Feasibility Study for In-situ Oxygen Separation for Hospitals: Technical Report and Market Analysis

O_2n-Site Inc.

Technical Report Submitted to:
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Capstone Design Project Spring 2006

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May 10, 2006

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Executive Summary

The purpose of this study is to consider the profitability of an onsite oxygen production system for a medical facility. This system is designed to meet the needs of hospitals that are currently on average using 3,000 gallons of liquid oxygen per month, paying average yearly costs of $19,000. The designed system incorporates a pressure swing adsorption system. Prior to the pressure swing adsorbers, there is a silica gel drying column that removes moisture and trace impurities from the stream. This feeds into the first pressure swing adsorption system, which removes nitrogen from the entering air stream. This stream is stored in a low-pressure storage vessel before it enters the next pressure swing adsorption system, which removes argon from the stream. The yearly energy cost for this system was determined to be $8,500. The selling price of this system to optimize demand and net present value of the business plan for this system was determined to be $66,500. The net present value for the seven-year estimated life of this business is $5,300,000. The amount of profit that could be obtained varied from approximately $8,500,000 to $1,600,000 as calculated by the net present value method. The study also revealed that there was a 0% risk of loosing money with the proposed design.

Regarding the possibility of using an onsite cryogenic process to meet hospital needs, this project concluded that this was economically unfeasible. Although a process that provides the needed product at the needed flowrate was successfully designed within operating cost requirements, the capital costs of this system inhibited typical hospitals from being able to invest in such a system.

1. Introduction

1.1 Medical uses of Pure Oxygen

One of the most important uses of oxygen is in the healthcare industry. Oxygen has uses in hospitals that include surgery, intensive care units, and inhalation therapy. Oxygen therapy also finds viable applications in portable devices used outside of hospitals and health care facilities. Oxygen used in medical applications must be maintained at a purity of 99.2 mole percentage oxygen according to standards set by the Food and Drug Administration. The medical applications of pure oxygen consequently create a great demand for a feasible and convenient means of purifying oxygen.

1.2 Air Separation Methods

With oxygen existing mostly in chemical compounds and in mixtures, various methods and techniques have developed around the need to obtain oxygen in its pure form and to satisfy various purity requirements. Electrolysis is a viable method to obtain oxygen gas. However, the amount of energy required for the reaction coupled with the cost of replacing the electrodes makes the process ever increasingly expensive. Creating oxygen gas with chemical reactions poses a problem in the purchase of reactants and the disposal of by-products such as very strong acids. Membrane separation offers a relatively cheap means of getting the oxygen out of air but does not achieve the necessary purity needed for medical applications. Pressure swing adsorption offers an alternative to cryogenic distillation as a means of generating a 99.2 mol% oxygen stream. Cryogenic distillation is a process that also provides the purity desired for medical operations and is the only process to deliver liquid product streams. For these reasons, cryogenic distillation and pressure swing adsorption became the focus of this study.

1.2.1 Electrolysis

Electrolysis involves the passing of a current through an ionic solution of water and submersing a pair of metal electrodes in the liquid. The ions of both the hydrogen and oxygen atoms gather at the cathode and anode respectively. The result is hydrogen and oxygen gas bubbling up from one of the electrodes. This oxygen can then be collected, but it is in minute amounts.

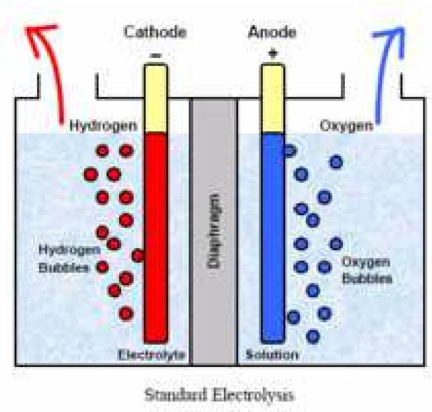

Figure 1: Electrolysis

http://www.greencarcongress.com/images/standard_electrolysis.png

Using water as feedstock is very advantageous because it is readily available. While this is an acceptable way to obtain pure oxygen, there exists an ongoing need for metal to supply the electrodes and power to supply the current. The metallic electrodes must be replaced because they combine with the ions, eventually consuming them past the point of usefulness. Based on only the cost of the energy needed to accomplish the electrolysis, this method is less preferred. The Gibbs free energy needed to produce one mol of oxygen from water

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 ,$$

is 475 kJ. [24][25] In determining the amount of energy needed to effectively perform this separation, only the Gibbs free energy need be considered. Assuming an ideal conversion of electricity into energy for this reaction, this calculates to be $38,000 a year in energy costs alone. This compared to the current yearly costs for a small plant needing the same amount of oxygen, about $19,000, shows why this method is rarely considered.

1.2.2 Chemical

As stated earlier, oxygen exists mostly in compounds. This method involves producing oxygen through utilization of a chemical reaction in which oxygen is produced as a product. An example is the reaction of Fluorine with water:

$$F_2(g) + H_2O(l) \rightarrow O_2(g) + 2HF(aq)$$

This reaction is an example of how pure oxygen gas can be acquired at the expense of having more than one product. Not only is the same problem present with having to regularly supply feed Fluorine, but that problem is compounded by the fact that another product of this reaction is liquid aqueous hydrofluoric acid. Hydrofluoric acid is a very strong acid and creates a safety hazard. These combined factors make chemical separation a less desirable alternative.

1.2.3 Membrane

This method of separation uses a selective barrier in the form of a polymer membrane to separate oxygen from nitrogen in the air. The majority of ready to purchase membrane separation devices utilizes hollow polymer fibers to achieve separation.

Figure 2: Thousands of hollow membrane fibers

http://www.storagecontrol.com/documents/permea_scs_broch.pdf

Membrane polymers work on the principal of gas diffusion through the polymer. Pressurized gas is passed down the bores of the polymers, while a lower pressure is maintained outside the fibers to create a partial pressure gradient across the fiber walls. This results in some gases permeating through the membrane walls faster than others. The slower permeating gases remain in the high-pressure stream and accumulate, while the quicker permeating gas accumulates in the low-pressure stream. [2] This is a very inexpensive way to separate nitrogen from oxygen and create an oxygen rich stream out of the membrane separator. The permeability of the membrane allows a fair amount of nitrogen to remain in the oxygen rich stream and does not achieve the necessary purity for medical applications.

1.2.4 Pressure Swing Adsorption (PSA)

In terms of separation for the purpose of oxygen generation, pressure swing adsorption is generally the most frequently applied method. Pressure swing adsorption, used almost exclusively with gases, is employed mostly in gas drying or air separation. Oxygen concentrators currently employ the use of nitrogen removal pressure swing adsorption to supply 94-95% oxygen to patients in need of oxygen therapy. PSA vessels contain adsorbent materials that have a pressurized feed stream flowing through them. Adsorbents are usually determined by their affinity to adsorb the non-product molecules while the preferred molecules, in this case oxygen, are allowed to flow through the bed and enter the product stream. PSA systems that remove nitrogen or oxygen usually employ molecular sieve zeolites or silica gel as the adsorbent material due to their selectivity of components. Since PSA is a semi-batch process the adsorbent bed needs periodic desorption. For this reason PSA systems usually employ a two bed system to allow for continuous operation. [1] One bed adsorbs the feed stream while the other is regenerated by lowering the pressure in that bed to atmospheric pressure causing the adsorbed molecules to desorb into a purge stream.

Figure 3: Molecular Sieve Zeolite 3A
http://www.tradekey.com/product_view/id/25010.htm

Using air as a feed stream PSA eliminates the need to constantly purchase feed materials to create oxygen. PSA is also a very reliable process that produces a nearly pure stream of 99 mol% oxygen with the addition of a system that can also be used to remove argon from air streams. The argon removal process operates under similar principles as nitrogen removal PSA, but is slightly more complex due the similarities between argon and oxygen. Argon pressure swing adsorbers were investigated in this project as well to increase the purity of the product stream to 99%.

A small storage tank maintained at pressure less than that of the compressed feed is used in addition to two equal sized beds to allow for continuous operation. Pictured below is a typical process flow diagram for a pressure swing adsorption system.

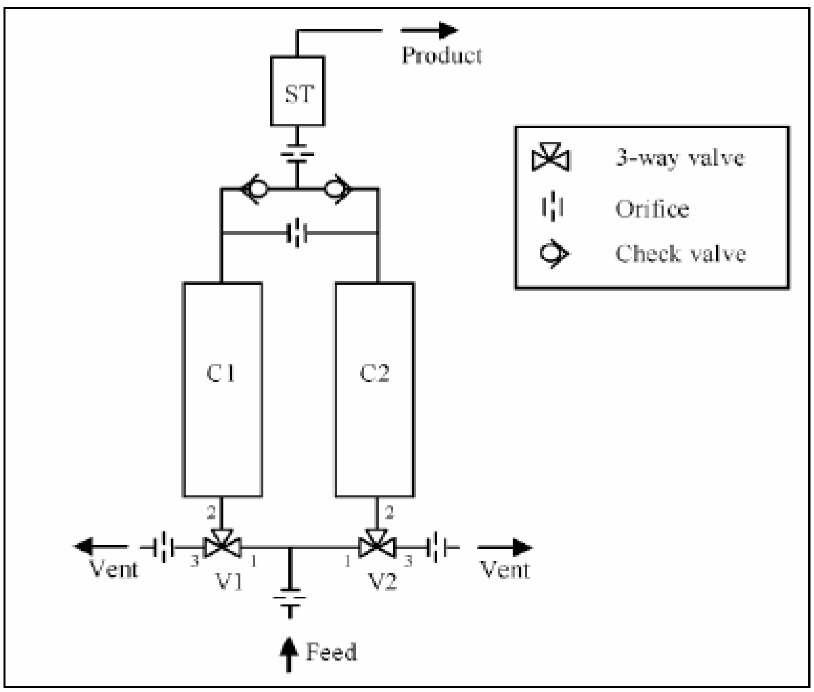

Figure 4: PSA System PFD [28]

As seen in Figure 4 each column will operate in one of two modes: 1) Pressurization or 2)Purge. While one column is operating in one stage the other will be in the alternating stage. Through this process continuous operation is achieved.

1.2.5 Cryogenic Distillation

Cryogenic distillation uses the same principles as distillation but the separation takes place at cryogenic temperatures, below -150 ^{o}C. This separation technique involves taking advantage of the relative volatility of components in a mixture. When cooled to low enough temperatures to liquefy the air, nitrogen and argon will vaporize before oxygen. Nitrogen and argon are then boiled off in a distillation column leaving almost exclusively oxygen. This separation has the ability to produce oxygen in the needed purity of 99.2% for medical use, and is one of the forms of most interest in creating an in-situ oxygen generating system.

1.3 Types of Cryogenic Distillation

To reach the extreme temperatures necessary to separate liquid oxygen from nitrogen, steps must be taken to cool air to the required temperatures. Refrigeration is an important process involved in lowering temperatures. The cycle most associated with refrigeration is the Brayton cycle. This cycle employs the use of a compressor, condenser, evaporator, Joule-Thomson valve, and a refrigerant. The refrigerant is chosen based on the desired cool temperature. The refrigerant is compressed, increasing the temperature. This heat is then dissipated by the condenser acting as a heat exchanger, before it is expanded through a Joule-Thomson valve. The Joule-Thomson effect finds its use in cryogenic distillation by cooling an already cooled, high-pressure gas further through isenthalpic expansion and partially liquefying the gas. The result is the expanding gas removes heat from the surrounding area.

Distillation, or fractionation, refers to the separation of a mixture of two or more components into two or more products. The bottom product of a distillation tower is always a liquid. In order for a separation to occur in a distillation tower, three prerequisites must be met. A second phase must be formed so that both liquid and vapor phases are present and can make contact on each stage. It is critical that the components to be separated have different volatilities, or tendencies to vaporize. Lastly, it is necessary that the two phases can be separated by some mechanical means, such as gravity.

An important characteristic of cryogenic distillation is the lack of resource for the condensation of the distillate coming off the top of the tower. Streams cool enough to condense air are not readily available. This limits the variability of the tower.

1.3.1 Linde Process

The first and perhaps most simple method to separate oxygen from nitrogen and air cryogenically is the Linde process. This simple process consists of a compressor, heat exchanger, Joule-Thomson (J-T) valve, and a collector that behaves as a flash tank. The air is first compressed, and then it is cooled by the heat exchanger. The stream is then further cooled by expansion through the Joule-Thomson valve. After expansion the gas partially liquefies and the oxygen rich liquid is collected in the flash tank. The nitrogen gas stream is used as the cooling fluid for the heat exchanger[3].

Figure 5 below is a historical design for a gas refrigeration Linde process. In this picture, the stream flows through the compressor, which corresponds to point 1 to 2 on the temperature-entropy diagram. This stream is then cooled through heat exchanger, points 2 to 3, accomplished through the piping in the picture. The gas is expanded isenthalpically, points 3 to 4, which lowers the temperature. The decrease in temperature accomplishes the liquefaction of the stream. If the expansion taking place from point 3 to 4 occurs with no change in enthalpy, it is clear that it is necessary that a certain pressure and temperature be reached prior to expansion. This is known as the inversion point.

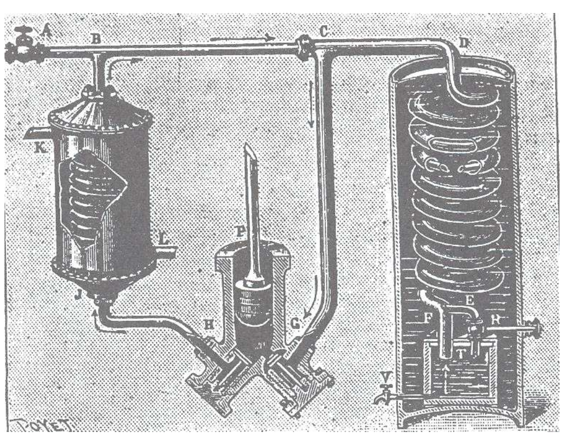

Figure 5: Linde Liquefaction Process [3]

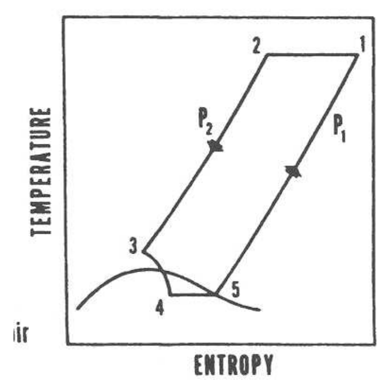

Figure 6: Temperature-Entropy Diagram for Linde Process[3]

To increase the purity of the liquid oxygen product to 99.2 % a distillation column is added after the expansion valve. The valve feed is used to supply heat to the reboiler since it is higher in temperature than the fluid after the expansion valve.[3]

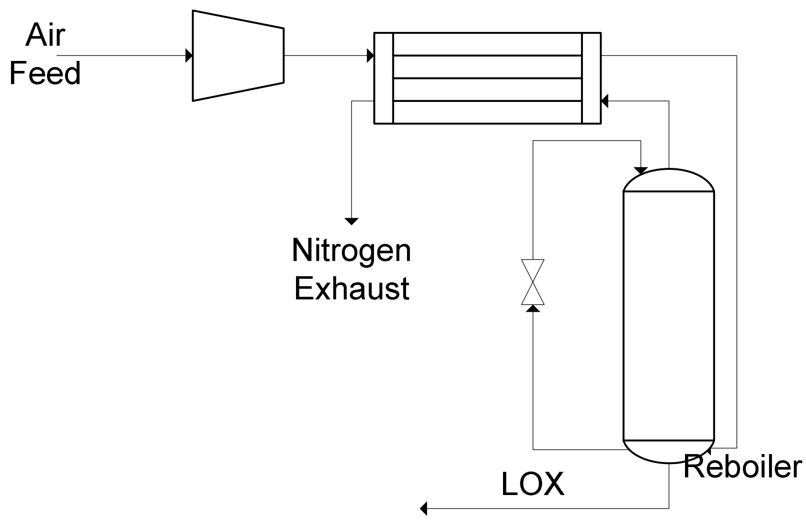

Figure 7: Single Linde Column[3]

1.3.2 Claude Process

Another very simple cryogenic oxygen process is the Claude process, which incorporates a refrigeration cycle into the Linde process. The added cooling of the refrigeration cycle helps to further cool the compressed air, increasing the efficiency of the process. The temperature entropy diagram of the process below in Figure 8 is similar to the simple Linde. The difference is that energy is now used more effectively via the expansion engine. This improvement is a common component in industry. The use of the expansion engine can actually aid in compressor energy, as well as enable more control of the gas as it expands and enters the distillation tower

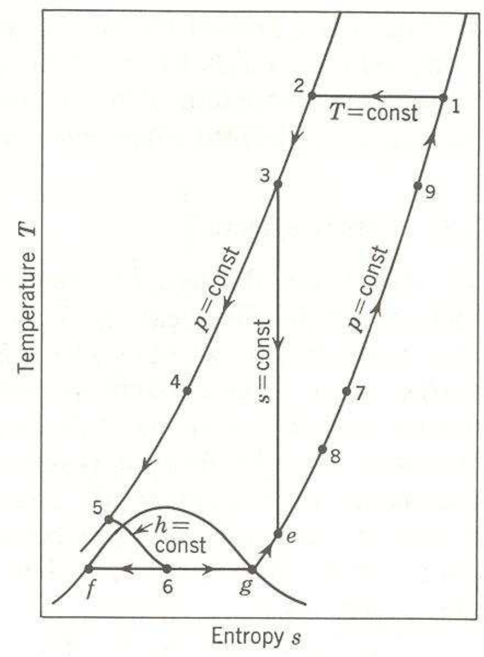

Figure 8: Temperature-Entropy Diagram for Linde Process [3]

The following is an example flow of the Claude process integrating a distillation tower. This corresponds to the above picture. As the feed stream passes through the compressor, points 1 to 2 in the temperature entropy diagram, is compressed and then cooled in three sequential heat exchangers, points 2 though 5. At this point the gas is expanded to liquefaction and distilled. The expansion engine is utilized by expanding the feed gas stream and cooling it additionally. This is shown in points 3 to e in the diagram in Figure 8.

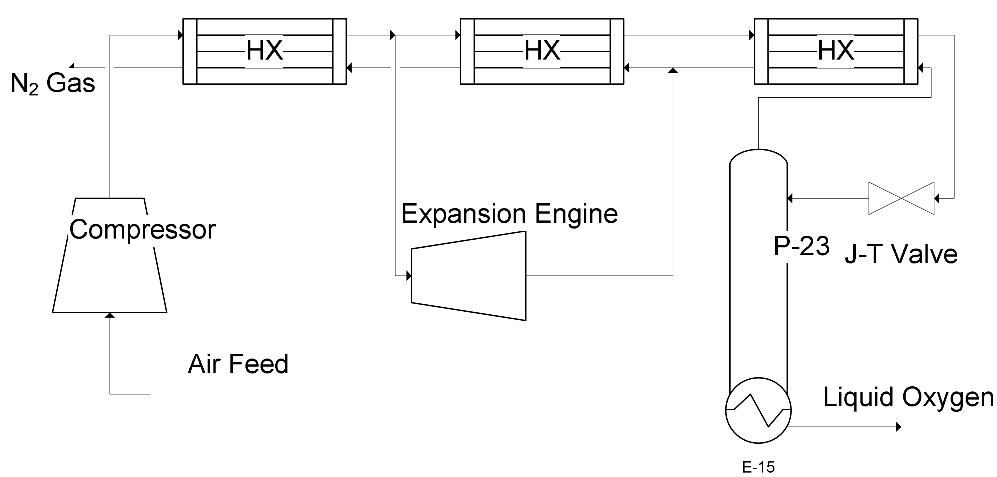

Figure 9: Claude Liquefaction Process

1.3.3 Double Linde Process

The single column Linde process is designed to focus mainly on the production of pure liquid oxygen. The nitrogen stream however is too impure for any pure gas applications. This problem was solved by the addition of another column, on top of the first, to purify the nitrogen stream. The oxygen rich stream is supplied to the upper column as feed along with some of the liquid nitrogen as the needed reflux. The result is a nitrogen rich stream in excess of 99% purity in addition to the near pure oxygen stream.[3]

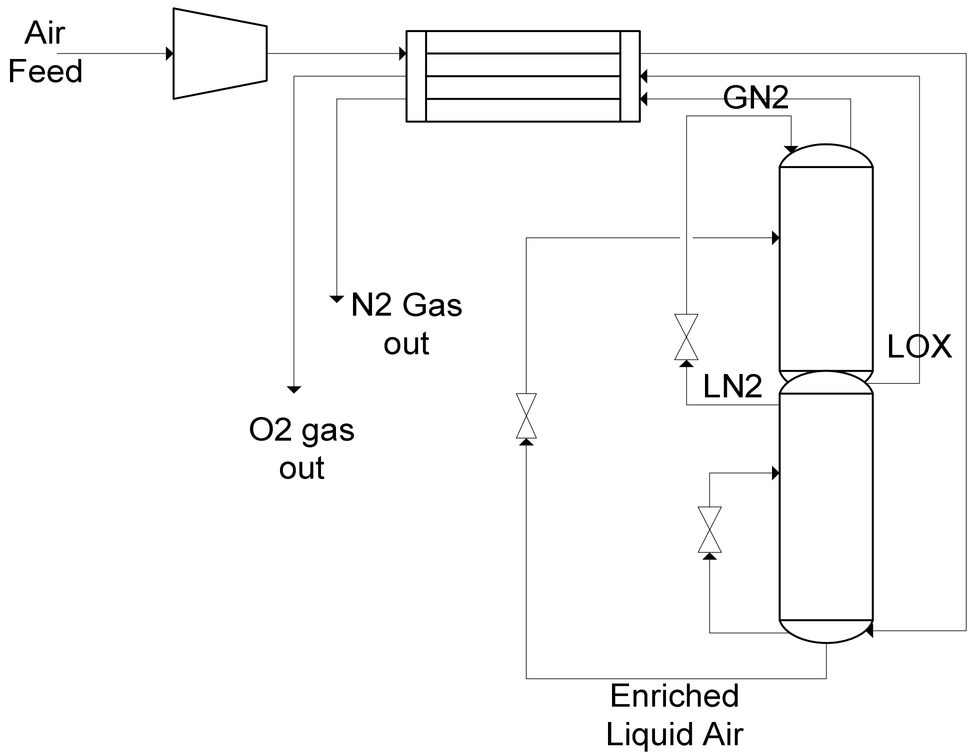

Figure 10: Double Linde Column

2. Oxygen Production Method Selection

Three options were investigated for the design of an onsite oxygen production system. Using the before mentioned technologies, the three designs incorporated cryogenics and adsorption in different combinations. The first option was an air feed into cryogenic distillation process. Next, a nitrogen pressure swing adsorption process preceding the cryogenic process was investigated with two alterations – one with an expansion engine and one without and expansion engine. Finally, a system incorporating a nitrogen adsorption process and an argon removal process using adsorption was investigated. The designs are detailed below.

2.1 Air Feed Cryogenic Design

Once cryogenic methods and adsorptions were determined to be the primary methods with which to design a medical grade oxygen production process, these methods were used to develop the best system. The starting point for the investigation of the best system began with the least complex, that of the simple Linde cycle. This design, with little modification, was determined not be a satisfactory design due to the high energy costs and low product yields.

The only modification to the simple Linde process made was the replacement of a flash tower with a distillation tower. This is essentially the same process. Differences include the bottoms now exit at a higher oxygen concentration and the distillate has a higher flowrate. This process has a feed of air, coming from the atmosphere, which is purified to remove carbon dioxide and trace impurities. This feed then flows into a compressor where it is compressed to a pressure of 3000 psi. This stream is cooled to ambient temperature using water as the cold side fluid. The stream then exchanges heat with the vaporized and cooled gas coming off the top of the distillation tower. In order to further cool the stream, it is used to heat the reboiler in the bottom of the distillation tower. Finally, the gas stream is expanded to atmospheric pressure across a J-T valve where it cools and partially liquefies. This mixed stream flows into a distillation tower at atmospheric pressure, where medical grace oxygen is the bottom product. A process flow diagram depicts this flow below.

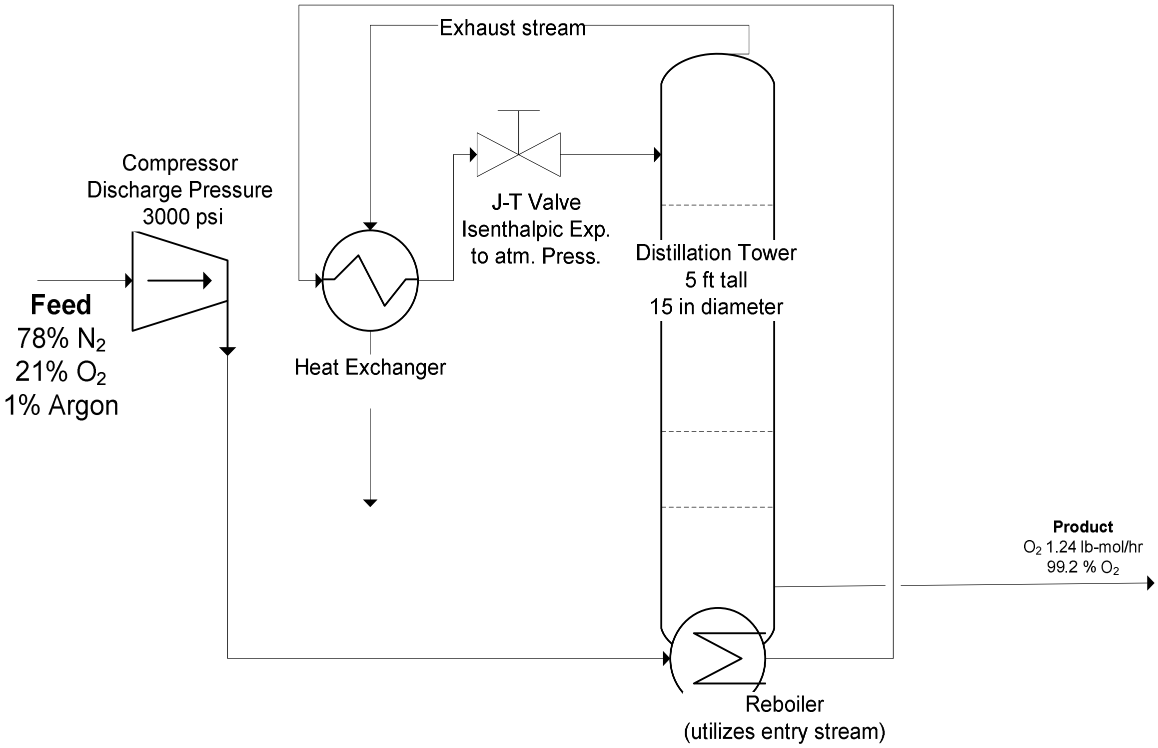

Figure 11: PFD for Air Feed Cryogenic Design

Simulation Science Pro II was used to calculate the yield of this process. For every mol of oxygen produced in this stream, 210 moles of feed are needed in the feed stream. In order to achieve the necessary flow for a hospital (3,000 gal liq. O_2/month ~ 1.24 lb-mol/hr), the required feed rate for this system was determined to be 265 lb-mol/hr, or 95,000 ft^3/hr. The energy needed to compress this amount of energy at this rate makes this process unfeasible. The results are listed in Table 1 below and compared to distribution costs.

Air Feed Process		Current hospital purchasing cost
Energy for 1.24 lbmol/hr	1400 kW	
Energy per month	$1x10^3$ MW	
Energy cost per year (at $.0581 /1000kWh)	**$700,000**	**$19,000**

Table 1: Air Feed Cryogenic Design Costs

From Table 1 it is obvious why this design is not feasible. Even disregarding capital costs, the money lost to energy costs deems this process economically unworthy of further consideration.

2.2 N_2 Pressure Swing Adsorption and Cryogenic Distillation

2.2.1 Design One with and Expansion Engine

Once the air feed into the cryogenic distillation system was determined not to be a feasible option, the option of additional adsorption was introduced. In an attempt to increase the overall yield for the process, a nitrogen pressure swing adsorption process was added to the design of the system. This pressure swing adsorption system, used to remove the nitrogen from the entering atmospheric air stream, precedes the compressor for the cryogenic process and increases the oxygen concentration in the entering stream. This design was first attempted by accomplishing the expansion using an expansion engine, derived from the Claude cycle. The process flow diagram for this design is below.

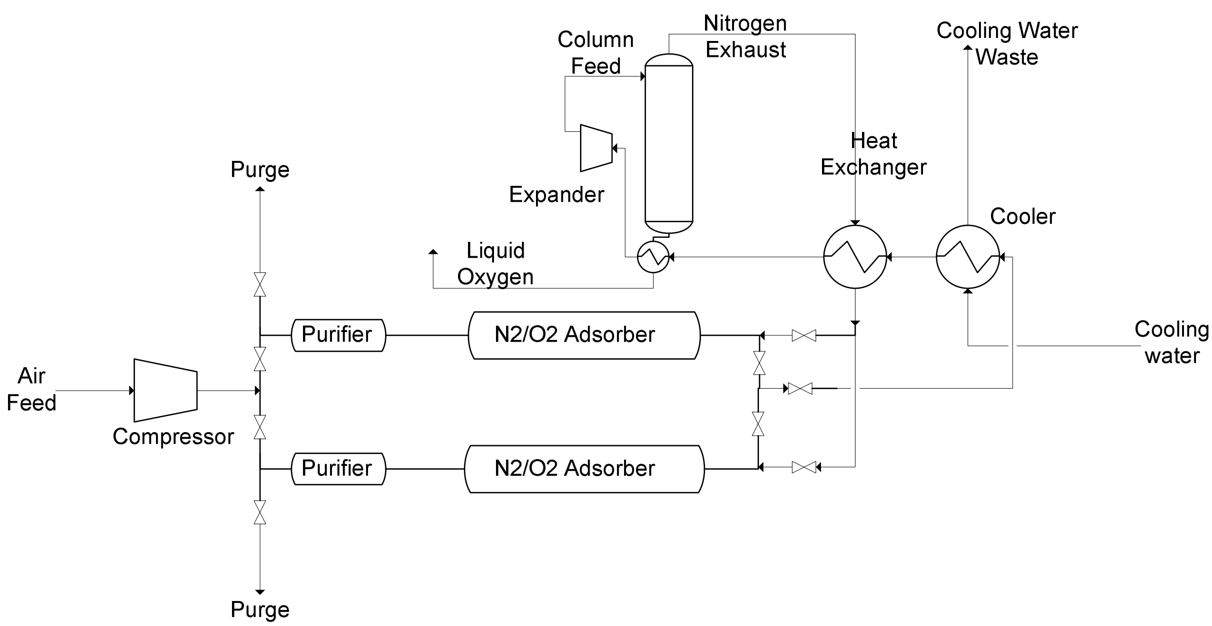

Figure 12: PFD for N_2 PSA and Cryogenic Distillation Design 1 with and Expansion Engine

Due to the expansion turbine, the compressor could be run at a much lower compression. The required feed for this design to meet hospital needs was determined, using Pro II, to be 55 lb-mol/hr, or 21,000 ft^3/hr, with a compression of 175 psi.

The energy needed to run this process was determined to be 86 kW. This is a feasible amount of energy, but still results in more yearly costs than the current cost of distribution purchasing price. A price quote was obtained for the compressor and expansion engine needed to perform this process. The compressor needed is a Gardner Denver model number PA 150 DS oil-free dry rotary screw air compressor [6].

The compressor is one of the more important components of the entire system because air must be first compressed to relatively high pressures to satisfy the conditions necessary for liquefaction. After obtaining a U value for the heat exchangers the areas were then found. The U valve obtain was 60 BTU/hr-^{0}F-ft^2. This resulted in an area of 84 ft^2.

The dimensions of the distillation column were found by reducing the size of the distillation column in successive simulations until the simulation no longer converged or a reasonable height was reached. Rather than use trays in the column, structured packing of approximate size to the column was used to increase the column's efficiency and decrease the size of the column even further. The only structured packing manufacturer available for simulation was Sulzer. The column was constructed out of aluminum metal because aluminum is one of several metals that are compatible at cryogenic temperatures. A cold box was designed to insulate the column. The insulating material would fill the remaining space in the box. The insulation utilized in the cold box was expanded Perlite.

For the piping of the system copper metal was used because of its compatibility at cryogenic temperatures. For various sections of pipe the diameters were determined using equations for optimum diameter from Peters et al.[10] The height of the column was determined to be five feet, with a diameter of 15 inches. The insulation used for the pipes was multi-layer insulation. Multi-layer insulation is ideal for areas exposed to the atmosphere. Multi-layer insulation also performs well as a cryogenic insulator after it is sealed under vacuum. The amount of insulation was determined using the equation approximating conductive heat transfer through a pipe. [11] The purchase thickness of multilayer insulation was 0.53 in. This thickness was used around all of the copper piping in the system. This thickness was used because the insulation is sold at a uniform thickness, thus the maximum thickness needed was used for all pipes. The cost estimate breakdown and comparison for this design are below.

Column	$5,300
Cold Box	$34
Compressor	$105,000
Heat Exchangers*	$14,560
Expander	$105,000
Pressure Swing Adsorber – O_2/N_2	$3,530
Pressure Swing Adsorber - Purifier	$1,900
Piping	$1,900
Total Equipment Cost	**$237,000**

Table 2: Equipment Costs for Cryogenic Process

*This amount is the cost of two heat exchangers: one carbon steel and one stainless steel.

Compressor Power	$35,300
Water	$900
Total	**$36,200**

Table 3: Total Operating Cost for One Year of Operation

Total Cost per Year for this design	Current hospital purchasing cost
$60,000	**$19,000**

It is clear from this cost estimation that this design is also not satisfactory. The yearly costs are still too great. This is mostly due to the high capital costs, but even with that, the energy still needs to decrease.

2.2.2 Design Two with Joule-Thomson Expansion

The high capital cost was due mostly to the presence of the expander. This could easily and directly be decreased by simply exchanging the expander for a J-T valve, which is a fraction of the cost. This design was investigated and optimized. The process flow is similar and is shown below in Figure 13.

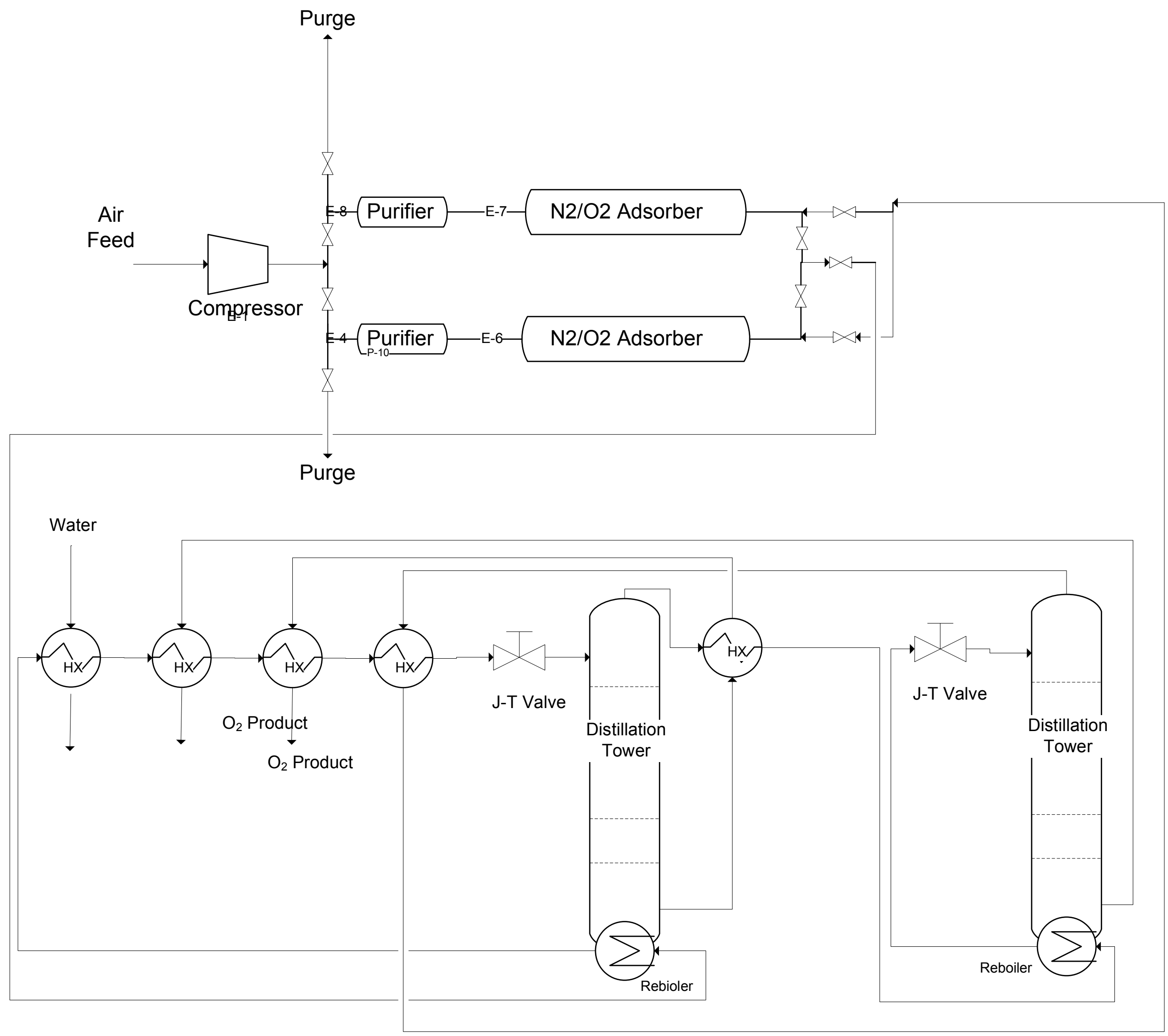

Figure 13: PFD for N_2 PSA and Cryogenic Distillation Design 2 with and J-T Valve

To improve the design, another tower was added to increase the yield. Typically, the tower height could just be increased, but due to hospital limitations, the decision was made to have two towers. The heat exchangers were arranged to maximize energy use.   The temperature pinch for each heat exchanger was set at 5–10 ^{o}F. Again, after obtaining a U value for the heat exchangers the areas were then found. The U valve obtain was 60 BTU/hr-^{0}F-ft^{2}. This resulted in an area of 84 ft^{2}. The first column operates at a pressure of 30 psi. The second column operates at atmospheric pressure. These pressures were manually varied to optimize product yield. The specifications for the columns are identical to the first design. The entering stream and the exhaust stream from the first column were used as the heat for the reboiler of each column.

The feed stream for this process is 8,400 ft^3/hr. The compressor operates at 2000 psi. The heat exchangers for this system were estimated as equipment that could be built locally within the company. This reduced the cost of these heat exchangers. The cost of the adsorption system remained the same as the first design. The following table show the equipment cost for this design.

Column	$10,600
Cold Box	$100
Compressor	$200,000*
Heat Exchangers	$4,000
Pressure Swing Adsorber - O_2/N_2	$3,530
Pressure Swing Adsorber – Purifier	$1,900
Piping	$2,300
Total Equipment Cost	**$237,000**

Table 4: Equipment Costs for Cryogenic Process

* Rick Turnquist, Sales Engineer for RIX Industries

The operating costs for this design are tabulated below.

Compressor Power	$35,300
Water	$900
Total	**$36,200**

Table 5: Total Operating Cost for One Year of Operation

Total Cost per Year for this design	Current hospital purchasing cost
$97,000	**$19,000**

The capital costs are high due specifically to the expensive compressor for this system. Rick Turnquist, Sales Engineer for RIX Industries, a gas compressor manufacturer based in California, quoted the compressor for this system [26]. The suggested compressor would be a 2JS4BG-43, a 4 stage 2JS similar to the air unit, but would top out at 2000 psig, with lower compression ratios to keep the temperatures down. It would run at 300 RPM with a 40 HP motor. Budgetary cost is $200,000. This was an unexpectedly high cost for the compressor. Also, since there is no longer an expansion engine, prior to expansion through the J-T valve, an inversion point had to be reached. This was a high pressure and low temperature. Thus, the process required more energy via compression to perform the needed expansion to accomplish the temperature decrease necessary for liquefaction. This resulted in higher energy costs for this system. It can be seen, that though an expansion engine was removed to decrease costs, the design did not substantially improve the capital costs, and actually increased operating costs. It is clear that this design is not successful either in comparison to the goal $19,000/yr.

2.3 Proof of Industrial Performance

These designs have proven to be more expensive than just purchasing the oxygen from a distributor. However, industrial plants are making a profit by performing a process similar to the cryogenic processes developed here; otherwise oxygen would not be sold. As can be seen from the previous designs, the debilitating factor is the difficulty in designing a system that uses a minimal amount of energy. If the energy costs are not sufficiently low, the system is not economically feasible. To show that the industrial process is indeed possible to perform at a profit, a design was created with no regard to capital costs. This design is shown below.

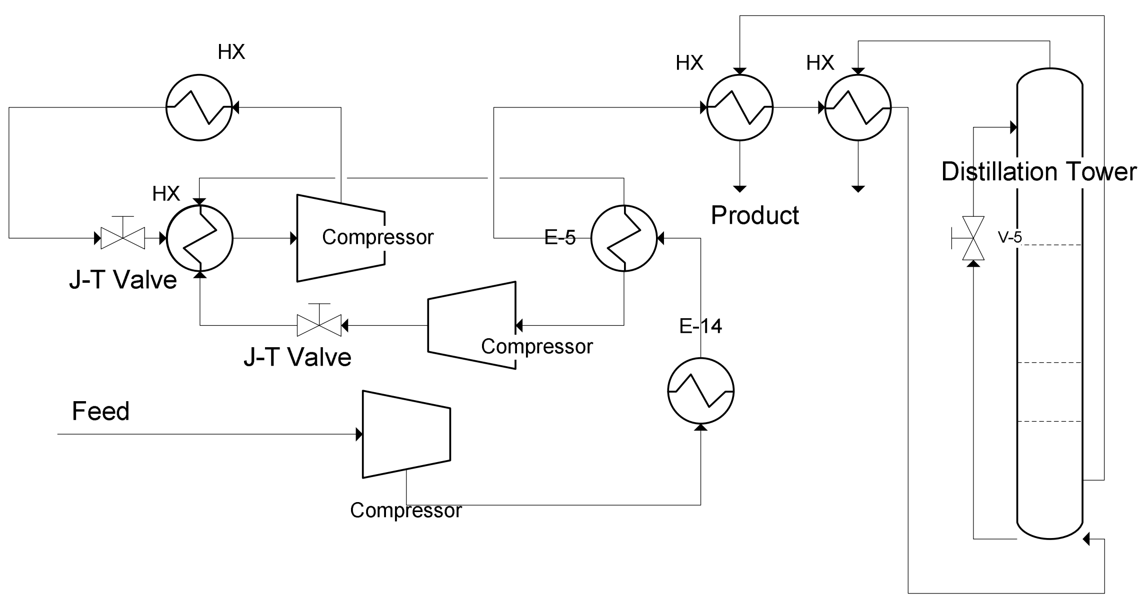

Figure 14: PFD for Energy Design disregarding capital cost

The entering feed of this design is 1,800 ft3/hr. This feed is compressed to 1,000 psi. After this compression the feed is cooled via water. The vital factor of this system is the addition of two refrigeration cycles. One refrigeration cycle utilizes R12 (dichlorodifluoromethane). This cycle is used to cool a methane refrigeration cycle. These two refrigeration cycles cascade into the cryogenic process stream. The stream coming out the water coolant heat exchanger is further cooled to a temperature of -115^{o}F by heat exchange with cold methane gas. The area for this heat exchanger was estimated to be 100ft^{2}. The lowering of this stream temperature is the alteration that enables such a high yield for this cryogenic process. Due to the lower temperature prior to cryogenic expansion, more of the gas is liquefied. The products rate for this system is still 1.24 lb-mol/hr medical grade oxygen, but the entering rate is much lower. The total energy costs for this system based on compressor work is only about 20.5 kW resulting in about $11,000 yearly.

Work Compressor 1	16.6 kW	Yearly Cost of Purchasing Oxygen
Work Compressor 2	2.3 kW	
Work Compressor 3	1.6 kW	
Total Work	20.5 kW	
Total Cost Per Year	**$10,750**	**$19,000**

Table 6: Energy Costs for Industry Design Proof

A process that produces the required 1.24 lb-mol/hr of medical grade oxygen has been developed to perform within the necessary operating costs of less than $19,000/yr. However, this design disregarded capital costs. So, although operating cost requirements have been satisfies, the high capital costs due to multiple compressors are ultimately what inhibit a typical size hospital from investing in a cryogenic distillation system.

2.4 PSA for N_2 and PSA for Argon

Due to either high operating costs or excessively high capital costs, the design of an onsite cryogenic distillation system for hospitals has been shown to be infeasible. For this reason the examination of using PSA to remove both the nitrogen and the argon from the product stream was undertaken. This nitrogen system has have both low operating an d minimal capital costs to persuade hospitals to abandon their current method of obtaining medical grade oxygen

2.4.1 Nitrogen adsorption

The adsorption of air is best modeled by the Langmuir equation for multi-component adsorption.[28]

$$q_i = Q_{\max} \frac{\left(\frac{b_i}{\eta_i}\right) P_i}{1 + \sum_{j=1}^{N} \left(\frac{b_j}{\eta_j}\right) P_j}$$

Where:

q_i = loading per mass (mol/kg) of component *i* on the adsorbent

Q_{max} = max loading (mol/kg) of any component onto the adsorbent

b_i = a constant for component *i*

N = the total number of components

η = an integration factor among components

P_i = partial pressure of component *i*

The following table was obtained for the Oxysiv 5 adsorbent

Component	Qmax(mol/kg)	b(Pa^-1)
N_2	3.074	1.02E-06
O_2	3.074	3.69E-07
Ar	3.074	3.40E-07

Table 7: Oxysiv 5 data[28]

Since the interactions between oxygen, nitrogen, and argon are negligible, η can be assumed to be zero reducing to the equation:

$$q_i = Q_{\max} \frac{b_i P_i}{1 + \sum_{j=1}^{N} b_i P_j}$$

The mass of adsorbent in the bed is determined through the use of this equation:

$$Q_F c_F t_x = q_F M L_x / L_B$$

Where:

Q_F = volumetric feed flowrate

t_x = time the front has been traveling at position L_x

q_F = loading per mass of adsorbent in equilibrium with the feed concentration

M = mass of adsorbent in the bed

c_F = concentration of solute in feed c

Mass transfer effects can be ignored because the column is operated to allow the feed to reach equilibrium in the column. Assuming ideal operations, all of the nitrogen in the feed stream will be removed from the resulting 95% oxygen stream. The argon that remains in the stream will now be 5% of the stream. The breakthrough of the front will be occur when $L_x = L_b$. The desired breakthrough time for this system is 1 minute; however, the system can be designed to accommodate different breakthrough times. Although the purity of the product stream has been increased greatly through nitrogen removal, the gas is still not at the necessary purity for medical use in hospitals. This makes the argon removal necessary to achieve the needed purity of 99.2%.

2.4.12 Argon Removal

There are currently two methods through which argon is removed from air through pressure swing adsorption. One method operates similar to the nitrogen removal system in that it operates under conditions in which the feed stream and adsorbent are in equilibrium. For maximum yield this system would require an adsorbent with a higher affinity to adsorb argon over oxygen. argon and oxygen have very similar physical properties and isotherms. This causes problems in adsorption because nearly equal amounts of nitrogen and argon are adsorbed. This can create a

99% purity stream, but the yield will be very low due to the high amounts of oxygen adsorbed from the stream.

A more practical method uses a kinetic adsorption model that takes advantage of the different rates of adsorption for compounds with similar isotherms. Although they both adsorb one compound usually adsorbs faster than the other due to differences in the effective diffusivities in the used compounds. By designing a system to stop adsorbing when a certain amount of one component has adsorbed while the other largely remains in the gas a practical separation is now possible. While this does not completely eliminate the adsorption of both compounds, the higher yield makes the design of a pressure swing adsorption system using this method more practical.

Using the adsorbent Bergbau-Forschung Molecular Sieve Carbon(BF-MSC), Rege and Yang[27] have successfully created a 99% purity oxygen stream using a kinetic model. Although the study by Rege and Yang does not explicitly state the model used, the Linear Driving Force model is assumed to be used,[28] governed by the equation:

$$\frac{\partial \bar{q}}{\partial t} = \frac{15D_e}{R_p^2}\left(q_{Rp} - \bar{q}\right)$$

Where:

$\bar{q}$ = average loading of component on the adsorbent

t = time

D_e = the effective intraparticle diffusivity

R_p = radius of a particle

q_{Rp} = loading at the particle surface

Based on this equation oxygen is shown to have a higher effective diffusivity than argon when adsorbed onto BF-MSC. The values that determine the effective diffusivity, D_e/R_p^2, are 5.2×10^{-3} s^{-1} and 1.74×10^{-4} s^{-1} for oxygen and argon respectively as calculated by Rege and Yang.[27]

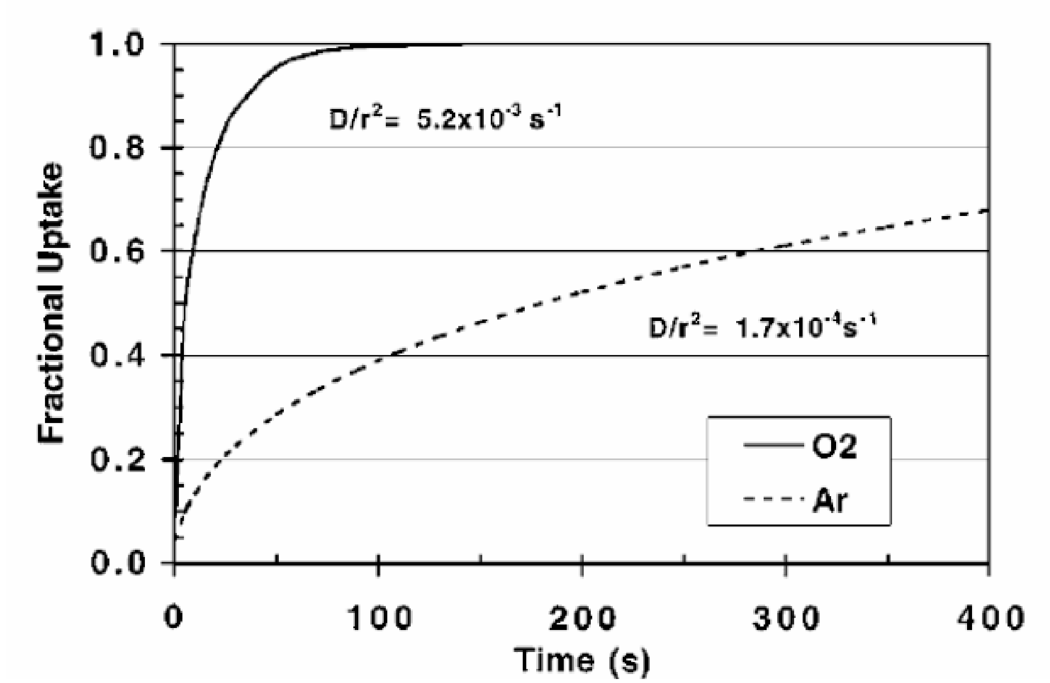

Figure 15: Fractional Uptake vs. Oxygen and Argon for BF-CMS[28]

Unlike equilibrium based adsorption where nitrogen is adsorbed into the molecular sieve, the desired gas oxygen is adsorbed and must be regenerated. As a result the PSA cycle for argon removal differs slightly from that of the system used for nitrogen.

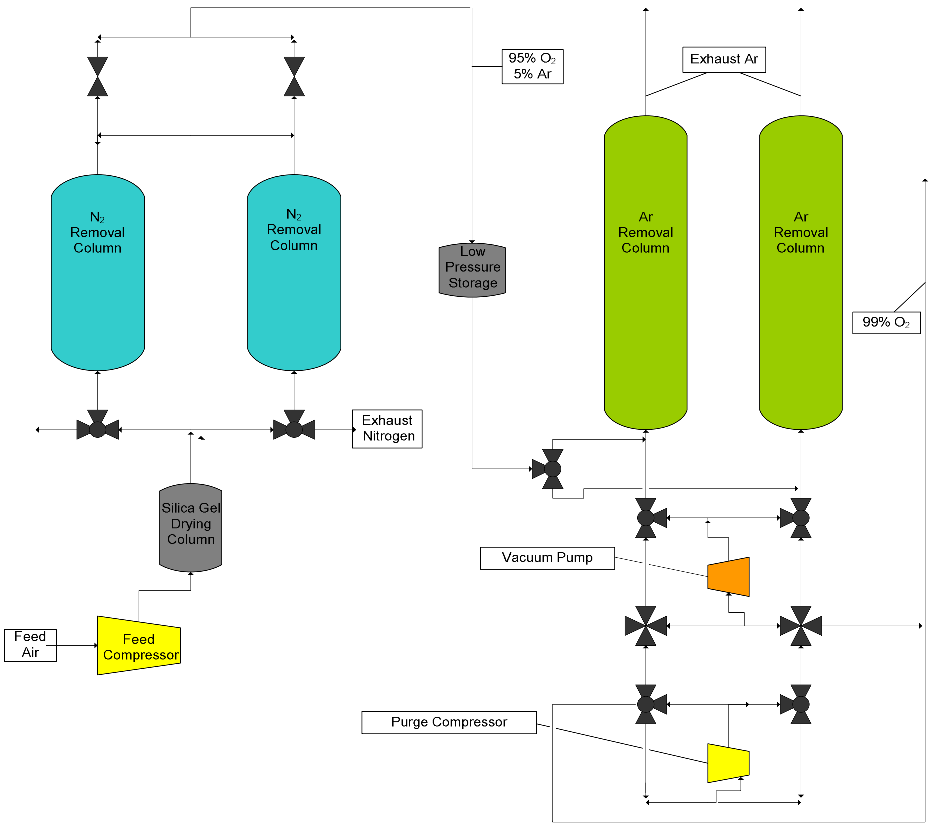

Figure 16: PFD for N_2 and Argon PSA System

Based on the different design options and the performance of each design, the two pressure swing adsorption system was chosen as the design for the oxygen production system. The above process flow diagram was used as the final design. This design was used for cost estimates and for the economic analysis.

3. O_2N-SITE SYSTEM

3.1 Current Hospital Systems

Currently hospitals use bulk liquid oxygen storage systems or compressed oxygen gas cylinders to supply their daily needs for pure oxygen. Liquid systems' main components include one or two large storage tanks, a reserve tank, and a liquid vaporizer. These systems range in size from 13,000 to 75,000 gallons. Larger facilities typically use these liquid storage systems, although some use cylinders. Smaller facilities primarily use cylinders because their need is much smaller and the cost of the bulk liquid system would be a large investment. Cylinders are available in a variety of sizes but the larger ones contain 330 SCF of gas and are about 60 inches in length by 9 inches in diameter.

3.2 Product

Hospitals typically use 1,500 to 3,000 gallons of liquid oxygen per month. This is equivalent to 18 kg per hour which was used in the design of the onsite generator. Purity of the oxygen is regulated by the Food and Drug Administration which requires that medical grade oxygen must be 99.2% pure with all water, carbon dioxide, and hydrocarbons removed. Fire safety standards are set by the National Fire Protection Agency. These standards establish minimal fire safety requirements for oxygen supply systems at medical facilities.[5] These standards include safe instillation location, capacity, materials, and testing.

3.3 Equipment Specifications

3.3.1 Equipment

The operating conditions used by Rege and Yang provide a result of 52.22% oxygen recovery while producing .01157 kg of product oxygen per kg of adsorbent in the bed.[27] Assuming the results of Rege and Yang to be accurate, the necessary amount of BF-CMS needed to provide the necessary 1.24 lb-mol/hr of product oxygen requires 3108 kg. (6852 lbs.) This is enough adsorbent for two columns making each column contain 1554 kg. (3426 lbs.) The volume of each column can then be found using the average molecular sieve carbon density 0.68 kg/L.[28] Each argon removal column will have a volume of 80.7 ft^3 (2285 L) The feed flowrate to the kinetic separation column must be 852 ft^3/hr to compensate for the 52.22% oxygen recovery rate and still supply then necessary 1.24 lb-mol/hr to the hospital.

To satisfy the necessary 852 ft^3 to the argon removal columns the nitrogen adsorption system must produce a 852 ft^3 product stream. Using equations ?? and ?? along with table ? for modeling, a mass of 109 kg (240 lbs.) is required for each nitrogen adsorption column. Assuming the exiting oxygen rich stream is roughly 21% of the feed flowrate the necessary inlet flowrate to the N_2/O_2 adsorption system is 4000 ft^3/hr

3.3.2 Compressors and pumps

The pressure necessary to accomplish equilibrium driven pressure swing adsorption is about three times atmospheric pressure. The initial compression of the feed air from atmospheric to 45 psia is accomplished by a 20 hp Belaire compressor model[29] # 278-5312D. The exiting stream is then decompressed to 2 atm in preparation for entry into the argon removal column. A .02 Thomas hp vacuum pump[30] model # 7011-0008 is used to depressurize the argon removal units down to .2 atm in order to purge the adsorbed oxygen from the column. A small amount of the .2 atm stream is re-compressed to be used as a purge. This is accomplished by a 1/7 hp Thomas pump[30] # 607CD32. An additional tank compressor can be added to fill compressed air tanks. This is of course up to the discretion of each individual hospital. Assuming continuous operation, the system requires 408 kWh per day, totaling a yearly cost of 146680 kWh.

Compressors Breakdown	Price	N_2 Removal	Ar Removal	Combined Costs
Compressors	***$***	***# of items***	***# of items***	***Total Cost***
Feed	5365	1		$5,365.00
Purge	150		1	$150.00
Vacuum pump	100		1	$100.00

Table 8: Compressor Cost Breakdown

3.3.3 System Materials

Aluminum is used to construct each of the adsorption columns, drying canister, and low pressure-storage tank due to its relative durability and inexpensive cost at $1.50/$ft^2$ [28]. The necessary amount of aluminum to construct two 7.2 ft tall columns is 22.6 ft^2 of aluminum. Likewise the argon columns require 259.2 ft^2 of aluminum. Steel is used to construct the frame that will house and hold the entire system due to its ability to withhold the stresses of the massive columns. 290 ft^2 of steel was used at a price of $2/$ft^2$. 16 ft of 1/2" Copper schedule 40 piping is used throughout the system at a cost of $3.61/ft.

Materials Breakdown	Price	N_2 Removal	Ar Removal	Combined Costs
Metal	***$/ft^2***	***ft^2***	***ft^2***	
Adsorption Columns (Al)	1.5	22.60	258.2	$421.20
Low pressure storage tank(Al)	1.5	11.98		$17.97
Dryer Canister(Al)	1.5	24.4		$36.60
Frame (Steel)	2	25	265	$580.00

Materials and Parts Breakdown	Price	N_2 Removal	Ar Removal	Combined Costs
Piping	***$/ft***	***ft***	***ft***	***Total Cost***
1/2" Sch. 40 Copper	3.61	6	10	$57.76

Table 9: Cost breakdown of building materials

3.3.4 Adsorbents

The adsorbents are the most important components in this system due to the fact that this system is based on adsorption. Silica gel is used to dry the air coming into the system. Approximately 52 lbs. of silica gel, at a price of $2/lb, was used in the system. Based on the design equations earlier, the necessary 480 lbs. of Oxysiv 5[31] \remove the necessary amount of N_2 can be purchased at a price $5.5/lb. The $20,555 purchasing cost of 6852 lbs BF-CMS is easily the single most expensive portion of the PSA unit. The large amount of purified oxygen required to service the needs of the hospital coupled with the 52.22% yield rate of BF-CMS contribute to the seemingly large required amount.

Adsorbents Breakdown	Price	N_2 Removal	Ar Removal	Combined Costs
Adsorbents	***$/lb***	***lb***	***Lb***	
Oxysiv 5 adsorbent	5.5	480		$2,640.00
BF-CMS	3		6851.8	$20,555.40
Silica gel	2	52		$104.00

Table 10: Cost breakdown of adsorbents

3.3.5 Other Parts

Other important parts of the system include the various valves involved wit regulating the flow of the gas throughout the different areas of the process. Also used in this design were several fans to make the compression as close to isothermal as possible. A computer was also added to control the system and the valves

Misc. parts Breakdown	Price $/*.item*	N_2 Removal	Ar Removal	Combined Costs
Fan	5	2	2	$20.00
3-way solenoid valve	86	2	2	$344.00
check valve	20	2	2	$80.00
computer	1000	1		$1,000.00
casing	100	1		$100.00

Table 11: Miscellaneous parts breakdown

3.3.6 Additional Costs (based on need)

According to the particular needs of the hospital an additional compressor and high pressure storage tank can be added to the system to supply compressed air to fill cylinders. This may be useful for facilities that have patients who have portable oxygen needs and could be used to fill any cylinders with compressed air to be used as possible backup tanks.

Additional Parts Breakdown	Price $	N_2 Removal	Ar Removal	Combined Costs
Tank fill Compressor	2500		1	$2,500.00
High pressure storage tank	150		1	$150.00

Table 12: Additional parts cost breakdown

This results in a total system cost of approximately $31,571.93, with the additional compressed gas attachments the price becomes $34,221.93. This price is substantially lower than the capital costs incurred when supplying 1.24 lbmol/hr through cryogenic distillation. The operating cost of this system is roughly 17 kW. At a price of $.058/kWh the yearly operating costs for this system are approximately $8,500. The energy breakdowns for this system are listed below

Energy Costs	
$/day	$23.66
$/month	$709.92
$/year	$8,519.04

Table 13: Energy cost breakdown

With a substantially lower capital cost than previous designs and relatively low energy costs, the PSA oxygen purification system is the design around which a market analysis and business plan will be modeled.

4. Marketing and Cost Analysis

4.1 Marketing

4.1.1 Market Need

Research of consumers in the market area established the basis for need of an onsite oxygen generation system. A device of this type would be able to provide a hospital with the large amount of pure oxygen that is required for daily operations. It would also alleviate dependence on medical gas distributors. Disadvantages of purchasing from a supplier include transportation difficulties and the hassle of continual re-ordering of bulk oxygen.

Several consumer factors were identified in designing the system. For larger (1 million standard cubic feet per hour) [22] facilities, the fact that they use a large amount of oxygen could make owning their own production equipment desirable. Also the large facilities would be better able to afford the initial investment of the equipment cost. For small facilities, there would be a reduction of costs associated with transportation of smaller quantities of product, base line fees such as storage equipment rental fees, and the higher rates associated with smaller orders.

The proposed process would provide the customer with equipment that would require minimal operating labor, primarily in system monitoring. There would be no changing of cylinders or hassles of ordering more product. The in-situ process, relying only on utilities, would be more reliable than the competition's due to the fact that it does not rely on transportation. Safety of the system will not play a huge role in consumer purchasing. The equipment maintenance cost for the proposed system would be higher than the competition and also play a role in the demand. A consumer could always order more product but additional expenses and hassle of more frequent ordering would make an onsite system more desirable.

4.1.2 Target Market

Oklahoma has been chosen for the initial market area. It was determined that there are approximately 350 medical facilities in the Oklahoma. This business plan addresses the existing opportunities in the state of Oklahoma, but this plan can be expanded, upon successful initial efforts, to accommodate needs nationally.

4.1.3 Product Need

There were several factors about the market that were considered in designing the onsite system. The oxygen that the proposed process would produce would be nearly identical to that which the competition supplies because it would have to comply with FDA standards of 99.2% purity for medical grade oxygen. This market is characteristic of an oligopoly, in which entering is difficult due to the fact that the limited competition forces companies to sell their product with limited profits. If one company lowers their prices then the others must lower their prices to sell their product. This causes the profit margins on the product to be at a minimum. These sales are also by contract so a consumer can get locked in at high rates while the price of the medical grade oxygen falls. Typically companies operating in this type of market abide by an understanding with their competitors about not reducing prices to the extent that no one profits. There is also consumer resistance to change that would have to be overcome to have the consumer choose this product over their existing system.

4.1.4 Competition

The major distributors in Oklahoma are Airgas, Aeriform, and Air Liquide. Airgas and Air Liquide can provide there customers both compressed cylinders of oxygen and bulk liquid. Aeriform only provides compressed cylinders. The market share that each supplier controls is unknown but their prices are assumed to be very similar due to the type of market that exists in this area. For this analysis it can be assumed that only one competitor exists in this market area.

4.1.5 Demand

The main factors identified that would affect the product demand include the following: convenience of the chosen system, reliability or availability of the product, safety of the system, equipment maintenance cost, and space requirements of the equipment. These factors were assigned weighted values, w_i, the basis of importance to a consumer. These values are shown in Table 13. Convenience was assigned the value of 0.40, since this is the main subjective factor to owning the equipment. Maintenance/operating cost and space were assigned weights of equal value, 0.20, because the associated costs are spread out over a longer time period and are not considered to be as significant. While safety and reliability, assigned a value of 0.10, are very important aspects of a system, they are assumed to be very strong points of all designs and therefore are only considered minimally in product selection. The current onsite generation design and also the competition's systems were assessed on a scale of 1 to 10 according to these categories. Reliability and safety were considered to be approximately the same for all systems. These values, y_i, were then normalized to unity for both the designed system and the competition's system. The products appeal, H_j, was then determined by the relationship,

$$H_j = \Sigma w_i y_i$$

An analysis of these factors was conducted to determine the factor of customer preference, β which is a measure of how much a customer would prefer a new product over the existing product. β can be determined by the following relationship,

$$\beta = \frac{H_1}{H_2}$$

This analysis is summarized in Table 13 and yielded a β value of 0.92.

Factor	w_i	Design Y_d	y_d	Competion Y_c	y_c
Convenience	0.40	9	0.90	7	0.70
Maintenance/Operating Cost	0.20	6	0.60	7	0.70
Space	0.20	6	0.60	6	0.60
Reliability	0.10	9	0.90	8	0.80
Safety	0.10	7	0.70	8	0.80
Total=	1.00	$H_d=\Sigma w_i y_d=$	0.76	$H_c=\Sigma w_i y_c=$	0.70

$$\beta = \frac{H_c}{H_d} = 0.921052632$$

Table 14: Customer Preference Analysis, β

The α function is a function of consumer knowledge and was determined to be a function of the rate of sales visits and word of mouth. During the initial period of startup α would behave as a linear relationship depending on the rate at which the salesman could make visits to potential customers. As sales visits increased, potential customers and customers would become more informed about the system. This would continue through the primary marketing phase. As more potential clients are reached the rate at which new clients would be informed about this new system would start to exponentially decay. Eventually only a few potential clients would remain. The α function established is illustrated in Figure 7.

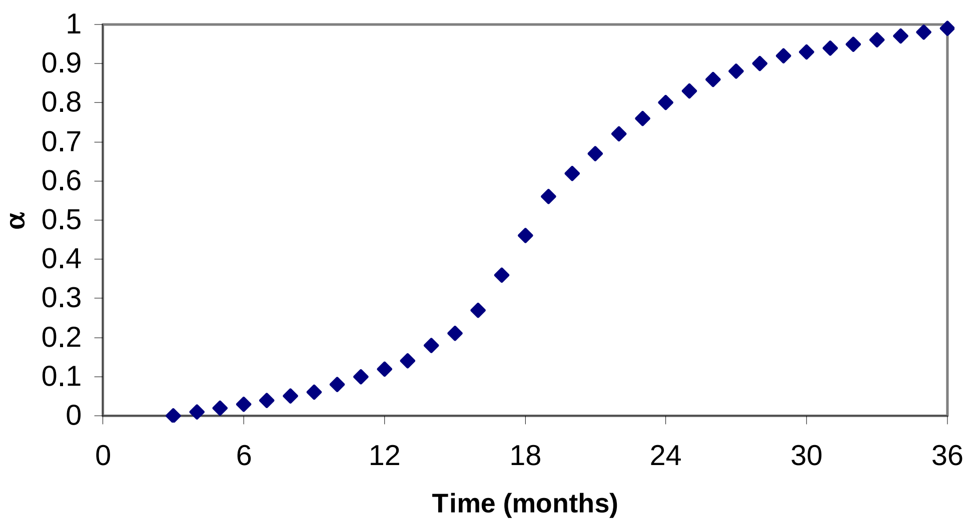

Figure 17: Consumer Knowledge Function- α

Using the Demand Model, a demand for the system was determine to establish an estimated number of units that could be sold. The demand model used is given as follows:

$$p_1 d_1 \beta = \alpha p_2 d_2 \frac{{d_1}^{\alpha}}{{d_2}^{\beta}}$$

where p_i and d_i are the price and demand, respectively, of the proposed design, (1), and of the competition, (2). The equation can be solved for d_1 by using the relationship:

$$d_1 + d_2 = D$$

where D is the total demand or the size of the market which was previously defined to be 350 for this market area. Solving equation 4 for d_2, substituting this for d_2 in equation 3, and rearranging yields the following relationship:

$$d_1 = \frac{\alpha}{\beta} \frac{p_2}{p_1} (D - d_1)^{(1-\beta)} {d_1}^{\alpha}$$

The potential number of sales was then determined by the market share that could be established, with the market share, ϕ, relationship being,

$$\phi = \frac{d_1}{D}$$

4.1.6 Sales

The employed salespeople would conduct sales of the proposed system. Responsibilities of the salesperson would include scheduling sales meeting with potential clients and visiting with approximately 2 clients per week. Repeat visits would also be conducted when requested or periodically depending on the degree of interest in the product.

Due to the behavior of the demand model used, α, the public knowledge of this product, was a limiting factor to sales. Based on the initial α trend, which corresponds to the effort of a single salesperson, it was decided that efforts were needed to increase the knowledge of the product during the initial years of the business. Thus, to optimize the business and the amount of time, seven people will be employed as salespeople initially, and the amount of salespeople will decrease with time. The total number of employees will not change with time, only their employment responsibilities. These changes are tabulated below.

Year	Salespeople*	Fabricators	Units Fabricated/yr	Total Units
1	5	3	36	36
2	5	3	36	72
3	3	5	60	132
4	3	5	60	192
5	1	7	84	276
6	1	7	84	360
7	1	7	84	444

Table 15: Employment Specifications Yearly

*Eight employees will be employed at all times of this business plan.

The new α change with time is shown below.

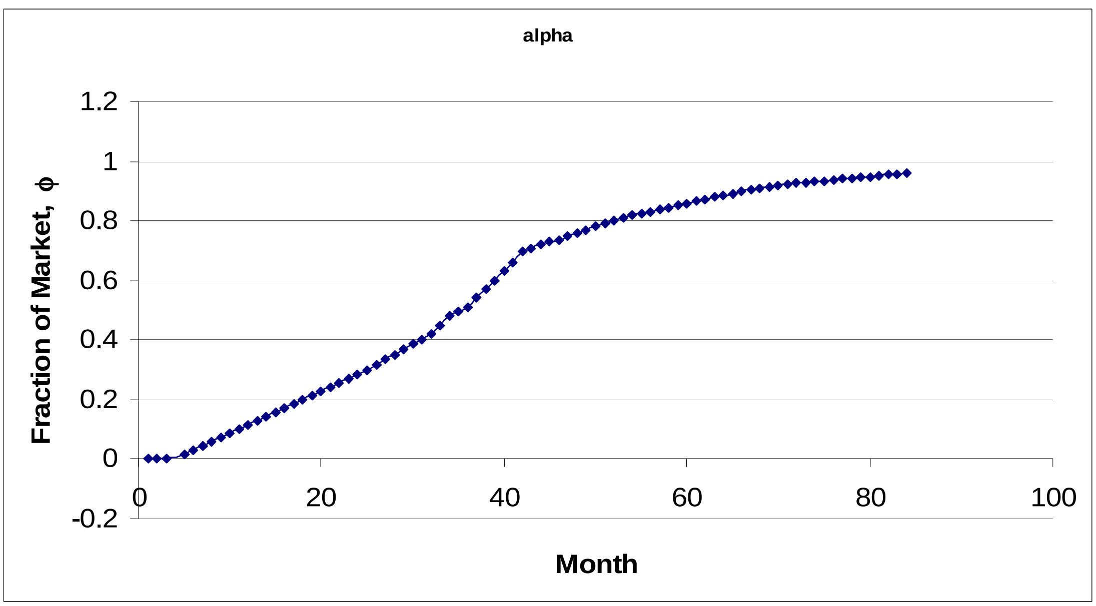

Figure 18: New Consumer Knowledge Function- α

With this alpha and demand model, the number of units sold per year was estimated. The following graph Figure 19 depicts the share of the market that the demand has through the lifetime of the business, which is seven years. The first three years are spent spreading knowledge about the new product. No sales will actually take place until an adequate knowledge of the product exists. Once this public knowledge is reached the public will naturally desire to buy the product, and sales will "sky rocket" as the graph shows. This will occur between the fourth and fifth year.

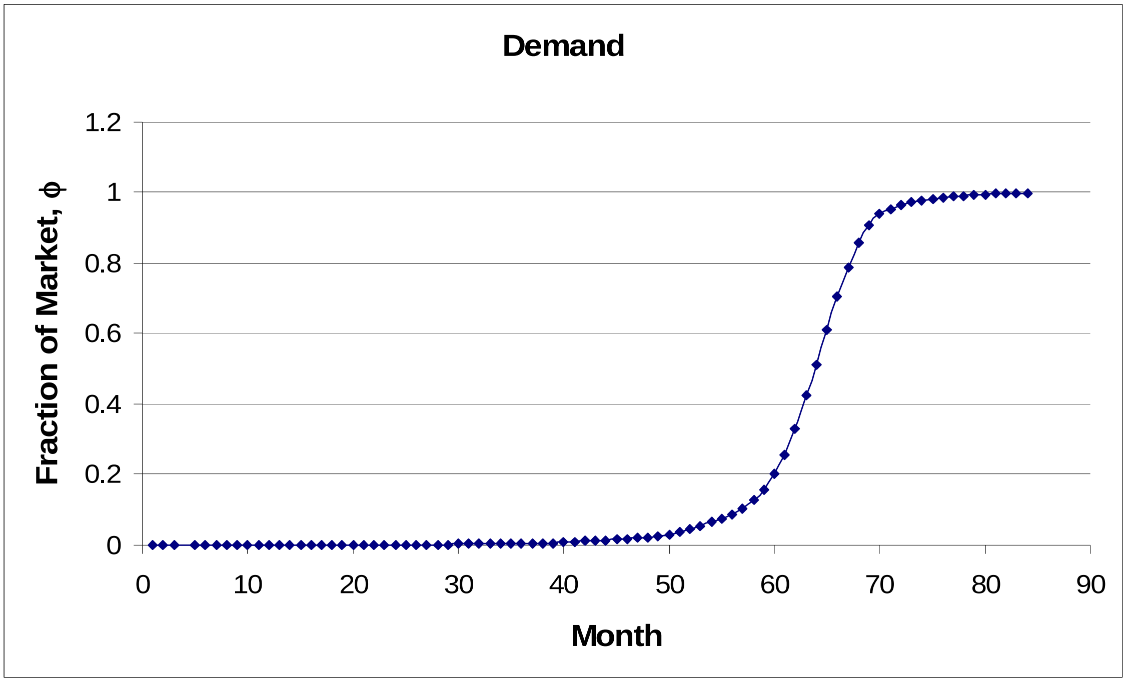

Figure 19: Demand as Fraction of Market per Month

The sales for this business are predicted to reach a saturation point. This means either everyone will be aware of the product and not desire to purchase it or will have purchased it. Equal knowledge of this product to other options will be reached in approximately seven years. The initial sales for the product will be low as knowledge is low. As more people become aware of the product, sales will pick up, most significantly in the fourth to fifth year and climaxing in the sixth year. Within these years, it is predicted that the majority of the products will be sold. By the end of the seventh year, the sales will again decrease to very few. Final prediction for the total number is sales is near 350.

4.1.7 Operations

Production equipment would need to be purchased with the initial investment, and would include welding equipment, various hand tools, a 1 ton truck, flatbed trailer, and office supplies. Due to the variable production rate, the working capital also varied and the rate was determined for each year based on one month's worth of costs. The fixed costs and investments are summarized in Table 2 and Table 3.

Tools	$10,000
Trucks (5)	$90,000
Trailers (5)	$17,500
Clerical Supplies	$2,000
Total	$119,500

Table 16: Fixed Costs

Working Capital		# of units
year 1	$29,571	0
year 2	$29,571	0
year 3	$29,571	0
year 4	$47,071	6
year 5	$210,404	62
year 6	$808,321	267
year 7	$64,571	12

Table 17: Working Capital

Initial operations for the company would allow for eight employees. The primary job of the salespeople would be to conduct the sales activities. The other two employees would be responsible for the fabrication of components, assembly of equipment, instillation of the system, startup, and operator training.

Fabrication would be conducted in one employee's garage until unit sales increased that would warrant the leasing of a shop facility. Final assembly would be conducted on site, since the equipment would be stationary.

4.1.8 Value of Project

A net present value for the project was determined to be \$5,300,000. The project was evaluated for profitability using the net present value formula, NPV, as represented in the following equation,

$$NPV = \sum_{k=1}^{n-1} \frac{CF_k}{(1+i)^k} + \frac{CF_n + V_s + I_w}{(1+i)^n} + -TCI \tag{12}$$

where CF = cash flows for each year

Vs = the salvage value of the initial capital investments

Iw = the total working capital

TCI = the initial investment.

The cash flows were determined by subtracting the operating costs and material costs from the revenue. A salvage value was established to be 25% of the initial capital investment based on experience of the resale of goods.

4.2 Optimization

To optimize the business plan, a selling price index was developed. The sale price index refers to the factor that the material cost for the system were multiplied by in order to determine the selling cost of the system. The selling price index of this product was optimized based on the NPV. An upper limit for the index had to be established, and this was set at the price that guaranteed the customer a yearly savings of 20%, compared to the cost of purchasing gas, \$19,000/year. Each change in the selling price index changed the behavior of the demand model, affecting the units sold and the ultimate NPV. Using Microsoft Excel Solver application along with simple macros, the demand of the product was determined with variations in the selling price index. This optimal price index was found to be 1.9 times the material cost of system fabrication. The NPV for this selling price was determined to be \$3,500,000 over the seven year life lifespan of the business. The optimal selling price of the system is 15,150, reached at the upper limit of the selling price index.

4.3 Risk Analysis

Variability in the NPV was established by considering the variability of operating costs and the number of units sold. These values are summarized in the following tables.

Operating Costs per year		deviation %
Salaries	$280,000	0%
Insurance and Permits	$23,900	20%
Equipment Replacement and Maint.	$11,950	10%
Fuel	$39,000	50%
Total	$354,850	

Table 18: Operating Costs and Deviations

Number of Units sold		
year 1	0	+/- 1 Unit
year 2	0	+/- 1 Unit
year 3	0	+/- 1 Unit
year 4	6	+/- 2 Unit
year 5	62	+/- 15 Unit
year 6	267	+/- 50 Unit
year 7	12	+/- 4 Unit

Table 19: Unit Sales Deviations

A Monte Carlo simulation was conducted that varied these parameters. Approximately 1000 calculations were performed and a histogram of the results was constructed. A risk curve was also obtained by summing the probabilities of the results. The following figure illustrates the results.

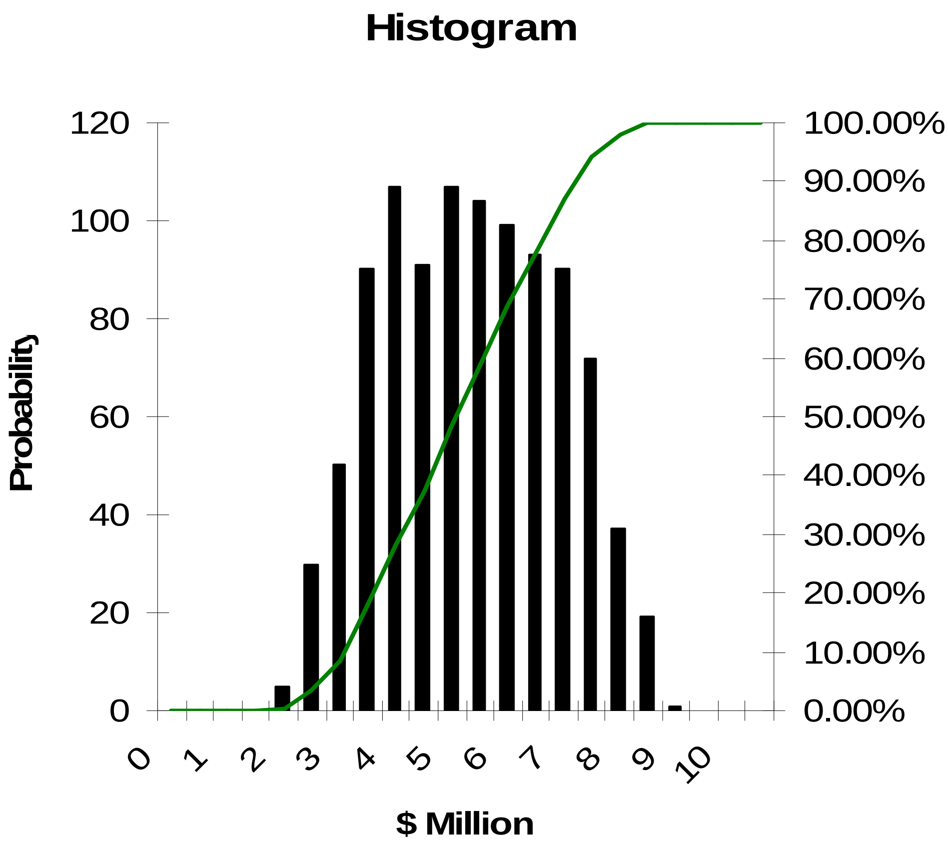

Figure 20: Risk Histogram and Risk Curve

The primary risk involved in the project is the number of units sold. Since this deviation is in whole units there are distinct areas in which the NPV can fall. There is an approximately 0% risk of loosing money by this analysis. This business plan, with sales predicted by the demand model, is a very wise investment.

5. COMPETITOR COST COMPARISON

5.1 Yearly Cost Comparison

Price estimates for what a hospital pays for a month of delivered oxygen were obtained from Airgas Mid South. A large hospital will pay on average $1,500 per month for three thousand gallons of oxygen.[4] Based on these prices a hospital pays roughly $19,000 per year for delivered oxygen. The one year savings would be approximately $5,000, for five years $25,000, and for 10 years, a total of $50,000 saved.

5.2 Industrial Size Plant Profitability

After doing a basic cost analysis of large plants it was found that a large plant producing 150 kg/hr of high purity oxygen can operate with a net profit. This profit is fairly small at roughly $0.02/kg of oxygen; with outputs closer to 2500 kg/hr the process will result in a profit of $0.05/kg of oxygen or one million dollars in profit per year.[20]

MODEL		AKDS-17	KZ-150(just O_2)	KZ-1600	Air liquide
Oxygen Output (averaged)	kg/hr	17	150	1650	2500
Output of Oxygen	kg O_2 /year	148,920	1,314,000	14,454,000	21,900,000
Power consumption	kWh/yr	372300	2102400	16622100	25185000
Operating Cost per year	$/yr	$22,091	$122,610	$966,205	$1,463,709
Revenue from Oxygen	$/yr	$17,240	$152,114	$1,673,249	$2,535,226
Net Operating Profit	$/yr	-$4,852	$29,503	$707,044	$1,071,517

Table 20: Operating costs and Revenues for Various Plant Production Rates

These larger plants have operating costs of approximately $1.5 million per year based solely on energy requirements. However, their revenue from oxygen sales alone for one year is over $2.5 million.[20]

An output of 17 kg/hr of oxygen will result in a net loss from the energy expenses required if only the oxygen is sold. The operating cost for such a plant will require roughly $22,000 per year while only producing $17,000 per year from oxygen sales. Thus at lower production rates the sale of oxygen alone is not enough to make the process profitable.[20]

5.3 Future Work

Suggested future work includes further investigation into the final cryogenic process designed in this project. This process was feasible in that its operating costs were estimated to be below the current cost of gas distribution prices. However, the capital costs are high. Study could be done over the development of this process with a minimal capital costs. Alterations to lower capital costs include using different refrigerants gases and optimizing compressor usage to insure economical compressor prices.

6. Conclusions

- A design incorporating two pressure swing adsorption systems, one for nitrogen and one for argon, is the recommended device for producing oxygen in a hospital that typically uses 3,000 gallons of liquid oxygen per month.
- The selling price of this system is $66,500, with yearly operating costs of $8,500 resulting in an average yearly savings for the hospital of approximately 20%, or $5,000.
- A risk analysis, by Monte Carlo simulation, for an onsite oxygen generator was estimated to have a 0% probability of losing money. The average net present value was determined to be $5.3 million, with a minimum of $1.8 million and a max of $8.7 million.
- Small scale design of cryogenic generator was successfully simulated in Pro/II but the economical analysis revealed that the capital costs for a process that performs within energy requirements was beyond the typical scope of a hospital.

7. REFERENCES

[1] Uigi. <http://www.uigi.com>.

[2] Air Products. <http://www.airproducts.com>.

[3] Perry, Robert H. and Don W. Green. Perry's Chemical Engineers' Handbook Seventh Edition. McGraw-Hill Professional, 1997.

[4] Airgas Mid South. 1225 West Reno, Oklahoma City, OK 73106. Phone 405-235-0009. Product pricing and quantities of oxygen and nitrogen.

[5] Nation Fire Protect Standards, NFPA 99 Standard for Health Care Facilities, 2002 Edition.

[6] GardnerDenver. <http://www.gardnerdenver.com>.

[7] Noble, Richard D. and Patricia A. Terry. Principles of chemical separations with environmental applications. New York : Cambridge University Press, 2004.

[8] Sisiwardane, Ranjani. et. Al Adsorption and Desorption of CO_2 on Solid Sorbents. U.S. Department of Energy: National Energy Technology Laboratory.

[9] Ruthven, Douglas M. Sorption of Oxygen, Nitrogen, Carbon Monoxide, Methane and Binary Mixtures of these Gases in 5A Molecular Sieve. Fredericton, N.B. Canada: Department of Chemical Engineering , University of New Brunswick, 1976.

[10] Peters, Max S., Klaus D. Timmerhaus, and Ronald E. West. Plant Design and Economics for Chemical Engineers. 5th Edition. Boston: McGraw-Hill Professional, 2004.

[11] Welty, James. R, et al. Fundamentals of Momentum, Heat, and Mass Transfer. 4th ed. John Wiley & Sons, Inc. 2001. U.S.A.

[12] Hajoca Corporation. 2100 S. Western Oklahoma City, OK, 73109. Phone 405-634-6200. Aluminum Pipe pricing.

[13] Delta Adsorbants.<http://deltaadsorbents.thomasnet.com>.

[14] DeWallace Technical. 19 Albany Street, Worcester, MA 01604. Phone 1-800-868-0969. Valve prices.

[15] API Heat Transfer. 2777 Walden Avenue Buffalo, NY 14225. Phone 1-877-274-4328. Heat Exchanger pricing.

[16] Wheeler Metals. 3100 W. 40th St. N Hwy 69 North and Arkansas River Bridge Muskogee, OK. 4ft X 8ft Aluminum & steel sheet metal. 1ft diameter pipe prices.

[17] Sulzer Chemtech U.S.A. Inc. Tulsa, OK. Phone 1-281-604-4100. Column Internals prices.

[18] Flynn, Thomas M. Cryogenic engineering. 2nd ed., rev. and expanded. New York : Marcel Dekker, 2005.

[19] OG&E. Electrical costs.<http://www.oge.com/es/bc/customer-rates.asp>

[20] Usykin, I.P., et al. Plant and Machinery for the Separation of Air by Low Temperature Methods. Design Atlas. Usyukin, Ed. Pergamon Press. New York.

[21] Encyclopedia of Chemical Technology, 4th ed. Vol. 1 A to Alkaloids. John Wiley & Sons, Inc. 1991.

[22] Barron, Randall F. Cryogenic systems. New York : Oxford University Press, 1985.\

[23] Adoca. <http://www.adcoa.net>.

[24] Electrolysis of Water <http://hyperphysics.phy-astr.gsu.edu/Hbase/thermo/electrol.html>

[25] Lide, David R. editor-in-chief. CRC Handbook of Chemistry and Physics. 79th ed. CRC Press LLC, 1998-1999.

[26] Turnquist, Rick. Sales Engineer, RIX Industries. RIX 2JS4B-150 Breathing Air Compressor quoted, April 2006.

[27] Rege, SU., RT Yang. Kinetic Separation of Oxygen and Argon Using Molecular Sieve Carbon. Ann Arbor, Mi: Springer, Adsorption pp 15-22, 2000

[28] Bortka, Adam., et al. Portable Oxygen Device Design: Membrane and Pressure Swing Adsorption Technology Alternatives and Market Analysis. Norman: Submitted to Dr. Miguel Bagajewicz, 2005

[29] PSA Compressor costs < http://www.industrial-air-compressors.com/ >PSA Compressor and

[30] Pump costs < http://www.rtpumps.com >

[31] Oxysiv 5 data < http://www.uop.com >