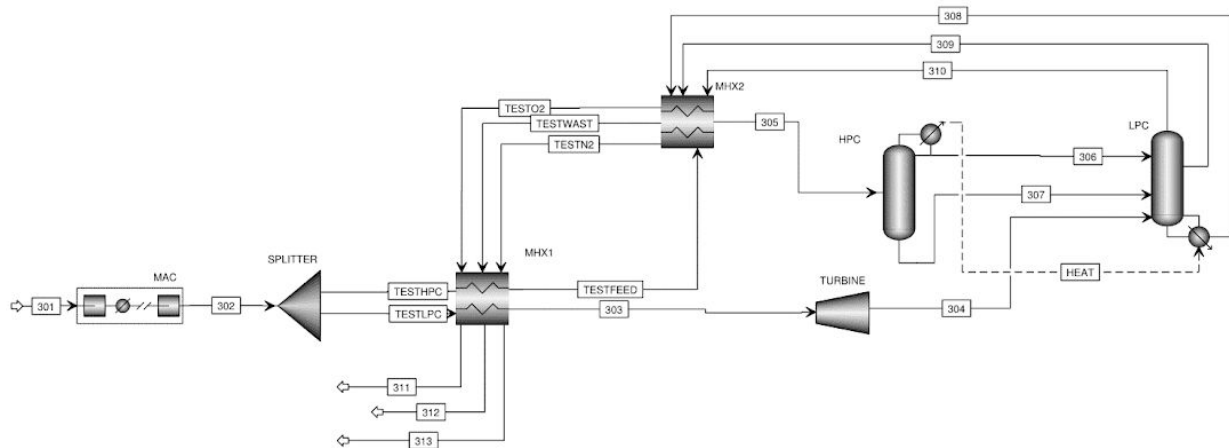




WATER	0.0	0.0	0.0
TOTAL FLOW:			
KMOL/HR	2250.0007	0.0	0.0
KG/HR	6.7761+04	0.0	0.0
L/MIN	4.3778+04	0.0	0.0
STATE VARIABLES:			
TEMP K	85.5742	305.3722	MISSING
PRES ATM	1.3609	6.4644	MISSING
VFRAC	0.2316	MISSING	MISSING
LFRAC	0.7684	MISSING	MISSING
SFRAC	0.0	MISSING	MISSING
ENTHALPY:			
CAL/MOL	-2651.3329	MISSING	MISSING
CAL/GM	-88.0371	MISSING	MISSING
CAL/SEC	-1.6571+06	MISSING	MISSING
ENTROPY:			
CAL/MOL-K	-21.2655	MISSING	MISSING
CAL/GM-K	-0.7061	MISSING	MISSING
DENSITY:			
MOL/CC	8.5659-04	MISSING	MISSING
GM/CC	2.5797-02	MISSING	MISSING
AVG MW	30.1161	MISSING	MISSING

## 95% Oxygen

### Flowsheet



In this simulation, two MHEATX blocks were used because, in reality, stream 303 would split from 302 in the middle of a single heat exchanger and only travel through about half of the exchanger. It was simpler to model on ASPEN using two blocks, where stream 303 only went through one heat exchanger.



Block Report

BLOCK: MHX1 MODEL: MHEATX

HOT SIDE: INLET STREAM OUTLET STREAM
TESTHPC TESTFEED
TESTLPC 303

COLD SIDE: INLET STREAM OUTLET STREAM
TESTN2 313
TESTO2 311
TESTWAST 312

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

PROPERTIES FOR STREAM TESTN2
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM TESTO2
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

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

Table with 4 columns: IN, OUT, RELATIVE DIFF. and rows for MOLE, MASS, ENTHALPY.

Table with 3 columns and rows for FEED STREAMS CO2E, PRODUCT STREAMS CO2E, NET STREAMS CO2E PRODUCTION, UTILITIES CO2E PRODUCTION, TOTAL CO2E PRODUCTION.

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM TESTLPC :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE F -150.000
SPECIFIED PRESSURE PSIA 102.000
MAXIMUM NO. ITERATIONS 50
CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM TESTN2 :
TWO PHASE TP FLASH



# Oxy Fuel for Clean Energy Generation

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```

SPECIFIED TEMPERATURE      F      80.0000
SPECIFIED PRESSURE         PSIA    23.0000
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM TESTO2 :

```

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE      F      80.0000
SPECIFIED PRESSURE         PSIA    23.0000
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM TESTWAST:

```

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE      F      80.0000
PRESSURE DROP              PSI     0.0
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM TESTHPC :

```

TWO PHASE FLASH
PRESSURE DROP              PSI     0.0
MAXIMUM NO. ITERATIONS     50
CONVERGENCE TOLERANCE     0.000100000
  
```

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
TESTLPC	-0.46189E+07	-150.00	102.00	1.0000
TESTN2	0.11601E+08	80.00	23.000	1.0000
TESTO2	0.42911E+07	80.00	23.000	1.0000
TESTWAST	0.81886E+07	80.00	23.720	1.0000
TESTHPC	-0.19461E+08	-162.76	102.00	1.0000

```

-----
TESTN2 | | | 313
----->| | 6377.7 LBMOL/HR | |----->
-180.00| | | 80.00
TESTO2 | | | 311
----->| | 2350.0 LBMOL/HR | |----->
-180.00| | | 80.00
TESTWAST | | | 312
----->| | 4500.0 LBMOL/HR | |----->
-180.00| | | 80.00
303 | | | TESTLPC
<-----| | 2645.5 LBMOL/HR | |-----<
-150.00| | | 95.00
TESTFEED | | | TESTHPC
<-----| | 10582. LBMOL/HR | |-----<
-162.76 | | | 95.00
  
```



MHEATX HCURVE: MHX1 HCURVE 2

INDEPENDENT VARIABLE: DUTY
STREAM: TESTLPC
PRESSURE PROFILE: CONSTANT
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

Table with 5 columns: DUTY, PRES, TEMP, VFRAC. Rows show data points for HCURVE 2, including values like 0.0, -4.1990+05, -8.3980+05, etc.

MHEATX HCURVE: MHX1 HCURVE 3

INDEPENDENT VARIABLE: DUTY
STREAM: TESTN2
PRESSURE PROFILE: CONSTANT
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

Table with 5 columns: DUTY, PRES, TEMP, VFRAC. Rows show data points for HCURVE 3, including values like 0.0, 1.0546+06, 2.1092+06, etc.



# Oxy Fuel for Clean Energy Generation

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```

! 7.3822+06 ! 23.0000 ! -14.7613 ! 1.0000 !
! 8.4368+06 ! 23.0000 ! 8.9192 ! 1.0000 !
! 9.4914+06 ! 23.0000 ! 32.6079 ! 1.0000 !
!-----+-----+-----+-----!
! 1.0546+07 ! 23.0000 ! 56.3023 ! 1.0000 !
! 1.1601+07 ! 23.0000 ! 80.0000 ! 1.0000 !
!-----+-----+-----+-----!

```

MHEATX HCURVE:        MX1        HCURVE 4

```

INDEPENDENT VARIABLE: DUTY
STREAM:                TESTO2
PRESSURE PROFILE:     CONSTANT
PROPERTY OPTION SET:  PENG-ROB    STANDARD PR EQUATION OF STATE

```

```

! DUTY        ! PRES        ! TEMP        ! VFRAC       !
!             !             !             !             !
!             !             !             !             !
! BTU/HR      ! PSIA        ! F            !             !
!             !             !             !             !
!=====+=====+=====+=====!
!        0.0    ! 23.0000    ! -180.4747   ! 1.0000    !
! 3.9010+05    ! 23.0000    ! -156.8737   ! 1.0000    !
! 7.8019+05    ! 23.0000    ! -133.2302   ! 1.0000    !
! 1.1703+06    ! 23.0000    ! -109.5549   ! 1.0000    !
! 1.5604+06    ! 23.0000    ! -85.8568    ! 1.0000    !
!-----+-----+-----+-----!
! 1.9505+06    ! 23.0000    ! -62.1440    ! 1.0000    !
! 2.3406+06    ! 23.0000    ! -38.4243    ! 1.0000    !
! 2.7307+06    ! 23.0000    ! -14.7055    ! 1.0000    !
! 3.1208+06    ! 23.0000    ! 9.0044      ! 1.0000    !
! 3.5109+06    ! 23.0000    ! 32.6973     ! 1.0000    !
!-----+-----+-----+-----!
! 3.9010+06    ! 23.0000    ! 56.3653     ! 1.0000    !
! 4.2911+06    ! 23.0000    ! 80.0000     ! 1.0000    !
!-----+-----+-----+-----!

```

MHEATX HCURVE:        MX1        HCURVE 1

```

INDEPENDENT VARIABLE: DUTY
STREAM:                TESTHPC
PRESSURE PROFILE:     CONSTANT
PROPERTY OPTION SET:  PENG-ROB    STANDARD PR EQUATION OF STATE

```

```

! DUTY        ! PRES        ! TEMP        ! VFRAC       !
!             !             !             !             !
!             !             !             !             !
! BTU/HR      ! PSIA        ! F            !             !
!             !             !             !             !
!=====+=====+=====+=====!
!        0.0    ! 102.0000   ! 95.0000     ! 1.0000    !
! -1.7692+06   ! 102.0000   ! 71.3126     ! 1.0000    !
! -3.5384+06   ! 102.0000   ! 47.6436     ! 1.0000    !
! -5.3076+06   ! 102.0000   ! 24.0007     ! 1.0000    !
! -7.0769+06   ! 102.0000   ! 0.3927      ! 1.0000    !

```



# Oxy Fuel for Clean Energy Generation

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```

!-----+-----+-----+-----!
! -8.8461+06 ! 102.0000 ! -23.1708 ! 1.0000 !
! -1.0615+07 ! 102.0000 ! -46.6782 ! 1.0000 !
! -1.2385+07 ! 102.0000 ! -70.1160 ! 1.0000 !
! -1.4154+07 ! 102.0000 ! -93.4673 ! 1.0000 !
! -1.5923+07 ! 102.0000 ! -116.7109 ! 1.0000 !
!-----+-----+-----+-----!
! -1.7692+07 ! 102.0000 ! -139.8194 ! 1.0000 !
! -1.9461+07 ! 102.0000 ! -162.7559 ! 1.0000 !
!-----+-----+-----+-----!

```

BLOCK: MHX1 MODEL: MHEATX

```

HOT SIDE:      INLET STREAM      OUTLET STREAM
               -----
               TESTHPC           TESTFEED
               TESTLPC           303

COLD SIDE:     INLET STREAM      OUTLET STREAM
               -----
               TESTN2            313
               TESTO2            311
               TESTWAST          312

```

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

PROPERTIES FOR STREAM TESTN2  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM TESTO2  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

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

```

*** MASS AND ENERGY BALANCE ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (LBMOL/HR)                26455.5    26455.5    0.00000
MASS (LB/HR )                   763251.    763251.    0.152526E-15
ENTHALPY (BTU/HR )              -0.225144E+08  -0.225144E+08  -0.165463E-15

```

```

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

```

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM TESTLPC :  
TWO PHASE TP FLASH



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```

SPECIFIED TEMPERATURE      F      -150.000
SPECIFIED PRESSURE         PSIA     102.000
MAXIMUM NO. ITERATIONS     50
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM TESTN2 :

```

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE      F      80.0000
SPECIFIED PRESSURE         PSIA     23.0000
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM TESTO2 :

```

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE      F      80.0000
SPECIFIED PRESSURE         PSIA     23.0000
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM TESTWAST:

```

TWO PHASE TP FLASH
SPECIFIED TEMPERATURE      F      80.0000
PRESSURE DROP              PSI      0.0
MAXIMUM NO. ITERATIONS     30
CONVERGENCE TOLERANCE     0.000100000
  
```

SPECIFICATIONS FOR STREAM TESTHPC :

```

TWO PHASE FLASH
PRESSURE DROP              PSI      0.0
MAXIMUM NO. ITERATIONS     50
CONVERGENCE TOLERANCE     0.000100000
  
```

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
TESTLPC	-0.46189E+07	-150.00	102.00	1.0000
TESTN2	0.11601E+08	80.00	23.000	1.0000
TESTO2	0.42911E+07	80.00	23.000	1.0000
TESTWAST	0.81886E+07	80.00	23.720	1.0000
TESTHPC	-0.19461E+08	-162.76	102.00	1.0000

```

-----
TESTN2 | | | 313
----->| 6377.7 LBMOL/HR |----->
-180.00 | | | 80.00
TESTO2 | | | 311
----->| 2350.0 LBMOL/HR |----->
-180.00 | | | 80.00
TESTWAST | | | 312
----->| 4500.0 LBMOL/HR |----->
-180.00 | | | 80.00
  
```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

303				TESTLPC
<-----	2645.5	LBMOL/HR	<-----	
-150.00			95.00	
TESTFEED			TESTHPC	
<-----	10582.	LBMOL/HR	<-----	
-162.76			95.00	

MHEATX HCURVE:        MHX1        HCURVE 2

-----  
 INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTLPC  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

! DUTY	! PRES	! TEMP	! VFRAC	!
! BTU/HR	! PSIA	! F	!	!
! 0.0	! 102.0000	! 95.0000	! 1.0000	!
! -4.1990+05	! 102.0000	! 72.5120	! 1.0000	!
! -8.3980+05	! 102.0000	! 50.0403	! 1.0000	!
! -1.2597+06	! 102.0000	! 27.5914	! 1.0000	!
! -1.6796+06	! 102.0000	! 5.1726	! 1.0000	!
! -2.0995+06	! 102.0000	! -17.2078	! 1.0000	!
! -2.5194+06	! 102.0000	! -39.5406	! 1.0000	!
! -2.9393+06	! 102.0000	! -61.8147	! 1.0000	!
! -3.3592+06	! 102.0000	! -84.0165	! 1.0000	!
! -3.7791+06	! 102.0000	! -106.1297	! 1.0000	!
! -4.1990+06	! 102.0000	! -128.1333	! 1.0000	!
! -4.6189+06	! 102.0000	! -150.0000	! 1.0000	!

MHEATX HCURVE:        MHX1        HCURVE 3

-----  
 INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTN2  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

! DUTY	! PRES	! TEMP	! VFRAC	!
! BTU/HR	! PSIA	! F	!	!
! 0.0	! 23.0000	! -180.0000	! 1.0000	!







```

!           !           !           !           !
!=====!=====!=====!=====!
!    0.0    !   102.0000 !    95.0000 !    1.0000 !
! -1.7692+06 ! 102.0000 !   71.3126 !    1.0000 !
! -3.5384+06 ! 102.0000 !   47.6436 !    1.0000 !
! -5.3076+06 ! 102.0000 !   24.0007 !    1.0000 !
! -7.0769+06 ! 102.0000 !    0.3927 !    1.0000 !
!-----+-----+-----+-----!
! -8.8461+06 ! 102.0000 !  -23.1708 !    1.0000 !
! -1.0615+07 ! 102.0000 !  -46.6782 !    1.0000 !
! -1.2385+07 ! 102.0000 !  -70.1160 !    1.0000 !
! -1.4154+07 ! 102.0000 !  -93.4673 !    1.0000 !
! -1.5923+07 ! 102.0000 ! -116.7109 !    1.0000 !
!-----+-----+-----+-----!
! -1.7692+07 ! 102.0000 ! -139.8194 !    1.0000 !
! -1.9461+07 ! 102.0000 ! -162.7559 !    1.0000 !
!-----+-----+-----+-----!

```

BLOCK: MXH1 MODEL: MHEATX

```

HOT SIDE:      INLET STREAM      OUTLET STREAM
               -----
               TESTHPC           TESTFEED
               TESTLPC           303

COLD SIDE:     INLET STREAM      OUTLET STREAM
               -----
               TESTN2            313
               TESTO2            311
               TESTWAST          312

```

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

PROPERTIES FOR STREAM TESTN2  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM TESTO2  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

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

```

***  MASS AND ENERGY BALANCE  ***
                                     IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (LBMOL/HR)                    26455.5      26455.5      0.00000
MASS (LB/HR )                       763251.      763251.      0.152526E-15
ENTHALPY (BTU/HR )                  -0.225144E+08  -0.225144E+08  -0.165463E-15

```

```

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

```



TOTAL CO2E PRODUCTION 0.00000 LB/HR

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM TESTLPC :

TWO PHASE TP FLASH  
 SPECIFIED TEMPERATURE F -150.000  
 SPECIFIED PRESSURE PSIA 102.000  
 MAXIMUM NO. ITERATIONS 50  
 CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM TESTN2 :

TWO PHASE TP FLASH  
 SPECIFIED TEMPERATURE F 80.0000  
 SPECIFIED PRESSURE PSIA 23.0000  
 MAXIMUM NO. ITERATIONS 30  
 CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM TESTO2 :

TWO PHASE TP FLASH  
 SPECIFIED TEMPERATURE F 80.0000  
 SPECIFIED PRESSURE PSIA 23.0000  
 MAXIMUM NO. ITERATIONS 30  
 CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM TESTWAST:

TWO PHASE TP FLASH  
 SPECIFIED TEMPERATURE F 80.0000  
 PRESSURE DROP PSI 0.0  
 MAXIMUM NO. ITERATIONS 30  
 CONVERGENCE TOLERANCE 0.000100000

SPECIFICATIONS FOR STREAM TESTHPC :

TWO PHASE FLASH  
 PRESSURE DROP PSI 0.0  
 MAXIMUM NO. ITERATIONS 50  
 CONVERGENCE TOLERANCE 0.000100000

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
TESTLPC	-0.46189E+07	-150.00	102.00	1.0000
TESTN2	0.11601E+08	80.00	23.000	1.0000
TESTO2	0.42911E+07	80.00	23.000	1.0000
TESTWAST	0.81886E+07	80.00	23.720	1.0000
TESTHPC	-0.19461E+08	-162.76	102.00	1.0000

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
TESTN2	6377.7		LBMOL/HR	313
	-180.00			80.00
TESTO2				311



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----->	2350.0	LBMOL/HR	----->
-180.00			80.00
TESTWAST			312
----->	4500.0	LBMOL/HR	----->
-180.00			80.00
303			TESTLPC
<-----	2645.5	LBMOL/HR	<-----
-150.00			95.00
TESTFEED			TESTHPC
<-----	10582.	LBMOL/HR	<-----
-162.76			95.00

MHEATX HCURVE:       MHX1       HCURVE 2

INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTLPC  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

! DUTY	! PRES	! TEMP	! VFRAC	!
! BTU/HR	! PSIA	! F	!	!
!=====!	!=====!	!=====!	!=====!	!
! 0.0	! 102.0000	! 95.0000	! 1.0000	!
! -4.1990+05	! 102.0000	! 72.5120	! 1.0000	!
! -8.3980+05	! 102.0000	! 50.0403	! 1.0000	!
! -1.2597+06	! 102.0000	! 27.5914	! 1.0000	!
! -1.6796+06	! 102.0000	! 5.1726	! 1.0000	!
!-----+!	!-----+!	!-----+!	!-----+!	!
! -2.0995+06	! 102.0000	! -17.2078	! 1.0000	!
! -2.5194+06	! 102.0000	! -39.5406	! 1.0000	!
! -2.9393+06	! 102.0000	! -61.8147	! 1.0000	!
! -3.3592+06	! 102.0000	! -84.0165	! 1.0000	!
! -3.7791+06	! 102.0000	! -106.1297	! 1.0000	!
!-----+!	!-----+!	!-----+!	!-----+!	!
! -4.1990+06	! 102.0000	! -128.1333	! 1.0000	!
! -4.6189+06	! 102.0000	! -150.0000	! 1.0000	!
!-----+!	!-----+!	!-----+!	!-----+!	!

MHEATX HCURVE:       MHX1       HCURVE 3

INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTN2  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

! DUTY	! PRES	! TEMP	! VFRAC	!
--------	--------	--------	---------	---



Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

BTU/HR	PSIA	F	
0.0	23.0000	-180.0000	1.0000
1.0546+06	23.0000	-156.4874	1.0000
2.1092+06	23.0000	-132.9315	1.0000
3.1638+06	23.0000	-109.3417	1.0000
4.2184+06	23.0000	-85.7249	1.0000
5.2730+06	23.0000	-62.0866	1.0000
6.3276+06	23.0000	-38.4309	1.0000
7.3822+06	23.0000	-14.7613	1.0000
8.4368+06	23.0000	8.9192	1.0000
9.4914+06	23.0000	32.6079	1.0000
1.0546+07	23.0000	56.3023	1.0000
1.1601+07	23.0000	80.0000	1.0000

MHEATX HCURVE:           MXH1           HCURVE 4

INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTO2  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

DUTY	PRES	TEMP	VFRAC
0.0	23.0000	-180.4747	1.0000
3.9010+05	23.0000	-156.8737	1.0000
7.8019+05	23.0000	-133.2302	1.0000
1.1703+06	23.0000	-109.5549	1.0000
1.5604+06	23.0000	-85.8568	1.0000
1.9505+06	23.0000	-62.1440	1.0000
2.3406+06	23.0000	-38.4243	1.0000
2.7307+06	23.0000	-14.7055	1.0000
3.1208+06	23.0000	9.0044	1.0000
3.5109+06	23.0000	32.6973	1.0000
3.9010+06	23.0000	56.3653	1.0000
4.2911+06	23.0000	80.0000	1.0000

MHEATX HCURVE:           MXH1           HCURVE 1

INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTHPC  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE



```

-----
!  DUTY      !  PRES      !  TEMP      !  VFRAC     !
!           !           !           !           !
!           !           !           !           !
!  BTU/HR   !  PSIA      !  F         !           !
!           !           !           !           !
!=====!=====!=====!=====!
!    0.0    !  102.0000 !   95.0000 !   1.0000 !
! -1.7692+06 !  102.0000 !   71.3126 !   1.0000 !
! -3.5384+06 !  102.0000 !   47.6436 !   1.0000 !
! -5.3076+06 !  102.0000 !   24.0007 !   1.0000 !
! -7.0769+06 !  102.0000 !    0.3927 !   1.0000 !
!-----+-----+-----+-----!
! -8.8461+06 !  102.0000 !  -23.1708 !   1.0000 !
! -1.0615+07 !  102.0000 !  -46.6782 !   1.0000 !
! -1.2385+07 !  102.0000 !  -70.1160 !   1.0000 !
! -1.4154+07 !  102.0000 !  -93.4673 !   1.0000 !
! -1.5923+07 !  102.0000 ! -116.7109 !   1.0000 !
!-----+-----+-----+-----!
! -1.7692+07 !  102.0000 ! -139.8194 !   1.0000 !
! -1.9461+07 !  102.0000 ! -162.7559 !   1.0000 !
-----

```

BLOCK: MHX1 MODEL: MHEATX

```

HOT SIDE:      INLET STREAM      OUTLET STREAM
               -----
               TESTHPC          TESTFEED
               TESTLPC          303

COLD SIDE:     INLET STREAM      OUTLET STREAM
               -----
               TESTN2           313
               TESTO2           311
               TESTWAST         312

```

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

PROPERTIES FOR STREAM TESTN2  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM TESTO2  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

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

```

***  MASS AND ENERGY BALANCE  ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
  MOLE (LBMOL/HR)              26455.5      26455.5          0.00000
  MASS (LB/HR )                 763251.      763251.          0.152526E-15

```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

ENTHALPY (BTU/HR )            -0.225144E+08    -0.225144E+08    -0.165463E-15

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM TESTLPC :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	-150.000
SPECIFIED PRESSURE	PSIA	102.000
MAXIMUM NO. ITERATIONS		50
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTN2 :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	80.0000
SPECIFIED PRESSURE	PSIA	23.0000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTO2 :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	80.0000
SPECIFIED PRESSURE	PSIA	23.0000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTWAST:

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	80.0000
PRESSURE DROP	PSI	0.0
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTHPC :

TWO PHASE FLASH		
PRESSURE DROP	PSI	0.0
MAXIMUM NO. ITERATIONS		50
CONVERGENCE TOLERANCE		0.000100000

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
TESTLPC	-0.46189E+07	-150.00	102.00	1.0000
TESTN2	0.11601E+08	80.00	23.000	1.0000
TESTO2	0.42911E+07	80.00	23.000	1.0000
TESTWAST	0.81886E+07	80.00	23.720	1.0000
TESTHPC	-0.19461E+08	-162.76	102.00	1.0000



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```

-----
TESTN2 | | 313
----->| 6377.7 LBMOL/HR |----->
-180.00 | | 80.00
| |
TESTO2 | | 311
----->| 2350.0 LBMOL/HR |----->
-180.00 | | 80.00
| |
TESTWAST | | 312
----->| 4500.0 LBMOL/HR |----->
-180.00 | | 80.00
| |
303 | | TESTLPC
<-----| 2645.5 LBMOL/HR |<-----
-150.00 | | 95.00
| |
TESTFEED | | TESTHPC
<-----| 10582. LBMOL/HR |<-----
-162.76 | | 95.00
| |
-----

```

MHEATX HCURVE:        MX1        HCURVE 2

```

INDEPENDENT VARIABLE: DUTY
STREAM:                TESTLPC
PRESSURE PROFILE:     CONSTANT
PROPERTY OPTION SET:  PENG-ROB    STANDARD PR EQUATION OF STATE

```

```

-----
! DUTY        ! PRES        ! TEMP        ! VFRAC        !
!             !             !             !             !
!             !             !             !             !
! BTU/HR      ! PSIA        ! F            !             !
!             !             !             !             !
!=====!=====!=====!=====!
!    0.0        ! 102.0000    ! 95.0000    ! 1.0000    !
! -4.1990+05 ! 102.0000    ! 72.5120    ! 1.0000    !
! -8.3980+05 ! 102.0000    ! 50.0403    ! 1.0000    !
! -1.2597+06 ! 102.0000    ! 27.5914    ! 1.0000    !
! -1.6796+06 ! 102.0000    ! 5.1726     ! 1.0000    !
!-----+-----+-----+-----!
! -2.0995+06 ! 102.0000    ! -17.2078    ! 1.0000    !
! -2.5194+06 ! 102.0000    ! -39.5406    ! 1.0000    !
! -2.9393+06 ! 102.0000    ! -61.8147    ! 1.0000    !
! -3.3592+06 ! 102.0000    ! -84.0165    ! 1.0000    !
! -3.7791+06 ! 102.0000    ! -106.1297    ! 1.0000    !
!-----+-----+-----+-----!
! -4.1990+06 ! 102.0000    ! -128.1333    ! 1.0000    !
! -4.6189+06 ! 102.0000    ! -150.0000    ! 1.0000    !
-----

```

MHEATX HCURVE:        MX1        HCURVE 3





# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTN2  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

```

-----
!  DUTY      !  PRES      !  TEMP      !  VFRAC      !
!           !           !           !           !
!           !           !           !           !
!  BTU/HR    !  PSIA      !  F         !           !
!           !           !           !           !
!=====!=====!=====!=====!
!   0.0      !  23.0000   ! -180.0000  !  1.0000   !
! 1.0546+06 !  23.0000   ! -156.4874  !  1.0000   !
! 2.1092+06 !  23.0000   ! -132.9315  !  1.0000   !
! 3.1638+06 !  23.0000   ! -109.3417  !  1.0000   !
! 4.2184+06 !  23.0000   !  -85.7249  !  1.0000   !
!-----!-----!-----!-----!
! 5.2730+06 !  23.0000   !  -62.0866  !  1.0000   !
! 6.3276+06 !  23.0000   !  -38.4309  !  1.0000   !
! 7.3822+06 !  23.0000   !  -14.7613  !  1.0000   !
! 8.4368+06 !  23.0000   !   8.9192   !  1.0000   !
! 9.4914+06 !  23.0000   !  32.6079   !  1.0000   !
!-----!-----!-----!-----!
! 1.0546+07 !  23.0000   !   56.3023  !  1.0000   !
! 1.1601+07 !  23.0000   !   80.0000  !  1.0000   !
-----

```

MHEATX HCURVE:        MXH1        HCURVE 4

INDEPENDENT VARIABLE: DUTY  
 STREAM: TESTO2  
 PRESSURE PROFILE: CONSTANT  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

```

-----
!  DUTY      !  PRES      !  TEMP      !  VFRAC      !
!           !           !           !           !
!           !           !           !           !
!  BTU/HR    !  PSIA      !  F         !           !
!           !           !           !           !
!=====!=====!=====!=====!
!   0.0      !  23.0000   ! -180.4747  !  1.0000   !
! 3.9010+05 !  23.0000   ! -156.8737  !  1.0000   !
! 7.8019+05 !  23.0000   ! -133.2302  !  1.0000   !
! 1.1703+06 !  23.0000   ! -109.5549  !  1.0000   !
! 1.5604+06 !  23.0000   !  -85.8568  !  1.0000   !
!-----!-----!-----!-----!
! 1.9505+06 !  23.0000   !  -62.1440  !  1.0000   !
! 2.3406+06 !  23.0000   !  -38.4243  !  1.0000   !
! 2.7307+06 !  23.0000   !  -14.7055  !  1.0000   !
! 3.1208+06 !  23.0000   !   9.0044   !  1.0000   !
! 3.5109+06 !  23.0000   !  32.6973   !  1.0000   !
!-----!-----!-----!-----!
! 3.9010+06 !  23.0000   !   56.3653  !  1.0000   !
! 4.2911+06 !  23.0000   !   80.0000  !  1.0000   !
-----

```



MHEATX HCURVE: MHX1 HCURVE 1

INDEPENDENT VARIABLE: DUTY
STREAM: TESTHPC
PRESSURE PROFILE: CONSTANT
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

Table with 5 columns: DUTY, PRES, TEMP, VFRAC, and an unlabeled column. It contains numerical data points separated by exclamation marks.

BLOCK: MHX1 MODEL: MHEATX

HOT SIDE: INLET STREAM OUTLET STREAM
TESTHPC TESTFEED
TESTLPC 303
COLD SIDE: INLET STREAM OUTLET STREAM
TESTN2 313
TESTO2 311
TESTWAST 312

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

PROPERTIES FOR STREAM TESTN2
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM TESTO2
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

PROPERTIES FOR STREAM TESTHPC



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (LBMOL/HR)	26455.5	26455.5	0.00000
MASS (LB/HR )	763251.	763251.	0.152526E-15
ENTHALPY (BTU/HR )	-0.225144E+08	-0.225144E+08	-0.165463E-15

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM TESTLPC :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	-150.000
SPECIFIED PRESSURE	PSIA	102.000
MAXIMUM NO. ITERATIONS		50
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTN2 :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	80.0000
SPECIFIED PRESSURE	PSIA	23.0000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTO2 :

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	80.0000
SPECIFIED PRESSURE	PSIA	23.0000
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTWAST:

TWO PHASE TP FLASH		
SPECIFIED TEMPERATURE	F	80.0000
PRESSURE DROP	PSI	0.0
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

SPECIFICATIONS FOR STREAM TESTHPC :

TWO PHASE FLASH		
PRESSURE DROP	PSI	0.0
MAXIMUM NO. ITERATIONS		50
CONVERGENCE TOLERANCE		0.000100000

\*\*\* RESULTS \*\*\*

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



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

TESTLPC	-0.46189E+07	-150.00	102.00	1.0000
TESTN2	0.11601E+08	80.00	23.000	1.0000
TESTO2	0.42911E+07	80.00	23.000	1.0000
TESTWAST	0.81886E+07	80.00	23.720	1.0000
TESTHPC	-0.19461E+08	-162.76	102.00	1.0000

```

-----
TESTN2 | | 313
----->|          6377.7    LBMOL/HR |----->
-180.00| |          80.00
TESTO2 | | 311
----->|          2350.0    LBMOL/HR |----->
-180.00| |          80.00
TESTWAST| | 312
----->|          4500.0    LBMOL/HR |----->
-180.00| |          80.00
303    | | TESTLPC
<-----|          2645.5    LBMOL/HR |<-----
-150.00| |          95.00
TESTFEED| | TESTHPC
<-----|          10582.    LBMOL/HR |<-----
-162.76| |          95.00
-----

```

MHEATX HCURVE:        MX1        HCURVE 2

```

-----
INDEPENDENT VARIABLE: DUTY
STREAM:                TESTLPC
PRESSURE PROFILE:     CONSTANT
PROPERTY OPTION SET:  PENG-ROB STANDARD PR EQUATION OF STATE

```

```

-----
!  DUTY      !  PRES      !  TEMP      !  VFRAC      !
!           !           !           !           !
!           !           !           !           !
!  BTU/HR   !  PSIA      !  F         !           !
!           !           !           !           !
!=====!=====!=====!=====!
!    0.0    !  102.0000 !  95.0000 !  1.0000 !
! -4.1990+05 !  102.0000 !  72.5120 !  1.0000 !
! -8.3980+05 !  102.0000 !  50.0403 !  1.0000 !
! -1.2597+06 !  102.0000 !  27.5914 !  1.0000 !
! -1.6796+06 !  102.0000 !   5.1726 !  1.0000 !
!-----+-----+-----+-----!
! -2.0995+06 !  102.0000 ! -17.2078 !  1.0000 !
! -2.5194+06 !  102.0000 ! -39.5406 !  1.0000 !
! -2.9393+06 !  102.0000 ! -61.8147 !  1.0000 !
! -3.3592+06 !  102.0000 ! -84.0165 !  1.0000 !
! -3.7791+06 !  102.0000 ! -106.1297 !  1.0000 !

```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```
!-----+-----+-----+-----!
! -4.1990+06 ! 102.0000 ! -128.1333 ! 1.0000 !
! -4.6189+06 ! 102.0000 ! -150.0000 ! 1.0000 !
!-----+-----+-----+-----!
```

MHEATX HCURVE:           MHX1           HCURVE 3

```
-----
INDEPENDENT VARIABLE: DUTY
STREAM:                TESTN2
PRESSURE PROFILE:     CONSTANT
PROPERTY OPTION SET:  PENG-ROB   STANDARD PR EQUATION OF STATE
```

```
-----
! DUTY        ! PRES        ! TEMP        ! VFRAC       !
!             !             !             !             !
!             !             !             !             !
! BTU/HR     ! PSIA        ! F           !             !
!             !             !             !             !
!=====+=====+=====+=====!
!     0.0     !     23.0000 !   -180.0000 !     1.0000 !
! 1.0546+06 !     23.0000 !  -156.4874 !     1.0000 !
! 2.1092+06 !     23.0000 !  -132.9315 !     1.0000 !
! 3.1638+06 !     23.0000 !  -109.3417 !     1.0000 !
! 4.2184+06 !     23.0000 !   -85.7249 !     1.0000 !
!-----+-----+-----+-----!
! 5.2730+06 !     23.0000 !   -62.0866 !     1.0000 !
! 6.3276+06 !     23.0000 !   -38.4309 !     1.0000 !
! 7.3822+06 !     23.0000 !  -14.7613 !     1.0000 !
! 8.4368+06 !     23.0000 !     8.9192 !     1.0000 !
! 9.4914+06 !     23.0000 !    32.6079 !     1.0000 !
!-----+-----+-----+-----!
! 1.0546+07 !     23.0000 !    56.3023 !     1.0000 !
! 1.1601+07 !     23.0000 !    80.0000 !     1.0000 !
!-----+-----+-----+-----!
```

MHEATX HCURVE:           MHX1           HCURVE 4

```
-----
INDEPENDENT VARIABLE: DUTY
STREAM:                TESTO2
PRESSURE PROFILE:     CONSTANT
PROPERTY OPTION SET:  PENG-ROB   STANDARD PR EQUATION OF STATE
```

```
-----
! DUTY        ! PRES        ! TEMP        ! VFRAC       !
!             !             !             !             !
!             !             !             !             !
! BTU/HR     ! PSIA        ! F           !             !
!             !             !             !             !
!=====+=====+=====+=====!
!     0.0     !     23.0000 !  -180.4747 !     1.0000 !
! 3.9010+05 !     23.0000 !  -156.8737 !     1.0000 !
! 7.8019+05 !     23.0000 !  -133.2302 !     1.0000 !
! 1.1703+06 !     23.0000 !  -109.5549 !     1.0000 !
! 1.5604+06 !     23.0000 !   -85.8568 !     1.0000 !
!-----+-----+-----+-----!
! 1.9505+06 !     23.0000 !   -62.1440 !     1.0000 !
! 2.3406+06 !     23.0000 !   -38.4243 !     1.0000 !
!-----+-----+-----+-----!
```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```

! 2.7307+06 ! 23.0000 ! -14.7055 ! 1.0000 !
! 3.1208+06 ! 23.0000 ! 9.0044 ! 1.0000 !
! 3.5109+06 ! 23.0000 ! 32.6973 ! 1.0000 !
!-----+-----+-----+-----!
! 3.9010+06 ! 23.0000 ! 56.3653 ! 1.0000 !
! 4.2911+06 ! 23.0000 ! 80.0000 ! 1.0000 !
!-----+-----+-----+-----!

```

MHEATX HCURVE:        MXH1        HCURVE 1

```

INDEPENDENT VARIABLE: DUTY
STREAM:                TESTHPC
PRESSURE PROFILE:     CONSTANT
PROPERTY OPTION SET:  PENG-ROB    STANDARD PR EQUATION OF STATE

```

```

!-----+-----+-----+-----!
! DUTY        ! PRES        ! TEMP        ! VFRAC       !
!             !             !             !             !
!             !             !             !             !
! BTU/HR      ! PSIA        ! F            !             !
!             !             !             !             !
!=====+=====+=====+=====!
!        0.0    ! 102.0000    ! 95.0000    ! 1.0000    !
! -1.7692+06    ! 102.0000    ! 71.3126    ! 1.0000    !
! -3.5384+06    ! 102.0000    ! 47.6436    ! 1.0000    !
! -5.3076+06    ! 102.0000    ! 24.0007    ! 1.0000    !
! -7.0769+06    ! 102.0000    ! 0.3927     ! 1.0000    !
!-----+-----+-----+-----!
! -8.8461+06    ! 102.0000    ! -23.1708    ! 1.0000    !
! -1.0615+07    ! 102.0000    ! -46.6782    ! 1.0000    !
! -1.2385+07    ! 102.0000    ! -70.1160    ! 1.0000    !
! -1.4154+07    ! 102.0000    ! -93.4673    ! 1.0000    !
! -1.5923+07    ! 102.0000    ! -116.7109   ! 1.0000    !
!-----+-----+-----+-----!
! -1.7692+07    ! 102.0000    ! -139.8194   ! 1.0000    !
! -1.9461+07    ! 102.0000    ! -162.7559   ! 1.0000    !
!-----+-----+-----+-----!

```

BLOCK:    MXH2        MODEL: MHEATX

```

HOT SIDE:        INLET STREAM        OUTLET STREAM
                 -----
                 TESTFEED        305

COLD SIDE:        INLET STREAM        OUTLET STREAM
                 -----
                 308                TESTO2
                 310                TESTN2
                 309                TESTWAST

```

PROPERTIES FOR STREAM 308  
PROPERTY OPTION SET:    PENG-ROB    STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM 310  
PROPERTY OPTION SET:    PENG-ROB    STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM 309



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM TESTFEED

PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (LBMOL/HR)	23809.9	23809.9	0.00000
MASS (LB/HR )	686926.	686926.	-0.169473E-15
ENTHALPY (BTU/HR )	-0.608114E+08	-0.608114E+08	0.00000

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*

SPECIFICATIONS FOR STREAM 308 :

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

SPECIFICATIONS FOR STREAM 310 :

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

SPECIFICATIONS FOR STREAM 309 :

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

SPECIFICATIONS FOR STREAM TESTFEED:

TWO PHASE FLASH		
PRESSURE DROP	PSI	0.0
MAXIMUM NO. ITERATIONS		30
CONVERGENCE TOLERANCE		0.000100000

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
308	0.84050E+07	-180.00	27.320	1.0000
310	0.60384E+07	-180.00	23.000	1.0000
309	0.41199E+07	-180.00	23.720	1.0000
TESTFEED	-0.18563E+08	-276.56	102.00	0.5920



```

-----
308 | | TESTO2
----->| 2350.0 LBMOL/HR |----->
-288.74 | | -180.00
310 | | TESTN2
----->| 6377.7 LBMOL/HR |----->
-312.60 | | -180.00
309 | | TESTWAST
----->| 4500.0 LBMOL/HR |----->
-308.23 | | -180.00
305 | | TESTFEED
<-----| 10582. LBMOL/HR |<-----
-276.56 | | -162.76
-----

```

BLOCK: MHX2 MODEL: MHEATX

-----

```

HOT SIDE:  INLET STREAM  OUTLET STREAM
            -----
            TESTFEED     305

COLD SIDE:  INLET STREAM  OUTLET STREAM
            -----
            308           TESTO2
            310           TESTN2
            309           TESTWAST

```

PROPERTIES FOR STREAM 308  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM 310  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM 309  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

```

*** MASS AND ENERGY BALANCE ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (LBMOL/HR)                 23809.9      23809.9          0.00000
MASS (LB/HR )                   686926.      686926.         -0.169473E-15
ENTHALPY (BTU/HR )              -0.608114E+08 -0.608114E+08  0.00000

```

```

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E                0.00000      LB/HR
PRODUCT STREAMS CO2E              0.00000      LB/HR

```





# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```

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

\*\*\* INPUT DATA \*\*\*

```

SPECIFICATIONS FOR STREAM 308  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F          -180.000
PRESSURE DROP                   PSI          0.0
MAXIMUM NO. ITERATIONS          30
CONVERGENCE TOLERANCE           0.000100000
  
```

```

SPECIFICATIONS FOR STREAM 310  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F          -180.000
PRESSURE DROP                   PSI          0.0
MAXIMUM NO. ITERATIONS          30
CONVERGENCE TOLERANCE           0.000100000
  
```

```

SPECIFICATIONS FOR STREAM 309  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F          -180.000
PRESSURE DROP                   PSI          0.0
MAXIMUM NO. ITERATIONS          30
CONVERGENCE TOLERANCE           0.000100000
  
```

```

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

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
308	0.84050E+07	-180.00	27.320	1.0000
310	0.60384E+07	-180.00	23.000	1.0000
309	0.41199E+07	-180.00	23.720	1.0000
TESTFEED	-0.18563E+08	-276.56	102.00	0.5920

```

-----
|
| 308 | | |
|----->| 2350.0 | LBMOL/HR |
| -288.74 | | |
| 310 | |
|----->| 6377.7 | LBMOL/HR |
| -312.60 | | |
| 309 | |
|----->| 4500.0 | LBMOL/HR |
| -308.23 | |
|
| TESTO2 |
|----->| -180.00 |
|
| TESTN2 |
|----->| -180.00 |
|
| TESTWAST |
|----->| -180.00 |
|
  
```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```

305 | | | TESTFEED
<-----| | | <-----
-276.56 | | | -162.76
| | |
-----| | |

```

BLOCK: MHX2 MODEL: MHEATX

```

HOT SIDE:  INLET STREAM  OUTLET STREAM
            -----
            TESTFEED      305

COLD SIDE:  INLET STREAM  OUTLET STREAM
            -----
            308            TESTO2
            310            TESTN2
            309            TESTWAST

```

PROPERTIES FOR STREAM 308  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM 310  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

PROPERTIES FOR STREAM 309  
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

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

```

*** MASS AND ENERGY BALANCE ***
                                IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (LBMOL/HR)                 23809.9      23809.9          0.00000
MASS (LB/HR )                   686926.      686926.        -0.169473E-15
ENTHALPY (BTU/HR )              -0.608114E+08  -0.608114E+08  0.00000

```

```

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

```

\*\*\* INPUT DATA \*\*\*

```

SPECIFICATIONS FOR STREAM 308 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F          -180.000
PRESSURE DROP                   PSI          0.0
MAXIMUM NO. ITERATIONS          30
CONVERGENCE TOLERANCE          0.000100000

```

SPECIFICATIONS FOR STREAM 310 :



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F          -180.000
PRESSURE DROP                   PSI          0.0
MAXIMUM NO. ITERATIONS          30
CONVERGENCE TOLERANCE           0.000100000
```

```
SPECIFICATIONS FOR STREAM 309 :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F          -180.000
PRESSURE DROP                   PSI          0.0
MAXIMUM NO. ITERATIONS          30
CONVERGENCE TOLERANCE           0.000100000
```

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

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
308	0.84050E+07	-180.00	27.320	1.0000
310	0.60384E+07	-180.00	23.000	1.0000
309	0.41199E+07	-180.00	23.720	1.0000
TESTFEED	-0.18563E+08	-276.56	102.00	0.5920

```

-----
|
| 308 | | TESTO2 | |
|----->| 2350.0 | LBMOL/HR |----->|
| -288.74 | | -180.00 |
|
| 310 | | TESTN2 | |
|----->| 6377.7 | LBMOL/HR |----->|
| -312.60 | | -180.00 |
|
| 309 | | TESTWAST | |
|----->| 4500.0 | LBMOL/HR |----->|
| -308.23 | | -180.00 |
|
| 305 | | TESTFEED | |
|<-----| 10582. | LBMOL/HR |<-----|
| -276.56 | | -162.76 |
|
|-----

```

BLOCK: MHX2 MODEL: MHEATX

```
HOT SIDE:   INLET STREAM   OUTLET STREAM
            -----
            TESTFEED       305
```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```

COLD SIDE:  INLET STREAM      OUTLET STREAM
             -----          -----
             308                TESTO2
             310                TESTN2
             309                TESTWAST
    
```

```

PROPERTIES FOR STREAM 308
PROPERTY OPTION SET:  PENG-ROB  STANDARD PR EQUATION OF STATE
    
```

```

PROPERTIES FOR STREAM 310
PROPERTY OPTION SET:  PENG-ROB  STANDARD PR EQUATION OF STATE
    
```

```

PROPERTIES FOR STREAM 309
PROPERTY OPTION SET:  PENG-ROB  STANDARD PR EQUATION OF STATE
    
```

```

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

```

***  MASS AND ENERGY BALANCE  ***
                                     IN          OUT          RELATIVE DIFF.
TOTAL BALANCE
MOLE (LBMOL/HR)                    23809.9      23809.9      0.00000
MASS (LB/HR )                      686926.     686926.     -0.169473E-15
ENTHALPY (BTU/HR )                 -0.608114E+08  -0.608114E+08  0.00000
    
```

```

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

\*\*\* INPUT DATA \*\*\*

```

SPECIFICATIONS FOR STREAM 308  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F              -180.000
PRESSURE DROP                  PSI              0.0
MAXIMUM NO. ITERATIONS        30
CONVERGENCE TOLERANCE         0.000100000
    
```

```

SPECIFICATIONS FOR STREAM 310  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F              -180.000
PRESSURE DROP                  PSI              0.0
MAXIMUM NO. ITERATIONS        30
CONVERGENCE TOLERANCE         0.000100000
    
```

```

SPECIFICATIONS FOR STREAM 309  :
TWO PHASE TP FLASH
SPECIFIED TEMPERATURE          F              -180.000
PRESSURE DROP                  PSI              0.0
MAXIMUM NO. ITERATIONS        30
CONVERGENCE TOLERANCE         0.000100000
    
```

```

SPECIFICATIONS FOR STREAM TESTFEED:
TWO PHASE FLASH
    
```



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

```

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

\*\*\* RESULTS \*\*\*

INLET STREAM	DUTY BTU/HR	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	OUTLET VAPOR FRAC
308	0.84050E+07	-180.00	27.320	1.0000
310	0.60384E+07	-180.00	23.000	1.0000
309	0.41199E+07	-180.00	23.720	1.0000
TESTFEED	-0.18563E+08	-276.56	102.00	0.5920

```

-----
308 | | | | TESTO2
----->| 2350.0 LBMOL/HR |----->
-288.74 | | | | -180.00
| | | | |
310 | | | | TESTN2
----->| 6377.7 LBMOL/HR |----->
-312.60 | | | | -180.00
| | | | |
309 | | | | TESTWAST
----->| 4500.0 LBMOL/HR |----->
-308.23 | | | | -180.00
| | | | |
305 | | | | TESTFEED
<-----| 10582. LBMOL/HR |<-----
-276.56 | | | | -162.76
| | | | |
-----
  
```

BLOCK: HPC MODEL: RADFRAC

```

-----
INLETS - 305 STAGE 14
OUTLETS - 306 STAGE 1
          307 STAGE 14
          HEAT STAGE 1
  
```

PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (LBMOL/HR)	10582.2	10582.2	0.00000
MASS (LB/HR )	305300.	305300.	0.366252E-12
ENTHALPY (BTU/HR )	-0.369355E+08	-0.369377E+08	0.600630E-04

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR



\*\*\*\*\*  
 \*\*\*\* INPUT DATA \*\*\*\*  
 \*\*\*\*\*

\*\*\*\* INPUT PARAMETERS \*\*\*\*

NUMBER OF STAGES	14
ALGORITHM OPTION	STANDARD
ABSORBER OPTION	NO
INITIALIZATION OPTION	STANDARD
HYDRAULIC PARAMETER CALCULATIONS	NO
INSIDE LOOP CONVERGENCE METHOD	BROYDEN
DESIGN SPECIFICATION METHOD	NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS	25
MAXIMUM NO. OF INSIDE LOOP ITERATIONS	10
MAXIMUM NUMBER OF FLASH ITERATIONS	30
FLASH TOLERANCE	0.000100000
OUTSIDE LOOP CONVERGENCE TOLERANCE	0.000100000

\*\*\*\* COL-SPECS \*\*\*\*

MOLAR VAPOR DIST / TOTAL DIST	0.0	
MOLAR REFLUX RATIO	1.25000	
REBOILER DUTY	BTU/HR	0.0

\*\*\*\* PROFILES \*\*\*\*

P-SPEC	STAGE	1	PRES, PSIA	92.0000
--------	-------	---	------------	---------

\*\*\*\*\*  
 \*\*\*\* RESULTS \*\*\*\*  
 \*\*\*\*\*

\*\*\* COMPONENT SPLIT FRACTIONS \*\*\*

		OUTLET STREAMS	
		-----	
		306	307
COMPONENT:			
OXYGEN	.94495E-02	.99055	
NITROGEN	.35111	.64889	

\*\*\* SUMMARY OF KEY RESULTS \*\*\*

TOP STAGE TEMPERATURE	F	-284.520
BOTTOM STAGE TEMPERATURE	F	-278.983
TOP STAGE LIQUID FLOW	LBMOL/HR	3,695.31
BOTTOM STAGE LIQUID FLOW	LBMOL/HR	7,625.94
TOP STAGE VAPOR FLOW	LBMOL/HR	0.0
BOILUP VAPOR FLOW	LBMOL/HR	6,355.77
MOLAR REFLUX RATIO		1.25000
CONDENSER DUTY (W/O SUBCOOL)	BTU/HR	-0.135317+08
REBOILER DUTY	BTU/HR	0.0



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

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

DEW POINT	0.20979E-04	STAGE= 12
BUBBLE POINT	0.66444E-05	STAGE= 12
COMPONENT MASS BALANCE	0.43573E-06	STAGE= 7 COMP=OXYGEN
ENERGY BALANCE	0.11648E-04	STAGE= 14

\*\*\*\* PROFILES \*\*\*\*

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

STAGE	TEMPERATURE F	PRESSURE PSIA	ENTHALPY BTU/LBMOL		HEAT DUTY BTU/HR
			LIQUID	VAPOR	
1	-284.52	92.000	-4690.2	-2657.1	-.13532+08
2	-284.34	92.100	-4693.6	-2655.8	
3	-284.12	92.200	-4698.0	-2654.2	
12	-279.99	93.100	-4781.7	-2622.9	
13	-279.46	93.200	-4791.4	-2618.9	
14	-278.98	93.300	-4799.9	-2615.3	

STAGE	FLOW RATE LBMOL/HR		FEED RATE LBMOL/HR			PRODUCT RATE LBMOL/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	6652.	0.000				2956.2440	
2	3684.	6652.					
3	3670.	6640.					
12	3426.	6411.					
13	3400.	6382.					
14	7626.	6356.			.10582+05	7625.9445	

\*\*\*\* MASS FLOW PROFILES \*\*\*\*

STAGE	FLOW RATE LB/HR		FEED RATE LB/HR			PRODUCT RATE LB/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.1865E+06	0.000				.82898+05	
2	0.1034E+06	0.1865E+06					
3	0.1032E+06	0.1863E+06					
12	0.9925E+05	0.1826E+06					
13	0.9884E+05	0.1821E+06					
14	0.2224E+06	0.1817E+06			.30530+06	.22240+06	

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

STAGE	OXYGEN	NITROGEN
1	0.71034E-02	0.99290
2	0.16215E-01	0.98379
3	0.27606E-01	0.97239
12	0.24065	0.75935
13	0.26609	0.73391
14	0.28865	0.71135

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

STAGE	OXYGEN	NITROGEN
1	0.30987E-02	0.99690
2	0.71034E-02	0.99290



```

3      0.12158E-01  0.98784
12     0.11809      0.88191
13     0.13246      0.86754
14     0.14563      0.85437
    
```

```

          ****      K-VALUES      ****
STAGE    OXYGEN      NITROGEN
1         0.43622     1.0040
2         0.43808     1.0093
3         0.44040     1.0159
12        0.49063     1.1614
13        0.49783     1.1821
14        0.50451     1.2011
    
```

```

          ****      MASS-X-PROFILE      ****
STAGE    OXYGEN      NITROGEN
1         0.81058E-02  0.99189
2         0.18479E-01  0.98152
3         0.31410E-01  0.96859
12        0.26578      0.73422
13        0.29286      0.70714
14        0.31671      0.68329
    
```

```

          ****      MASS-Y-PROFILE      ****
STAGE    OXYGEN      NITROGEN
1         0.35380E-02  0.99646
2         0.81058E-02  0.99189
3         0.13864E-01  0.98614
12        0.13266      0.86734
13        0.14851      0.85149
14        0.16297      0.83703
    
```

```

*****
***** HYDRAULIC PARAMETERS *****
*****
    
```

\*\*\* DEFINITIONS \*\*\*

```

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

```

          TEMPERATURE
          F
STAGE    LIQUID FROM      VAPOR TO
    
```







# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

FLOODING FACTOR		0.80000
MINIMUM COLUMN DIAMETER	FT	1.00000
MINIMUM DC AREA/COLUMN AREA		0.100000
HOLE AREA/ACTIVE AREA		0.100000

TRAY SPECIFICATIONS  
-----

TRAY TYPE		SIEVE
NUMBER OF PASSES		4
TRAY SPACING	FT	0.75000

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

STAGE WITH MAXIMUM DIAMETER		14
COLUMN DIAMETER	FT	9.87219
DC AREA/COLUMN AREA		0.093750
SIDE DOWNCOMER VELOCITY	FT/SEC	0.17533
FLOW PATH LENGTH	FT	1.85257
SIDE DOWNCOMER WIDTH	FT	0.60053
SIDE WEIR LENGTH	FT	4.71928
CENTER DOWNCOMER WIDTH	FT	0.38778
CENTER WEIR LENGTH	FT	9.86457
OFF-CENTER DOWNCOMER WIDTH	FT	0.43654
OFF-CENTER SHORT WEIR LENGTH	FT	8.53224
OFF-CENTER LONG WEIR LENGTH	FT	8.98378
TRAY CENTER TO OCDC CENTER	FT	2.26473

\*\*\*\*\* SIZING PROFILES \*\*\*\*\*

STAGE	DIAMETER	TOTAL AREA	ACTIVE AREA	SIDE DC AREA
	FT	SQFT	PER PANEL SQFT	PER PANEL SQFT
2	9.8722	76.545	15.309	1.7940
3	9.8722	76.545	15.309	1.7940
4	9.8722	76.545	15.309	1.7940
5	9.8722	76.545	15.309	1.7940
6	9.8722	76.545	15.309	1.7940
7	9.8722	76.545	15.309	1.7940
8	9.8722	76.545	15.309	1.7940
9	9.8722	76.545	15.309	1.7940
10	9.8722	76.545	15.309	1.7940
11	9.8722	76.545	15.309	1.7940
12	9.8722	76.545	15.309	1.7940
13	9.8722	76.545	15.309	1.7940
14	9.8722	76.545	15.309	1.7940

\*\*\*\*\* ADDITIONAL SIZING PROFILES \*\*\*\*\*

STAGE	FLOODING FACTOR	PRES. DROP PSI	DC BACKUP FT	DC BACKUP/ (TSPC+WHT)
2	50.22	0.3997E-01	0.2822	34.73
3	50.04	0.4002E-01	0.2815	34.64
4	49.82	0.4009E-01	0.2806	34.53
5	49.55	0.4016E-01	0.2795	34.40
6	49.25	0.4026E-01	0.2783	34.25



# Oxy Fuel for Clean Energy Generation

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7	48.90	0.4037E-01	0.2769	34.07
8	48.53	0.4049E-01	0.2753	33.89
9	48.12	0.4063E-01	0.2738	33.69
10	47.71	0.4078E-01	0.2722	33.50
11	47.31	0.4093E-01	0.2706	33.31
12	46.93	0.4108E-01	0.2692	33.13
13	46.59	0.4122E-01	0.2679	32.97
14	80.00	0.5721E-01	0.3927	48.33

STAGE	HEIGHT OVER WEIR FT	DC REL FROTH DENS	TR LIQ REL FROTH DENS	FRA APPR TO SYS LIMIT
2	0.6175E-01	0.6048	0.3950	16.30
3	0.6145E-01	0.6049	0.3953	16.27
4	0.6109E-01	0.6051	0.3956	16.22
5	0.6065E-01	0.6053	0.3960	16.17
6	0.6015E-01	0.6055	0.3964	16.11
7	0.5957E-01	0.6057	0.3969	16.04
8	0.5895E-01	0.6060	0.3974	15.96
9	0.5828E-01	0.6062	0.3980	15.88
10	0.5761E-01	0.6064	0.3985	15.80
11	0.5696E-01	0.6066	0.3990	15.72
12	0.5634E-01	0.6068	0.3995	15.65
13	0.5579E-01	0.6070	0.4000	15.58
14	0.1209	0.6071	0.2808	26.29

BLOCK: LPC MODEL: RADFRAC

```

-----
INLETS  - 307      STAGE 12
          304      STAGE 18
          306      STAGE  1
          HEAT     STAGE 38
OUTLETS - 310      STAGE  1
          308      STAGE 38
          309      STAGE  8
  
```

PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***			
TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (LBMOL/HR)	13227.7	13227.7	0.137513E-15
MASS (LB/HR )	381625.	381625.	0.258762E-08
ENTHALPY (BTU/HR )	-0.429223E+08	-0.424392E+08	-0.112548E-01

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

```

*****
**** INPUT DATA ****
*****
  
```

\*\*\*\* INPUT PARAMETERS \*\*\*\*



```

NUMBER OF STAGES                38
ALGORITHM OPTION                 STANDARD
ABSORBER OPTION                  NO
INITIALIZATION OPTION           STANDARD
HYDRAULIC PARAMETER CALCULATIONS NO
INSIDE LOOP CONVERGENCE METHOD   BROYDEN
DESIGN SPECIFICATION METHOD      NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS 25
MAXIMUM NO. OF INSIDE LOOP ITERATIONS 10
MAXIMUM NUMBER OF FLASH ITERATIONS 30
FLASH TOLERANCE                 0.000100000
OUTSIDE LOOP CONVERGENCE TOLERANCE 0.000100000

```

\*\*\*\* COL-SPECS \*\*\*\*

```

MOLAR VAPOR DIST / TOTAL DIST          1.00000
MOLAR BOTTOMS RATE                     LBMOL/HR 2,350.00
CONDENSER DUTY (W/O SUBCOOL)          BTU/HR 0.0

```

\*\*\*\* PROFILES \*\*\*\*

```

P-SPEC          STAGE 1  PRES, PSIA          23.0000

```

```

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

```

\*\*\* COMPONENT SPLIT FRACTIONS \*\*\*

```

                                OUTLET STREAMS
                                -----
                                310          308          309
COMPONENT:
OXYGEN          .20054E-01  .80091      .17904
NITROGEN        .60498          .11982E-01 .38303

```

\*\*\* SUMMARY OF KEY RESULTS \*\*\*

```

TOP STAGE TEMPERATURE          F          -312.602
BOTTOM STAGE TEMPERATURE       F          -288.739
TOP STAGE LIQUID FLOW          LBMOL/HR 2,426.07
BOTTOM STAGE LIQUID FLOW       LBMOL/HR 2,350.00
TOP STAGE VAPOR FLOW           LBMOL/HR 6,377.74
BOILUP VAPOR FLOW             LBMOL/HR 5,033.14
MOLAR BOILUP RATIO              2.14176
CONDENSER DUTY (W/O SUBCOOL)   BTU/HR    0.0
REBOILER DUTY                  BTU/HR    0.140149+08

```

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

```

DEW POINT                0.33563E-04  STAGE= 34
BUBBLE POINT             0.16473E-04  STAGE= 29
COMPONENT MASS BALANCE   0.22176E-05  STAGE= 36  COMP=NITROGEN
ENERGY BALANCE           0.54292E-05  STAGE= 36

```

\*\*\*\* PROFILES \*\*\*\*



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

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

STAGE	TEMPERATURE F	PRESSURE PSIA	ENTHALPY BTU/LBMOL		HEAT DUTY BTU/HR
			LIQUID	VAPOR	
1	-312.60	23.000	-5107.9	-2750.0	
2	-312.24	23.000	-5120.0	-2747.3	
7	-308.88	23.600	-5201.2	-2724.2	
8	-308.23	23.720	-5214.7	-2719.8	
9	-307.88	23.840	-5220.2	-2717.5	
10	-307.68	23.960	-5221.8	-2716.3	
11	-307.55	24.080	-5221.7	-2715.5	
12	-307.44	24.200	-5220.9	-2715.0	
13	-307.31	24.320	-5220.8	-2714.2	
16	-306.50	24.680	-5230.4	-2709.0	
17	-305.89	24.800	-5241.4	-2704.9	
18	-305.80	24.920	-5240.2	-2704.4	
37	-291.89	27.200	-5376.9	-2609.2	
38	-288.74	27.320	-5387.8	-2587.2	.14015+08

STAGE	FLOW RATE LBMOL/HR		FEED RATE LBMOL/HR			PRODUCT RATE LBMOL/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	2426.	6378.	2441.2205	515.0234			6377.7357
2	2404.	5848.					
7	2270.	5717.					
8	2248.	0.1019E+05					4500.0000
9	2238.	0.1017E+05					
10	2234.	0.1016E+05					
11	2232.	0.1016E+05					
12	8575.	0.1015E+05	6346.6577	1279.2868			
13	8571.	8870.					
16	8509.	8839.					
17	8010.	8805.		2645.5471			
18	8013.	5660.					
37	7383.	5149.					
38	2350.	5033.					2350.0000

\*\*\*\* MASS FLOW PROFILES \*\*\*\*

STAGE	FLOW RATE LB/HR		FEED RATE LB/HR			PRODUCT RATE LB/HR	
	LIQUID	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	VAPOR
1	0.6824E+05	0.1789E+06	.68466+05	.14433+05			.17888+06
2	0.6790E+05	0.1642E+06					
7	0.6596E+05	0.1623E+06					
8	0.6564E+05	0.2900E+06					.12804+06
9	0.6550E+05	0.2897E+06					
10	0.6543E+05	0.2895E+06					
11	0.6539E+05	0.2895E+06					
12	0.2513E+06	0.2894E+06	.18594+06	.36462+05			
13	0.2513E+06	0.2529E+06					
16	0.2506E+06	0.2526E+06					
17	0.2368E+06	0.2522E+06		.76325+05			
18	0.2369E+06	0.1621E+06					
37	0.2325E+06	0.1579E+06					



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

38 0.7470E+05 0.1578E+06

.74698+05

```
**** MOLE-X-PROFILE ****
STAGE  OXYGEN      NITROGEN
  1    0.28310E-01  0.97169
  2    0.56382E-01  0.94362
  7    0.26182      0.73818
  8    0.29746      0.70254
  9    0.31349      0.68651
 10    0.32032      0.67968
 11    0.32301      0.67699
 12    0.32388      0.67612
 13    0.32673      0.67327
 16    0.35893      0.64107
 17    0.38904      0.61096
 18    0.38910      0.61090
 37    0.87253      0.12747
 38    0.94672      0.53283E-01
```

```
**** MOLE-Y-PROFILE ****
STAGE  OXYGEN      NITROGEN
  1    0.87347E-02  0.99127
  2    0.17681E-01  0.98232
  7    0.94579E-01  0.90542
  8    0.11052      0.88948
  9    0.11807      0.88193
 10    0.12143      0.87857
 11    0.12285      0.87715
 12    0.12340      0.87660
 13    0.12490      0.87510
 16    0.14132      0.85868
 17    0.15731      0.84269
 18    0.15750      0.84250
 37    0.66456      0.33544
 38    0.83790      0.16210
```

```
**** K-VALUES ****
STAGE  OXYGEN      NITROGEN
  1    0.30853      1.0201
  2    0.31359      1.0410
  7    0.36124      1.2265
  8    0.37154      1.2661
  9    0.37665      1.2846
 10    0.37910      1.2926
 11    0.38033      1.2957
 12    0.38101      1.2965
 13    0.38228      1.2998
 16    0.39372      1.3395
 17    0.40434      1.3793
 18    0.40477      1.3791
 37    0.76164      2.6317
 38    0.88505      3.0424
```

```
**** MASS-X-PROFILE ****
STAGE  OXYGEN      NITROGEN
  1    0.32208E-01  0.96779
  2    0.63891E-01  0.93611
  7    0.28833      0.71167
  8    0.32598      0.67402
```



9	0.34280	0.65720
10	0.34994	0.65006
11	0.35275	0.64725
12	0.35366	0.64634
13	0.35663	0.64337
16	0.39008	0.60992
17	0.42108	0.57892
18	0.42114	0.57886
37	0.88661	0.11339
38	0.95304	0.46958E-01

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

STAGE	OXYGEN	NITROGEN
1	0.99650E-02	0.99004
2	0.20146E-01	0.97985
7	0.10660	0.89340
8	0.12429	0.87571
9	0.13264	0.86736
10	0.13635	0.86365
11	0.13792	0.86208
12	0.13852	0.86148
13	0.14018	0.85982
16	0.15824	0.84176
17	0.17575	0.82425
18	0.17596	0.82404
37	0.69353	0.30647
38	0.85516	0.14484

\*\*\*\*\*  
 \*\*\*\*\* HYDRAULIC PARAMETERS \*\*\*\*\*  
 \*\*\*\*\*

\*\*\* DEFINITIONS \*\*\*

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

TEMPERATURE

STAGE	LIQUID FROM	VAPOR TO
1	-312.60	-312.24
2	-312.24	-311.68
7	-308.88	-308.23
8	-308.23	-307.88



9	-307.88	-307.68
10	-307.68	-307.55
11	-307.55	-307.44
12	-307.44	-307.35
13	-307.31	-307.13
16	-306.50	-305.89
17	-305.89	-286.49
18	-305.80	-305.71
37	-291.89	-288.74
38	-288.74	-288.74

STAGE	MASS FLOW LB/HR		VOLUME FLOW CUFT/HR		MOLECULAR WEIGHT	
	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO
1	68236.	0.16422E+06	1376.9	0.37942E+06	28.126	28.084
2	67898.	0.16388E+06	1356.2	0.37753E+06	28.238	28.130
7	65955.	0.16194E+06	1224.5	0.36841E+06	29.057	28.454
8	65644.	0.28967E+06	1203.4	0.65648E+06	29.199	28.484
9	65499.	0.28953E+06	1194.1	0.65335E+06	29.263	28.497
10	65429.	0.28946E+06	1190.2	0.65026E+06	29.290	28.503
11	65391.	0.28942E+06	1188.6	0.64721E+06	29.301	28.505
12	0.25127E+06	0.28936E+06	4567.3	0.64741E+06	29.304	28.510
13	0.25126E+06	0.25289E+06	4563.7	0.56061E+06	29.316	28.522
16	0.25055E+06	0.25218E+06	4501.4	0.55317E+06	29.444	28.640
17	0.23681E+06	0.23843E+06	4209.4	0.59685E+06	29.564	28.708
18	0.23689E+06	0.16219E+06	4211.8	0.35260E+06	29.564	28.642
37	0.23250E+06	0.15780E+06	3499.0	0.32104E+06	31.491	31.353
38	74698.	0.0000	1097.1	0.0000	31.786	

STAGE	DENSITY LB/CUFT		VISCOSITY CP		SURFACE TENSION DYNE/CM
	LIQUID FROM	VAPOR TO	LIQUID FROM	VAPOR TO	LIQUID FROM
1	49.557	0.43283	0.13638	0.58238E-02	26.153
2	50.064	0.43409	0.13772	0.58496E-02	26.090
7	53.863	0.43957	0.14649	0.60151E-02	25.584
8	54.550	0.44125	0.14798	0.60319E-02	25.493
9	54.853	0.44315	0.14852	0.60415E-02	25.448
10	54.974	0.44514	0.14861	0.60477E-02	25.424
11	55.013	0.44718	0.14849	0.60525E-02	25.411
12	55.016	0.44696	0.14829	0.60564E-02	25.401
13	55.058	0.45110	0.14819	0.60672E-02	25.387
16	55.661	0.45588	0.14903	0.61281E-02	25.288
17	56.257	0.39949	0.15025	0.68859E-02	25.208
18	56.243	0.45997	0.15002	0.61363E-02	25.200
37	66.448	0.49153	0.16612	0.71307E-02	23.644
38	68.087		0.16789		23.338

STAGE	MARANGONI INDEX	FLOW PARAM	QR	REDUCED F-FACTOR
	DYNE/CM		CUFT/HR	(LB-CUFT) **.5/HR
1		0.38832E-01	35614.	0.24962E+06
2	-.62909E-01	0.38579E-01	35308.	0.24874E+06
7	-.10344	0.36792E-01	33418.	0.24426E+06
8	-.91072E-01	0.20381E-01	59284.	0.43608E+06
9	-.45348E-01	0.20334E-01	58963.	0.43493E+06
10	-.23600E-01	0.20340E-01	58752.	0.43385E+06
11	-.13762E-01	0.20370E-01	58590.	0.43280E+06





12	-.55294E-02	0.78270E-01	58592.	0.43282E+06
13	-.14097E-01	0.89934E-01	50954.	0.37653E+06
16	-.49021E-01	0.89917E-01	50269.	0.37350E+06
17	-.80429E-01	0.83693E-01	50475.	0.37724E+06
18	-.73392E-02	0.13208	32018.	0.23914E+06
37	-.42462	0.12672	27715.	0.22508E+06
38	-.30567		0.0000	0.0000

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

\*\*\*\*\*  
 \*\*\* SECTION 1 \*\*\*  
 \*\*\*\*\*

STARTING STAGE NUMBER 1  
 ENDING STAGE NUMBER 37  
 FLOODING CALCULATION METHOD GLITSCH6

DESIGN PARAMETERS  
 -----

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

TRAY SPECIFICATIONS  
 -----

TRAY TYPE SIEVE  
 NUMBER OF PASSES 1  
 TRAY SPACING FT 1.00000

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

STAGE WITH MAXIMUM DIAMETER 12  
 COLUMN DIAMETER FT 11.3722  
 DC AREA/COLUMN AREA 0.100000  
 DOWNCOMER VELOCITY FT/SEC 0.12491  
 FLOW PATH LENGTH FT 7.81325  
 SIDE DOWNCOMER WIDTH FT 1.77947  
 SIDE WEIR LENGTH FT 8.26316  
 CENTER DOWNCOMER WIDTH FT 0.0  
 CENTER WEIR LENGTH FT MISSING  
 OFF-CENTER DOWNCOMER WIDTH FT 0.0  
 OFF-CENTER SHORT WEIR LENGTH FT MISSING  
 OFF-CENTER LONG WEIR LENGTH FT MISSING  
 TRAY CENTER TO OCDC CENTER FT 0.0

\*\*\*\* SIZING PROFILES \*\*\*\*



## Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

STAGE	DIAMETER	TOTAL AREA	ACTIVE AREA	SIDE DC AREA
	FT	SQFT	SQFT	SQFT
1	11.372	101.57	81.258	10.157
2	11.372	101.57	81.258	10.157
3	11.372	101.57	81.258	10.157
4	11.372	101.57	81.258	10.157
5	11.372	101.57	81.258	10.157
6	11.372	101.57	81.258	10.157
7	11.372	101.57	81.258	10.157
8	11.372	101.57	81.258	10.157
9	11.372	101.57	81.258	10.157
10	11.372	101.57	81.258	10.157
11	11.372	101.57	81.258	10.157
12	11.372	101.57	81.258	10.157
13	11.372	101.57	81.258	10.157
14	11.372	101.57	81.258	10.157
15	11.372	101.57	81.258	10.157
16	11.372	101.57	81.258	10.157
17	11.372	101.57	81.258	10.157
18	11.372	101.57	81.258	10.157
19	11.372	101.57	81.258	10.157
20	11.372	101.57	81.258	10.157
21	11.372	101.57	81.258	10.157
22	11.372	101.57	81.258	10.157
23	11.372	101.57	81.258	10.157
24	11.372	101.57	81.258	10.157
25	11.372	101.57	81.258	10.157
26	11.372	101.57	81.258	10.157
27	11.372	101.57	81.258	10.157
28	11.372	101.57	81.258	10.157
29	11.372	101.57	81.258	10.157
30	11.372	101.57	81.258	10.157
31	11.372	101.57	81.258	10.157
32	11.372	101.57	81.258	10.157
33	11.372	101.57	81.258	10.157
34	11.372	101.57	81.258	10.157
35	11.372	101.57	81.258	10.157
36	11.372	101.57	81.258	10.157
37	11.372	101.57	81.258	10.157

\*\*\*\* ADDITIONAL SIZING PROFILES \*\*\*\*

STAGE	FLOODING	PRES. DROP	DC BACKUP	DC BACKUP/
	FACTOR			(TSPC+WHT)
		PSI	FT	
1	43.67	0.5039E-01	0.4619	42.64
2	43.27	0.5056E-01	0.4571	42.20
3	42.81	0.5079E-01	0.4517	41.69
4	42.30	0.5106E-01	0.4456	41.13
5	41.77	0.5138E-01	0.4393	40.55
6	41.24	0.5171E-01	0.4332	39.99
7	40.75	0.5203E-01	0.4279	39.49
8	68.87	0.7522E-01	0.4901	45.24
9	68.49	0.7514E-01	0.4869	44.94
10	68.25	0.7502E-01	0.4852	44.78
11	68.07	0.7486E-01	0.4842	44.69
12	80.00	0.9105E-01	1.672	154.3
13	71.67	0.8307E-01	1.646	152.0



## Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

14	71.46	0.8302E-01	1.641	151.5
15	71.17	0.8299E-01	1.631	150.5
16	70.71	0.8302E-01	1.612	148.8
17	69.81	0.8241E-01	1.464	135.2
18	49.79	0.7051E-01	1.445	133.4
19	49.74	0.7050E-01	1.446	133.5
20	49.70	0.7049E-01	1.448	133.6
21	49.66	0.7048E-01	1.449	133.7
22	49.61	0.7047E-01	1.450	133.9
23	49.57	0.7046E-01	1.451	134.0
24	49.53	0.7046E-01	1.453	134.1
25	49.49	0.7045E-01	1.454	134.2
26	49.44	0.7044E-01	1.455	134.3
27	49.40	0.7043E-01	1.456	134.4
28	49.35	0.7043E-01	1.457	134.5
29	49.29	0.7043E-01	1.457	134.5
30	49.21	0.7045E-01	1.456	134.4
31	49.08	0.7050E-01	1.451	134.0
32	48.81	0.7062E-01	1.439	132.9
33	48.28	0.7092E-01	1.412	130.3
34	47.26	0.7159E-01	1.357	125.2
35	45.65	0.7285E-01	1.272	117.4
36	43.87	0.7461E-01	1.182	109.1
37	42.61	0.7629E-01	1.118	103.2

STAGE	HEIGHT OVER WEIR FT	DC REL FROTH DENS	TR LIQ REL FROTH DENS	FRA APPR TO SYS LIMIT
1	0.1221	0.6075	0.3350	18.54
2	0.1206	0.6076	0.3358	18.44
3	0.1190	0.6076	0.3366	18.32
4	0.1171	0.6077	0.3375	18.20
5	0.1152	0.6078	0.3383	18.07
6	0.1133	0.6079	0.3392	17.95
7	0.1116	0.6080	0.3400	17.83
8	0.1463	0.6080	0.2245	31.74
9	0.1454	0.6081	0.2249	31.63
10	0.1449	0.6081	0.2253	31.54
11	0.1446	0.6081	0.2257	31.47
12	0.3711	0.6081	0.2257	31.55
13	0.3453	0.6081	0.2491	27.46
14	0.3444	0.6081	0.2496	27.39
15	0.3430	0.6081	0.2500	27.30
16	0.3405	0.6081	0.2506	27.19
17	0.3262	0.6081	0.2488	27.28
18	0.2588	0.6081	0.3449	17.37
19	0.2587	0.6081	0.3453	17.35
20	0.2586	0.6081	0.3457	17.32
21	0.2585	0.6081	0.3461	17.30
22	0.2584	0.6081	0.3465	17.27
23	0.2583	0.6081	0.3469	17.25
24	0.2582	0.6081	0.3473	17.22
25	0.2581	0.6081	0.3477	17.20
26	0.2580	0.6081	0.3481	17.18
27	0.2579	0.6081	0.3485	17.15
28	0.2578	0.6081	0.3489	17.13
29	0.2576	0.6081	0.3493	17.10
30	0.2572	0.6081	0.3497	17.07
31	0.2566	0.6081	0.3502	17.03



# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

32	0.2552	0.6081	0.3509	16.97
33	0.2523	0.6082	0.3520	16.85
34	0.2465	0.6082	0.3537	16.65
35	0.2376	0.6082	0.3561	16.35
36	0.2279	0.6083	0.3582	16.05
37	0.2210	0.6083	0.3591	15.88

BLOCK: MAC MODEL: MCOMPR

INLET STREAMS: 301 TO STAGE 1  
 OUTLET STREAMS: 302 FROM STAGE 3  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE (LBMOL/HR)	13227.7	13227.7	0.00000
MASS (LB/HR )	381625.	381625.	0.00000
ENTHALPY (BTU/HR )	692448.	0.136150E+07	-0.491410

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*

ISENTROPIC CENTRIFUGAL COMPRESSOR  
 NUMBER OF STAGES 3  
 FINAL PRESSURE, PSIA 105.000  
 DISTRIBUTION AMONG STAGES EQUAL P-RATIO

COMPRESSOR SPECIFICATIONS PER STAGE

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

COOLER SPECIFICATIONS PER STAGE

STAGE NUMBER	PRESSURE DROP PSI	TEMPERATURE F
1	3.000	95.00
2	3.000	95.00
3	3.000	95.00

\*\*\* RESULTS \*\*\*

FINAL PRESSURE, PSIA 102.000  
 TOTAL WORK REQUIRED, HP 18,717.9  
 TOTAL COOLING DUTY , BTU/HR -0.469573+08



\*\*\* PROFILE \*\*\*

COMPRESSOR PROFILE

STAGE NUMBER	OUTLET PRESSURE PSIA	PRESSURE RATIO	OUTLET TEMPERATURE F
1	28.31	1.926	239.8
2	54.52	2.154	282.4
3	105.0	2.038	267.6

STAGE NUMBER	INDICATED HORSEPOWER HP	BRAKE HORSEPOWER HP
1	5625.	5625.
2	6819.	6819.
3	6273.	6273.

STAGE NUMBER	HEAD DEVELOPED FT-LBF/LB	VOLUMETRIC FLOW CUFT/HR	ISENTROPIC EFFICIENCY
1	0.2101E+05	0.5257E+07	0.7200
2	0.2547E+05	0.3109E+07	0.7200
3	0.2344E+05	0.1526E+07	0.7200

COOLER PROFILE

STAGE NUMBER	OUTLET TEMPERATURE F	OUTLET PRESSURE PSIA	COOLING LOAD BTU/HR	VAPOR FRACTION
1	95.00	25.31	-.1342E+08	1.000
2	95.00	51.52	-.1743E+08	1.000
3	95.00	102.0	-.1611E+08	1.000

BLOCK: SPLITTER MODEL: FSPLIT

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INLET STREAM: 302  
 OUTLET STREAMS: TESTHPC TESTLPC  
 PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

	IN	OUT	RELATIVE DIFF.
--	----	-----	----------------

TOTAL BALANCE	IN	OUT	RELATIVE DIFF.
MOLE (LBMOL/HR)	13227.7	13227.7	0.00000
MASS (LB/HR )	381625.	381625.	0.00000
ENTHALPY (BTU/HR )	0.136150E+07	0.136150E+07	-0.171010E-15

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

FEED STREAMS CO2E	0.00000	LB/HR
PRODUCT STREAMS CO2E	0.00000	LB/HR
NET STREAMS CO2E PRODUCTION	0.00000	LB/HR
UTILITIES CO2E PRODUCTION	0.00000	LB/HR
TOTAL CO2E PRODUCTION	0.00000	LB/HR

\*\*\* INPUT DATA \*\*\*

FRACTION OF FLOW STRM=TESTHPC FRAC= 0.80000



\*\*\* RESULTS \*\*\*

STREAM= TESTHPC SPLIT= 0.80000 KEY= 0 STREAM-ORDER= 1
TESTLPC 0.20000 0 2

BLOCK: TURBINE MODEL: COMPR

INLET STREAM: 303
OUTLET STREAM: 304
PROPERTY OPTION SET: PENG-ROB STANDARD PR EQUATION OF STATE

\*\*\* MASS AND ENERGY BALANCE \*\*\*

Table with 4 columns: IN, OUT, RELATIVE DIFF. and rows for MOLE (LBMOL/HR), MASS (LB/HR), ENTHALPY (BTU/HR)

\*\*\* CO2 EQUIVALENT SUMMARY \*\*\*

Table with 3 columns and rows for FEED STREAMS CO2E, PRODUCT STREAMS CO2E, NET STREAMS CO2E PRODUCTION, UTILITIES CO2E PRODUCTION, TOTAL CO2E PRODUCTION

\*\*\* INPUT DATA \*\*\*

ISENTROPIC TURBINE
OUTLET PRESSURE PSIA 24.9831
ISENTROPIC EFFICIENCY 0.90000
MECHANICAL EFFICIENCY 1.00000

\*\*\* RESULTS \*\*\*

INDICATED HORSEPOWER REQUIREMENT HP -643.754
BRAKE HORSEPOWER REQUIREMENT HP -643.754
NET WORK REQUIRED HP -643.754
POWER LOSSES HP 0.0
ISENTROPIC HORSEPOWER REQUIREMENT HP -715.282
CALCULATED OUTLET TEMP F -244.445
ISENTROPIC TEMPERATURE F -254.083
EFFICIENCY (POLYTR/ISENTR) USED 0.90000
OUTLET VAPOR FRACTION 1.00000
HEAD DEVELOPED, FT-LBF/LB -18,555.6
MECHANICAL EFFICIENCY USED 1.00000
INLET HEAT CAPACITY RATIO 1.45678
INLET VOLUMETRIC FLOW RATE, CUFT/HR 83,304.3
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR 238,883.
INLET COMPRESSIBILITY FACTOR 0.96649
OUTLET COMPRESSIBILITY FACTOR 0.97671
AV. ISENT. VOL. EXPONENT 1.40045
AV. ISENT. TEMP EXPONENT 1.41082
AV. ACTUAL VOL. EXPONENT 1.33537
AV. ACTUAL TEMP EXPONENT 1.34884



Stream Report

HEAT

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STREAM ID                   HEAT  
 FROM :                    HPC  
 TO :                       LPC  
 CLASS:                    HEAT

STREAM ATTRIBUTES:

HEAT  
 Q            BTU/HR       1.3532+07  
 TBEG        F            -284.3381  
 TEND        F            -284.5198

301 302 303 304 305

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STREAM ID	301	302	303	304	305
FROM :	----	MAC	MHX1	TURBINE	MHX2
TO :	MAC	SPLITTER	TURBINE	LPC	HPC

CONV. MAX. REL. ERR:	0.0	0.0	0.0	0.0	6.4629-05
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SUBSTREAM: MIXED

PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	MIXED
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COMPONENTS: LBMOL/HR

OXYGEN	2777.8245	2777.8245	555.5649	555.5649	2222.2596
NITROGEN	1.0450+04	1.0450+04	2089.9822	2089.9822	8359.9290
METHANE	0.0	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0	0.0
WATER	0.0	0.0	0.0	0.0	0.0

TOTAL FLOW:

LBMOL/HR	1.3228+04	1.3228+04	2645.5471	2645.5471	1.0582+04
LB/HR	3.8163+05	3.8163+05	7.6325+04	7.6325+04	3.0530+05
CUFT/HR	5.2571+06	7.6968+05	8.3304+04	2.3888+05	1.0397+05

STATE VARIABLES:

TEMP    F	85.0000	95.0000	-150.0000	-244.4446	-276.5624
PRES   PSIA	14.7000	102.0000	102.0000	24.9831	102.0000
VFRAC	1.0000	1.0000	1.0000	1.0000	0.5920
LFRAC	0.0	0.0	0.0	0.0	0.4080
SFRAC	0.0	0.0	0.0	0.0	0.0

ENTHALPY:

BTU/LBMOL	52.3482	102.9280	-1642.9873	-2262.1364	-3490.3427
BTU/LB	1.8145	3.5676	-56.9485	-78.4092	-120.9807
BTU/HR	6.9245+05	1.3615+06	-4.3466+06	-5.9846+06	-3.6935+07

ENTROPY:

BTU/LBMOL-R	1.1179	-2.6315	-6.7913	-6.4642	-15.6134
BTU/LB-R	3.8750-02	-9.1211-02	-0.2354	-0.2241	-0.5412

DENSITY:

LBMOL/CUFT	2.5162-03	1.7186-02	3.1758-02	1.1075-02	0.1018
LB/CUFT	7.2593-02	0.4958	0.9162	0.3195	2.9364
AVG MW	28.8504	28.8504	28.8504	28.8504	28.8504

306 307 308 309 310

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## Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

STREAM ID	306	307	308	309	310
FROM :	HPC	HPC	LPC	LPC	LPC
TO :	LPC	LPC	MHX2	MHX2	MHX2
SUBSTREAM: MIXED					
PHASE:	LIQUID	LIQUID	LIQUID	VAPOR	VAPOR
COMPONENTS: LBMOL/HR					
OXYGEN	20.9993	2201.2603	2224.7852	497.3315	55.7076
NITROGEN	2935.2447	5424.6843	125.2148	4002.6685	6322.0281
METHANE	0.0	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0	0.0
WATER	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
LBMOL/HR	2956.2440	7625.9445	2350.0000	4500.0000	6377.7357
LB/HR	8.2898+04	2.2240+05	7.4698+04	1.2804+05	1.7888+05
CUFT/HR	1876.3850	4529.3597	1097.0931	2.9129+05	4.1266+05
STATE VARIABLES:					
TEMP F	-284.5198	-278.9830	-288.7385	-308.2283	-312.6017
PRES PSIA	92.0000	93.3000	27.3200	23.7200	23.0000
VFRAC	0.0	0.0	0.0	1.0000	1.0000
LFRAC	1.0000	1.0000	1.0000	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	-4690.2072	-4799.9267	-5387.8371	-2719.8030	-2749.9823
BTU/LB	-167.2578	-164.5848	-169.5011	-95.5862	-98.0446
BTU/HR	-1.3865+07	-3.6604+07	-1.2661+07	-1.2239+07	-1.7539+07
ENTROPY:					
BTU/LBMOL-R	-23.4715	-22.4895	-25.1940	-9.2213	-9.9594
BTU/LB-R	-0.8370	-0.7711	-0.7926	-0.3241	-0.3551
DENSITY:					
LBMOL/CUFT	1.5755	1.6837	2.1420	1.5448-02	1.5455-02
LB/CUFT	44.1798	49.1023	68.0873	0.4396	0.4335
AVG MW	28.0418	29.1639	31.7865	28.4539	28.0483

311 312 313 TESTFEED TESTHPC

STREAM ID	311	312	313	TESTFEED	TESTHPC
FROM :	MHX1	MHX1	MHX1	MHX1	SPLITTER
TO :	----	----	----	MHX2	MHX1
SUBSTREAM: MIXED					
PHASE:	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
COMPONENTS: LBMOL/HR					
OXYGEN	2224.7852	497.3315	55.7076	2222.2596	2222.2596
NITROGEN	125.2148	4002.6685	6322.0281	8359.9290	8359.9290
METHANE	0.0	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0	0.0
WATER	0.0	0.0	0.0	0.0	0.0
TOTAL FLOW:					
LBMOL/HR	2350.0000	4500.0000	6377.7357	1.0582+04	1.0582+04
LB/HR	7.4698+04	1.2804+05	1.7888+05	3.0530+05	3.0530+05
CUFT/HR	5.9091+05	1.0979+06	1.6049+06	3.1794+05	6.1574+05
STATE VARIABLES:					
TEMP F	80.0000	80.0000	80.0000	-162.7559	95.0000
PRES PSIA	23.0000	23.7200	23.0000	102.0000	102.0000
VFRAC	1.0000	1.0000	1.0000	1.0000	1.0000
LFRAC	0.0	0.0	0.0	0.0	0.0





# Oxy Fuel for Clean Energy Generation

Hally, Muqem, Richter, Schanstra

SFRAC	0.0	0.0	0.0	0.0	0.0
ENTHALPY:					
BTU/LBMOL	14.7239	15.4395	15.7264	-1736.1408	102.9280
BTU/LB	0.4632	0.5426	0.5607	-60.1774	3.5676
BTU/HR	3.4601+04	6.9478+04	1.0030+05	-1.8372+07	1.0892+06
ENTROPY:					
BTU/LBMOL-R	-0.4461	-0.2302	-0.7595	-7.0984	-2.6315
BTU/LB-R	-1.4036-02	-8.0906-03	-2.7077-02	-0.2460	-9.1211-02
DENSITY:					
LBMOL/CUFT	3.9769-03	4.0988-03	3.9740-03	3.3284-02	1.7186-02
LB/CUFT	0.1264	0.1166	0.1115	0.9603	0.4958
AVG MW	31.7865	28.4539	28.0483	28.8504	28.8504

TESTLPC TESTN2 TESTO2 TESTWAST

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STREAM ID	TESTLPC	TESTN2	TESTO2	TESTWAST
FROM :	SPLITTER	MHX2	MHX2	MHX2
TO :	MHX1	MHX1	MHX1	MHX1

SUBSTREAM: MIXED

PHASE: VAPOR VAPOR VAPOR VAPOR

COMPONENTS: LBMOL/HR

OXYGEN	555.5649	55.7076	2224.7852	497.3315
NITROGEN	2089.9822	6322.0281	125.2148	4002.6685
METHANE	0.0	0.0	0.0	0.0
CO2	0.0	0.0	0.0	0.0
WATER	0.0	0.0	0.0	0.0

TOTAL FLOW:

LBMOL/HR	2645.5471	6377.7357	2350.0000	4500.0000
LB/HR	7.6325+04	1.7888+05	7.4698+04	1.2804+05
CUFT/HR	1.5394+05	8.2405+05	2.5457+05	5.6347+05

STATE VARIABLES:

TEMP F	95.0000	-180.0000	-180.0000	-180.0000
PRES PSIA	102.0000	23.0000	27.3200	23.7200
VFRAC	1.0000	1.0000	1.0000	1.0000
LFRAC	0.0	0.0	0.0	0.0
SFRAC	0.0	0.0	0.0	0.0

ENTHALPY:

BTU/LBMOL	102.9280	-1803.1912	-1811.2572	-1804.2589
BTU/LB	3.5676	-64.2888	-56.9821	-63.4098
BTU/HR	2.7230+05	-1.1500+07	-4.2565+06	-8.1192+06

ENTROPY:

BTU/LBMOL-R	-2.6315	-5.3603	-5.4042	-4.8330
BTU/LB-R	-9.1211-02	-0.1911	-0.1700	-0.1699

DENSITY:

LBMOL/CUFT	1.7186-02	7.7395-03	9.2312-03	7.9862-03
LB/CUFT	0.4958	0.2171	0.2934	0.2272
AVG MW	28.8504	28.0483	31.7865	28.4539