Membrane Separation of Air to Produce Oxygen

Technical Report Submitted to:
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Table of Contents

Table of Figures

Table of Tables

1.0 Executive Summary

The objective of this project is to determine if the production of a ceramic oxide membrane unit for separating oxygen from air is a profitable alternative to the production of oxygen storage units. Design was based on the requirements of the 30 million Chronic Obstructive Pulmonary Disease (COPD) sufferers, for whom the unit is designed to help. The unit must be portable, provide adequate battery life, and provide 95% oxygen at a minimum of 5 Liters/minute. In addition, the unit was compared to leading competitors in the market that produced portable oxygen concentrators that yield 5 L/min flow rates. These competitors are the Inogen One, Airsep Lifestyle, and Airsep Freestyle. In the report, a design of a ceramic oxide membrane unit was designed and priced, and a risk analysis for production as well as plant design was proposed.

A compact unit measuring 12.2 inches long, 15.2 inches tall, and 9.5 inches wide at a weight of 9.94 pounds was designed for use with a 12 volt source. Based on research, a 4 hour Lithium Ion battery was the source of power in the unit. It produces a minimum of 5 L/min of oxygen with 99.9% purity at a temperature of 298.15K through the use of a BICUVOX membrane. BICUVOX ($Bi_2Cu_{0.1}V_{0.9}O_{5.35}$) is a ceramic oxide that transports oxygen through the membrane through ionic conductivity. The Copper Vandate has as an anion-deficient Perovskite-like crystal structure that is advantageous to the movement of oxygen anions through vacancies, or defects, in its crystal lattice. The selling price of the unit was determined to be $6500 using consumer pricing theory.

Risk analysis was conducted on the best of three scenarios based on the level of involvement in the production of device components in house. The scenarios are the manufacturing of all device components, manufacturing only the membranes and heat exchangers, and finally manufacturing only the heat exchangers. For each scenario a probability of 20% was assigned to all raw material prices. After conducting the scenarios, it was found that the processes of producing only the heat exchangers produced the best results. The other options were not profitable, while producing the heat exchangers and buying the other equipment showed the potential for profitability. Unfortunately, based on the financial analysis done, this product is not profitable at this time. The costs associated with constructing it, while taking into account the competitions model and selling price, proved to be too large. As membrane technology grows, membrane based oxygen generators will most likely seize the majority of the market from pressure swing absorption systems.

2.0 Introduction

2.1 Statement of Purpose

This project is intended to produce a device that will deliver therapeutic oxygen supplement to persons suffering from Chronic Obstructive Pulmonary Diseases (COPD) and other ailments of the pulmonary tract. The device is to be portable with the capacity to deliver a stream of nearly pure oxygen at a rate of 5 L/min. Many treatment methods are currently available for sufferers of COPD. However, the reliability, safety and cost of these options tend to outweigh the benefit. In the design of the device care must be taken to ensure that a reliable, safe and cost effective product is designed and introduced to the consumer.

2.2 Chronic Obstructive Pulmonary Disease

According to the Center for Disease Control[1] (CDC), there are approximately 24 million people in the United States alone that have some form of COPD. These conditions include asthma, chronic bronchitis and emphysema. In the United States, according to the American Lung Association, COPD is the fourth ranked killer behind heart disease, cancer and stroke[2]. Currently there are no cures for these ailments and many patients must be placed on lifetime oxygen therapy (LTOT) for relief from their respiratory distress. With the aide of supplemental oxygen therapy, many of these patients can still live healthy, normal lives.

COPD is primarily a disease that affects the elderly, especially those with a history of tobacco use; however, people of any age can be diagnosed with the disease in one of its many forms. The following chart from the National Heart, Lung and Blood Institute[3] shows the distribution of COPD sufferers by age group, sex and ethnicity. Oxygen needs will vary based on the severity of the disease. At onset, COPD patients may need only sporadic oxygen after strenuous activities. As the disease progresses oxygen may be necessary 15 to 24 hours per day. A minimum concentration of 35% oxygen is necessary to provide any benefit, while many patients require above 90%. Most importantly, oxygen therapy can increase the life span of COPD patients by 6 to 7 years. The effectiveness of oxygen therapy is dependent upon the disease, reaction of the patient, and other drugs the patient is taking.[22]

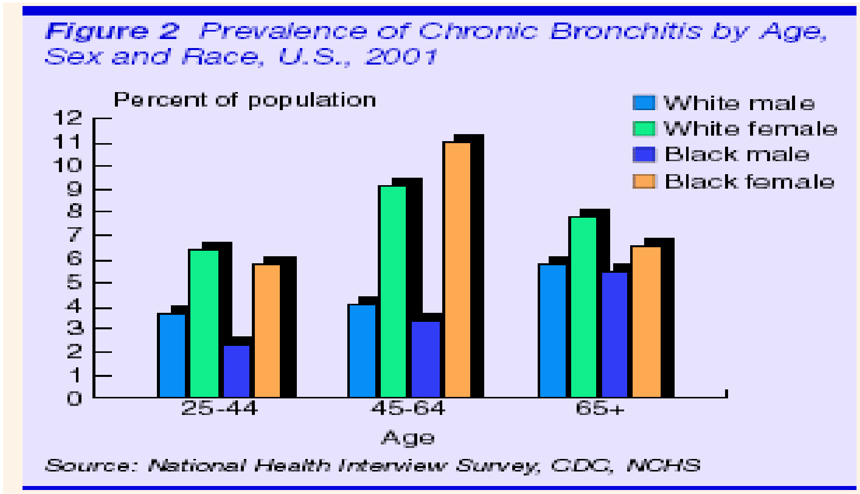


Figure 1: Percent of Population Diagnosed with COPD by age, sex and race[3]

3.0 Current Suppliers of Supplemental Oxygen

3.1 Compressed Bottled Oxygen

Bottled oxygen is the primary source for supplemental oxygen therapy users. This method is the oldest and most trusted form of oxygen delivery system stemming back to the early 1900s. Bottled oxygen supplies for portable use by oxygen therapy patients have limitations and restrictions that need to be addressed to produce a product that caters to the needs of its users. The foremost is the reliance on tank refilling personnel that must make routine visits to the patients' homes. The need for autonomy is one of the greatest freedoms that patients can achieve, living fuller lives without the reliance on others to fulfill appointments and ensure a continuous and uninterrupted supply of oxygen.

Figure 2. Nasal Cannula[3]

Typical bottled oxygen tanks hold about 164 L of compressed oxygen. At a flow rate of 5 L/min these tanks will exhaust themselves in a little over half an hour. It is imperative; therefore, that the patients have many backup cylinders on hand and that supplies are not cut off by the vendors. The most common cylinder in use for oxygen therapy is the M-6 or B rated cylinder which is pictured below[4].

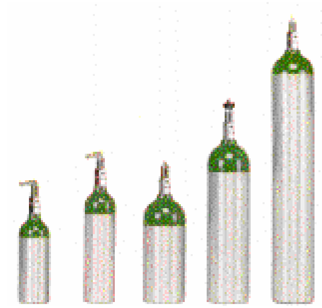


Figure 3. Oxygen Tanks

To allow the patient longer use life of their oxygen bottles, many companies produce conservers that allow the flow of oxygen only during inhalation. Depending on the conservation ratio, the time available for use on a typical M-6 cylinder can be increased by 500%, or approximately 2.7 hours[4]. This is still a relatively small amount of time for oxygen delivery. The finite volume contained in the cylinders will not allow the patient to venture far from a refill station or their homes without taking additional cylinders with them.

Compressed oxygen cylinders can also pose a substantial safety risk for their patrons and those around them. Cylinders can be pressured up to 2000 PSI, which, if dropped, can turn into a deadly projectile. If the valve or regulator is upset or damaged compressed gas can evacuate the cylinder rapidly, propelling the cylinder at high velocity without a means for control.

As figure 3 shows, there is no specific size of oxygen tank. Catalina Cylinders offers tanks ranging from 34 liters of oxygen to 680 liters, with weights of 0.7 lbs and 7.9 lbs, respectively. The largest tank offers approximately 2.25 hours of direct, 5 L/min oxygen feed. This can be increased greatly with an inhalation only feed. However, it is just over 2 foot tall.

3.2 Liquefied Bottled Oxygen

Liquefied oxygen supply is comparable to compressed oxygen cylinders in as much as the patient must cater to the supplier's time frame in order to refill their cylinders. Liquid cylinders typically weigh slightly more, but will last longer under typical circumstances. However, liquid oxygen will evaporate and the bottles constantly vent, therefore, if the cylinders are not used they will still deplete in quantity over time[5]. Liquefied oxygen cylinders also pose a substantial risk due to the cryogenic temperatures that are needed to cause oxygen to condense into the liquid phase. The temperature required to maintain oxygen in the liquid phase is below -183°C. This is extremely dangerous in the event that the cylinders leak or there is an accident during home refilling. Such low temperatures can cause irreparable tissue damage in a matter of moments.

3.3 Oxygen Concentrators

There are a number of new and emerging companies that have taken on oxygen concentration as an alternative to cylinder gasses. Oxygen concentrators are any number of devices that separate oxygen from air. Because concentrators separate the oxygen from air instead of storing and transporting it, they can operate virtually anywhere without worry of running out of oxygen. Concentrators do, however, run on electric power which makes them susceptible to power outages and/or battery lifespan. Many of the products currently on the market are rather bulk and weigh in excess of 50 lb. With the additional bulk, comes additional cost. Many of the concentrator units are priced in the range from $2000-$5000. The high price and heavy dependence on electrical power hinder concentrators from replacing traditional tank systems as the primary pathway for oxygen therapy. Additionally, most concentrators cannot achieve 5 L/min of oxygen, and the purity generally falls around 90-95%.

3.3.1 Portable Oxygen Concentrators

There are only two competitors in the portable, tank-less oxygen therapy market: Airsep Lifestyle & InogenOne System. Both operate using pressure swing absorption. The Airsep Lifestyle weighs in at 9.75 pounds, with a battery life of 50 minutes, and provides 1-5 L/min of 90% pure oxygen.[23] The InogenOne System weighs 9.7 pounds, with a 3 hour battery life, and provides 1-5 L/min of 90% pure oxygen.[24]

3.4 Criteria and Need for Design

The devices listed above all contain fundamental flaws in their design, application, safety, cost or any combination thereof. Because of the flaws in these systems there is an opportunity to develop a superior system that provides the consumer with a well designed, safe and cost effective alternative.

Recent advances in fuel cell technology have paved the way for new materials to be implemented into the design of such a device. The application of solid oxide conducting membranes into an oxygen concentrator vastly improves the quality of these devices while allowing the consumer a wider selection of delivery systems. The device to be built must provide the consumer with a quality product that remains reliable at a competitive price. This study investigates the feasibility of designing such a device while keeping the customer in mind.

3.5 Solid Oxide Membranes

Solid oxide ceramic membranes are not governed by the equations of typical transport of permeable membranes, since the driving force is not a pressure or diffusivity difference on the respective sides of the membrane. Oxide membranes conduct species through the electrolytic material by surface reaction at the cathode to form O^{2-} ions. The ions are then transported through the material via defects in the material known as oxygen vacancies. The vacancies are atomic level defects in the packing arrangement of the material which can be equated to holes in the matrix the size of an oxygen atom or ion. The oxygen ions formed in the surface reaction move through these holes toward the anode of the cell. At the anode, the oxygen ions react again with electrons to form molecular diatomic oxygen.

Since the separation and diffusion of oxygen through the membrane does not rely on pressure concentration differences across the material, there is no need to pressurize the feed or pump away the permeate stream to continue the reaction. The driving force is the potential gradient created by the electrical current.

There are many types of ceramics currently being investigated for use in these applications. Of these, the most popularly investigated ceramics are common zirconias[7], typically stabilized with a low percentage of yttria. There are also other common ceramics that are lumped into a category called Perovskites. Perovskites are any of a group of materials that exhibit a structure similar to perovskite[8], $CaTiO_3$. The Perovskite structure is shown in figure 4, where the small red dots represent oxygen, the medium size blue dots are the small metal cation, and green dots represent the large metal cation. Perovskites are anion-deficient. Therefore, there are gaps in the locations of the red dots, or oxygen. This allows the oxygen move through the structure in the defects. Although BICUVOX is not a member of the Perovskite group, it acts similarly. There are two layers, BiO_2^{2+} and $V_{0.9}Cu_{0.1}O_{5.35}$, that are interleaved. The later is the Perovskite-like layer, having a similar ABO_3 structure. By substituting the 10% copper for the vanadium gives the Perovskite form. This also prevents the vanadium from lining up, preventing anion movement.

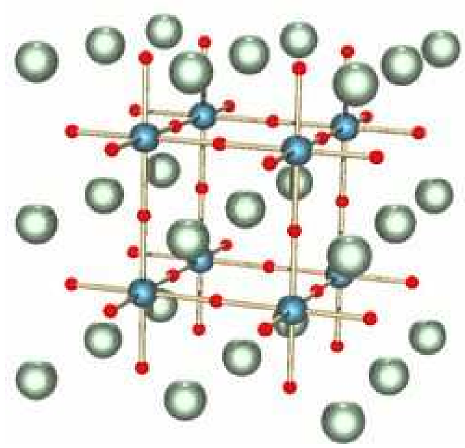


Figure 4. Perovskite Structure

There are also emerging materials being investigated for these purposes. Of the emerging materials, bismuth vanadates have shown potential at lower temperatures than other materials presently under study. Bismuth vanadates, such as Bicuvox.10, are ceramics that have part of the vanadium substituted by metals such as zinc or copper. According to Xia[9] et al, Bicuvox.10 shows ion conductivities 50-100 times larger than other common oxide materials.

The membrane is the limiting technology. As membrane technology advances, the size of the unit will decrease, as will the power needed. The oxygen therapy market does not facilitate the necessary research, at least from a financial standpoint. However, membrane technology is not limited to oxygen generation. These materials are being extensively tested for their application in fuel cell technology.

4.0 System Design

4.1 System Description

The overall system to produce oxygen from air using ion exchange in a BICUVOX membrane consists of seven main components: two Thomas G12/07-N feed pumps, two heat exchangers, one 12V current source, a membrane stack, and three nichrome heating wires in the air stream. A diagram of the system showing these components is shown in figure 5.

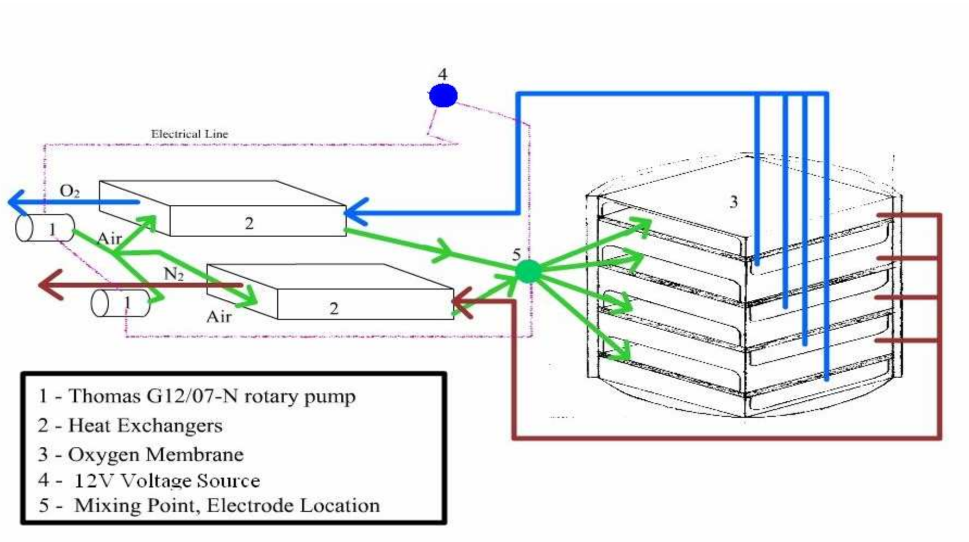


Figure 5: System Overview

The process for the system may be described briefly as follows. Air is fed from the two pumps, each producing 11.9 L/min (STP) which flow into a series 620 binary fixed flow splitter[19]. From the splitter the air is fed to the two heat exchangers where it interacts countercurrently with oxygen or lean air (LA, 99% nitrogen) depending on the heat exchanger. After the air has been heated by either the oxygen or LA lean air in the heat exchangers it is mixed into a single air stream. At the mixing point of the two streams, three nichrome resistance wires are placed across the channel opening to heat the air stream further. Once the air stream has been heated by the nichrome resistance wires to a temperature of 831.15K, it is passed through a BICUVOX membrane where the air stream is separated into oxygen and LA lean air with 100% efficiency. Out of one side of the membrane comes oxygen with a flow rate of 14.11 L/min, and out of the other side comes lean air with a flow rate of 69.91 L/min. The LA lean air and the oxygen are then fed back into the heat exchangers to interact with the feed air so that an exit temperature of 298.15K is reached for both the LA lean air and oxygen streams. The LA lean air exits the system at a flow rate of 24.76 L/min and the oxygen exits at 5 L/min.

The pumps are connected to the heat exchangers, and the heat exchangers are connected to the membrane with 1/8 inch O.D. seamless stainless steel tubing with a 0.035 inch wall[20]. An electrical system gives power to both pumps, the heat exchanger, the nichrome resistance wire, and the inconel electrodes embedded within the membranes. In addition, a feedback control system allows for control of temperature in the membrane stack and control of the oxygen concentration. The control system is programmed to allow for a low oxygen and low temperature alarm. An LED located on the outside of the unit lets the user know if the operating temperature is too high or the oxygen concentration is too low.

4.2 System Process Flow Diagram

Figure 6 shows the layout of the system (not to scale), along with the insulation, cushioning, radiation shield, and temperatures at certain points throughout the system.

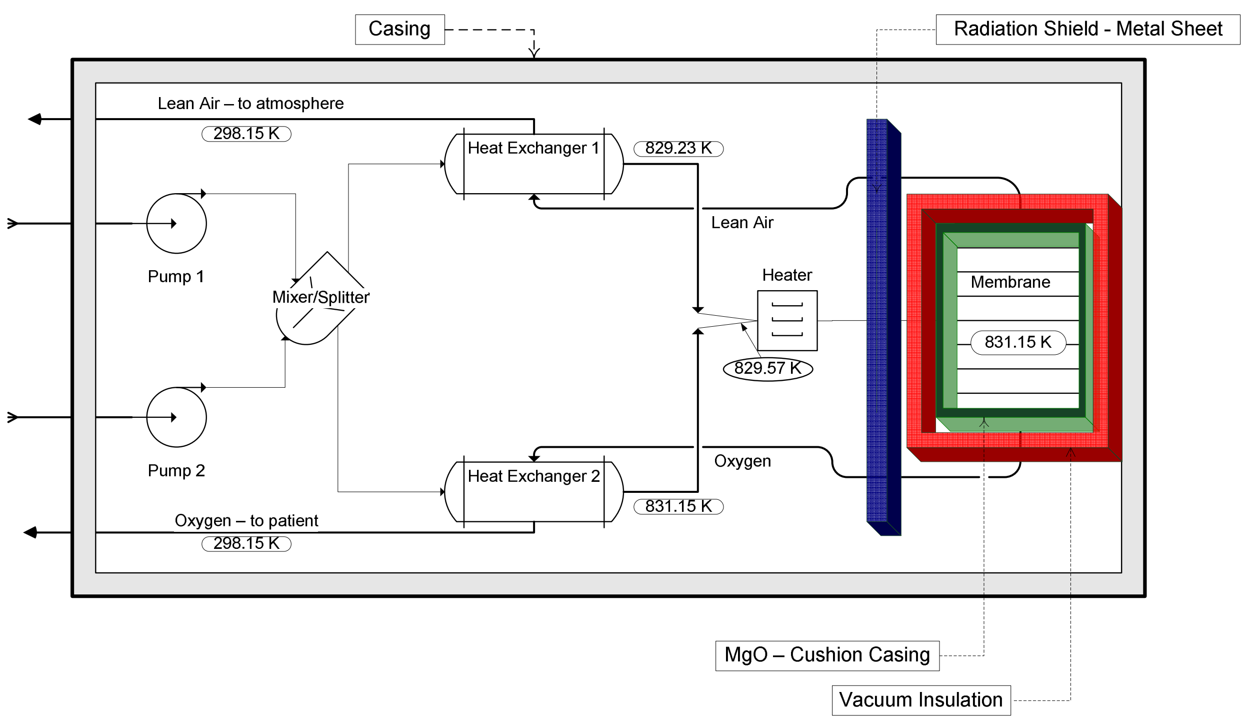


Figure 6: System PFD

5.0 Device Component Descriptions

5.1 Membrane Specifications

5.1.1 Sizing Membrane Components

Since the typical driving force equations for permeable membranes do not apply in the case of solid oxide cells, different equations must be used to size the membrane sheets. To accomplish this, electrochemical equations will be employed. The separation is driven by the availability of electrons to react with the oxygen in the air and therefore, the current needed to achieve the separation must be found. To find the required current the Faraday expression Law is used as follows:

$$I_m = \frac{4QF}{n} \quad (1)$$

Where Q is the molar flow rate required, F is the Faraday constant, 94685 Coulombs/mol electrons, n is the number of membrane sheets that are employed, and the 4 refers to number of moles of electrons needed per mole of oxygen. The cells in this device are arranged in parallel and therefore the current found from equation (1) is a constant in all of the membrane cells.

To determine the area required for the desired separation to occur, the current density of the material must be known. According to Xia[9] et al Bicuvox.10 has been shown experimentally to produce current densities for BICUVOX.10 in the range from 0.3 to 1 A/cm^2, with a value of 0.75 A/cm^2 is a logical assumption. Dividing the result of equation (1) by the current density gives the total membrane area required. Dividing this result by the total number of cells in the device will give the area required per membrane.

The voltage drop across the membrane cell is determined using the Nernst Potential equation:

$$E = \frac{RT}{zF} \ln \frac{y_{O_{2,h}}}{y_{O_{2,l}}} \quad (2)$$

Where z is the valence of the ion, R is the ideal gas constant, T is the operating temperature, F is the Faraday constant, y is the concentration of oxygen, and h and l refer to the high and low concentrations, respectively.

The sizing of the membranes is only dependent on the charge density and the surface area. The thickness of the membranes can be chosen arbitrarily because the charge density is a function of the surface area only. The surface charge density also does not change depending on the distribution of the surface area. With a fixed amount of charge on a surface, and an area A, if the surface is broken into new fractions then the charge will also break in the same proportion and the charge density will remain constant. There is a limitation, however, in the usable thickness of the membrane sheets. Sheets that are too small will show poor mechanical properties, making them susceptible to fracture and crack formation. It has been suggested that these properties begin to show up around 0.36 cm. However, this is not proven, and the actual fracture-prone thickness may be a function of some other property.

5.1.2 Membrane Stack Design Results

The membrane stack will is proposed to be composed of the ceramic oxide membrane, Iconel electrodes, and airflow channels constructed between the membranes on both sides. The surface area required per membrane cell is found from (1) to be 12.87 cm^2. This gives a side length of square cells equal to 3.59 cm or 1.41 in. The thickness of the membranes was set at 0.38 cm. This corresponds to a volume of ceramic equal to 187.2 cm^3. Using an estimate for the density based on average values for ceramic materials, 6.56 g/cc[10], a weight of electrolyte was calculated to be 2.7 lb. The Iconel electrodes are set at 0.1 cm thick with the same surface dimensions as the ceramic components. There will also be air channels above and below each of the membranes to provide air flow to the unit and to carry separated oxygen to the patient. The air channel height is set at 0.5 cm. The total height is calculated to be 16.9 cm or 6.65 in. without insulation or the inner casing materials. All of these numbers can be seen in table 1. This splits the data into source (taken from Boivin et al.), spec – something that can be varied, or calculation. Unfortunately, BICUVOX is a relatively new technology. Although there is most likely a large amount of data regarding its performance, it is not readily provided at this time. Eventually this proprietary information will likely be made public. The basis for our model was *Electrode-Electrolyte BIMEVOX System for Moderate Temperature Oxygen Separation*, J.C. Boivin, et al.[25]

Table 1. BICUVOX Membrane Specifications[25]

number of plates	208	*Source*	plates
Temperature	550	*Source*	C
total volumetric flow rate of permeate	5	*Spec*	L/min
molar gas volume (STP)	24.04	*Calc*	L/mol
molar flow rate of permeate/plate	0.00002	*Calc*	mol/s/plate
electron stoichiometry	4	*Source*	mol electrons/mol O2
Faraday constant	96485	*Source*	C/mol electrons
Current	6.431	*Calc*	A
current density for BICUVOX.10	0.75	*Source*	A/cm2
total plate area required	12.87	*Calc*	cm2
side length of square plates	1.41	*Calc*	in
thickness of plates	0.38	*Source*	cm
air gap height	0.5	*Source*	cm
Electrode height	0.2	*Source*	cm
total cell stack height	287.24	*Calc*	cm
number of columns	4	*Spec*	
height per column	6.65	*Calc*	in
electrical potential for each cell	0.057	*Calc*	V
total potential for stack	11.923	*Calc*	V
power required	76.675	*Calc*	W

The height is based on the structure shown in figure 7. It is a patented design by the U.S. Air Force. It allows for the same membrane height in a smaller area. The air will enter through the hole in the middle, diffuse through the membrane, and oxygen or lean air will exit on its respective side. If this design was not chosen, a membrane height of about 25 inches would be necessary.

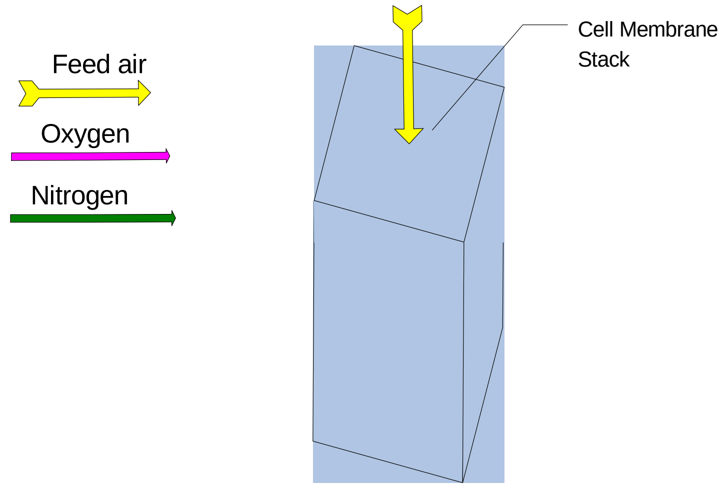


Figure 7. Membrane Stack Design

5.1.3 Additional Membranes Considered

In addition to BICUVOX ($Bi_2Cu_{0.1}V_{0.9}O_{3.5}$), several other membranes were considered for use. These included Yttria-Stabilized Zirconia (YSZ), Samarium Doped Ceria (SDC), and Strontium and Magnesium Doped Lanthanum (LSGM). The basis for choosing a membrane took into account several factors: ionic conductivity, operating temperatures, and size. In figure 8, the four membranes are shown on a graph of ionic conductivities versus the temperatures. It is obvious that BICUVOX has a high conductivity at lower temperatures than any of the other membranes. When the operating temperature is irrelevant, SDC at 900°C and LSGM 800°C can both show similar ionic conductivities to that of BICUVOX at 600°C. However, rarely, if ever, is operating temperature irrelevant.

Another option is Gadolinium Doped Ceria (GDC). It shows slightly better conductivity than SDC and is capable of operating at lower temperatures. However, the conductivity is not great enough to justify the additional costs, $100/kg, in the current system.[21] Additionally, it does not compare to the conductivity of BICUVOX. BICUVOX was chosen based on these criteria, and appears to be, at least currently, the future of oxide membranes. However, with most of these membranes being explored by the rapidly growing field of fuel cells suggests that advancement of membrane technology should also grow rapidly in the future.

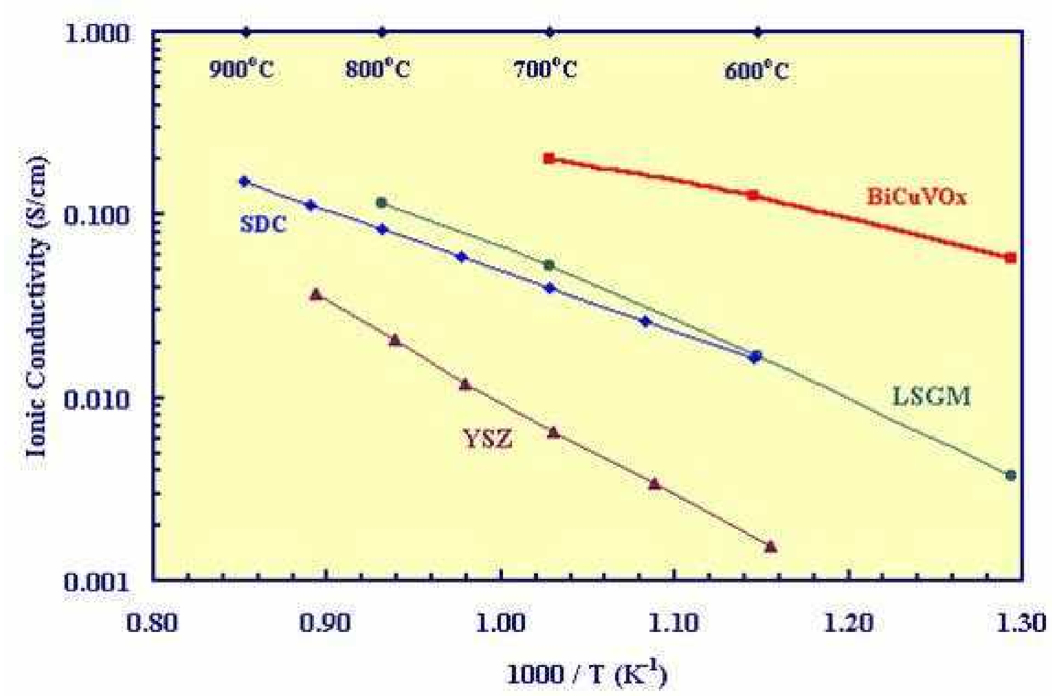


Figure 8: Variation of Ionic Conductivity with Temperature and Electrolyte Material[22]

5.2 Internal Casing

A Magnesium oxide casing will be used around the membrane stack as a cushion to prevent damage during transportation. The magnesium oxide will also provide a smooth, solid surface on which to bond the insulation. The membrane cell stack must be supported to ensure that it is not damaged due to sliding about as the device is transported. Also, there is a need for a smooth, solid surface on which to bond the vacuum panel insulation. Magnesium oxide is used to perform this function in the device. There is not a need for a large amount of material; the thickness of the sheet is arbitrarily set at 0.5 cm. The inner casing's purpose is to provide a bonding surface for the sealant to the insulation. This material has been selected because of its mechanical properties and low cost. The mechanical properties of this material, including thermal expansion coefficient, are similar to those of the membrane stack and the insulation. The thermal expansion coefficient of MgO is $10.8*10^{-6}$/°C. This value is in the range of expected values of the membrane stack and will not cause additional stresses to the cells. This material is also fairly inert and poses no risk to the health of the consumer[11]. According to the MSDS on MgO, the only risk associated with this material is in the event of crushing or grinding to a powder, which may produce small solid particles that can become airborne and ingested or become an eye irritant. The use of the sealant and insulation materials will prevent the magnesium oxide from crushing and becoming a safety hazard.

5.3 Heating Element

The design of this device requires that the membrane stack be heated to 550°C (before oxygen flux begins. To achieve the desired amount of heat transferred to the cell stack and the incoming air; three Nichrome wire heating elements are placed across the incoming air channel. The wires cover the length of the flow channel, measuring 1.41 inches. As can be seen in figure 6, the nichrome wire is the final heating before the air enters the membrane. The initial heating is done through the heat exchangers, which also cool the oxygen and lean air. The wires require a power input of 277 W if the temperature of the cells is to reach operation within 10 minutes. See Start-up section for more detail on time-to-use calculations.

5.4 Heat Exchangers

Microchannel heat exchangers for oxygen and air and air and lean air (LA) were designed to allow for the maximum possible heat transfer for the smallest heat transfer area. A smaller heat transfer area means a smaller amount of foil used for construction, and therefore a lower material cost. A large distinction between traditional heat exchangers and microchannel heat exchangers is that normal correlations for determining the Nusselt Number in heating channels do not apply. One common correlation is the Gnielinski correlation. Adams et al. performed experiments with channels ranging in diameter from 0.76mm to 1.09mm. They found that deviations at larger diameters were smaller than in heat exchangers with smaller diameters. At the upper limit of their experiment, traditional correlations matched experimental data quite well, with an error of only (they didn't give an error!). To account for the pumping pressure of 2 PSI for the Thomas rotary pumps at 14.875 L/min the pressure drop for the heat exchangers (both entering and exiting), the stainless steel tubes connecting the pumps and the membrane with the heat exchangers, the splitter to separate the feed air into the heat exchangers, the BICUVOX membrane, as well as any pressure variations in the pump should collectively be less than the total allowable pressure of the pump. The pump will not be designed to accommodate for the system, but rather an off the shelf pump will be used and the system will be sized to it. This will be less expensive than using a custom made pump. To account for other pressure drops in the system, the heat exchangers were designed such that they have a pressure drop no more than half of the total pumping pressure of the pump.

An example of the two heat exchangers, pictured in Fig () figure 9, consists of two rows of square channels separated by foil that is 0.152 millimeters thick. This thickness is the thinnest copper foil available from our supplier, AllFoils. Oxygen or LA lean air coming in from the membranes is fed to the top row where it is cooled by ambient air coming in counter currently on the bottom row. The heat exchanger is given rigidity by means of a copper outer shell that is 1mm thick. This thickness is about that of a penny, which should be thick enough to allow for lack of excessive bending.

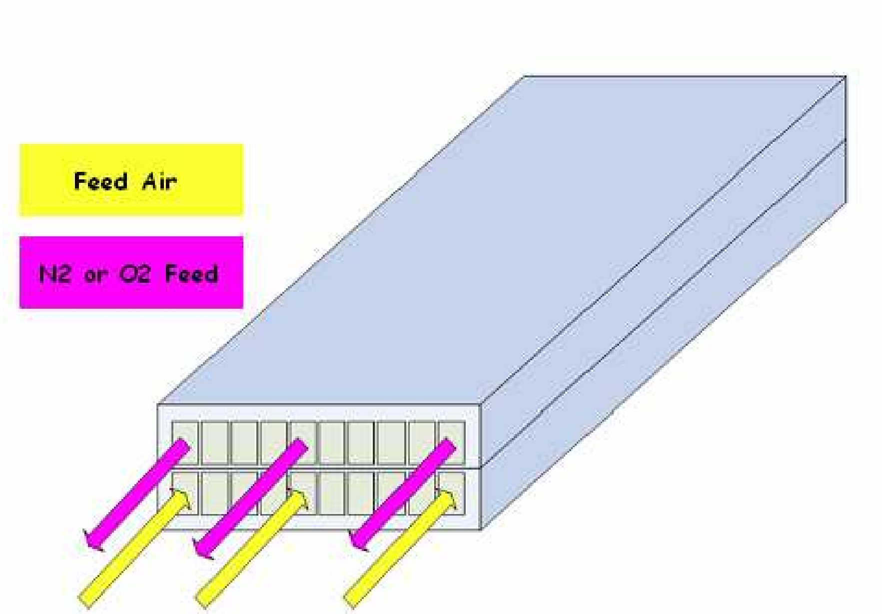


Figure 9: Heat Exchanger Layout

5.4.1 Sizing Heat Exchangers

In the oxygen and air heat exchanger, air comes into the bottom row of channels in the heat exchanger and oxygen comes into the top row of channels of the heat exchanger. The oxygen and air run counter currently through the heat exchanger such that the oxygen may exit the overall unit, while the air may enter the overall unit (including all components). That is, the air enters the heat exchanger from outside the unit and exits the heat exchanger to inside the overall unit and the oxygen enters the heat exchanger from inside the overall unit, and exits the heat exchanger to outside the overall unit. When sizing the oxygen heat exchanger two constraints were used. The first constraint is that the entering air temperature must be at the temperature of the ambient air, 294.35 K. The second constraint is that the exiting temperature of the oxygen stream must be no greater than 298.15 K to avoid burning the patients.

Similar constraints were used for the air and lean air heat exchanger, which is constructed in a similar way to the oxygen and air heat exchanger. The principle difference is that lean air is passed counter currently instead of oxygen.

A final objective that was placed on the heat exchangers was to obtain an outlet air temperature that is close enough to the membrane operating temperature as possible.

This temperature was set to correspond to the 0.75 A/cm3 for BICUVOX, as described in section 5.1.1. The temperature of 831.15K is the lowest corresponding temperature that can attain this value with a large cell voltage and power density. A side view of the model for the O_2 heat exchanger design is given in figure 5.The model for the LA lean air and air heat exchanger is similar to the O_2 heat exchanger design with the exception of O_2 being replaced with lean air.

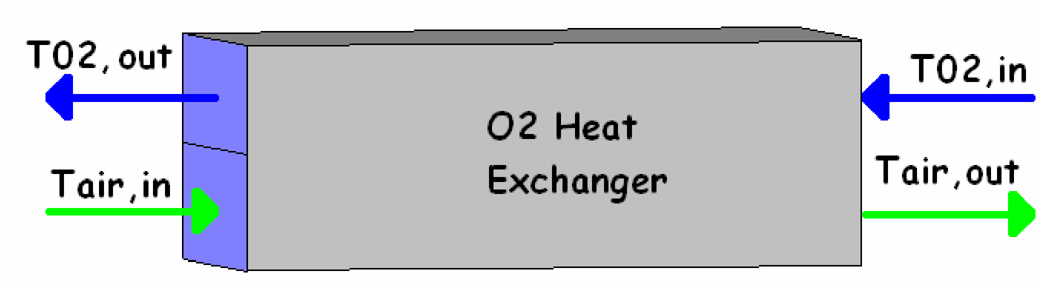


Figure 2: Remove

To determine the outlet temperatures of the air from the oxygen and air and the LA and air heat exchangers, an energy balance between the two channels was taken so that the heat lost from one row of channels equals the heat gained by the other row of channels. That is, in the case of the oxygen and air heat exchanger, the heat lost by oxygen as it leaves the system equals the heat gained by the air as it enters the system. This was done by changing the distribution of the total air flow rate of 29.76 L/min coming from both pumps between the two heat exchangers. Following the energy balance analysis, the outlet temperature of the air out of the oxygen and air heat exchanger was found to be 831.149 K, which is close to the desired outlet temperature. The outlet temperature of the air from the LA lean air and air heat exchanger was found to be

829.23K. When performing this analysis, the second law of thermodynamics was considered. According to this law, the inlet temperature of the hot fluid (i.e. oxygen or LA lean air) must not be less than the outlet temperature of the cold fluid (i.e. air). If this was violated, it would mean that heat would be traveling from colder hot fluid to warmer cold fluid. This law was followed by changing the inlet flow rate of air to each heat exchanger such that it balanced the heat transfer of the LA or oxygen streams.

A temperature of 829.57K is reached when the outlet air stream temperatures from both heat exchangers are mixed. This temperature is very close to the operating temperature of the BICUVOX membrane, so little additional heating is needed from the nichrome wire.

The second step taken in sizing the heat exchanger was to determine the overall heat transfer between the two streams in each row by guessing an equivalent diameter, assuming bulk properties (i.e. at the average of the inlet and outlet temperatures of each stream), and fixing the length and the width (i.e. summation of the total number of tubes multiplied by the width of each tube and the width of each foil wall). This second step is accomplished using an overall heat transfer coefficient which includes a modified Nusselt number correlation that is appropriate for flow in microchannels. Since Reynolds numbers were nearly always found to be less than 2300 a correlation for the Nusselt number by Choi et al[13] was used. This correlation was developed using nitrogen as a working fluid with channels ranging in diameter from 3 – 81.2 μm with lengths ranging from 24 – 52 mm. The length and the diameter of the microchannels are sometimes out of this range, but it will be used since no other correlations were found for this Reynolds number range for gases in microchannels.

The correlation is defined as follows:

$$Nu = 0.00972\,\mathrm{Re}^{1.17}\,\mathrm{Pr}^{\frac{1}{3}} \tag{3}$$

Where:

Re = the Reynolds number for the air evaluated at bulk properties

Pr = the Prandtl number for the air evaluated at bulk properties

If the Reynolds Number is greater than 3000, a correlation by Wu and Little may be used. It wasn't however applied in the analysis.

$$Nu = 0.00222\,\mathrm{Re}^{1.09}\,\mathrm{Pr}^{0.4}$$

The third step in sizing the heat exchanger was to determine the pressure drop in the heat exchanger. The first calculation is to calculate the friction factor. The fanning friction factor may be used, but it should be multiplied by a correction factor of 1.75 to accommodate for any irregularities from the correlation due to the flow occurring in microchannels[14]. The correction factor may be determined from Figure 1 in M.J. Kohl et al[14]. This value is the maximum deviation of composite experimental data from the theoretical friction factor prediction for 11 different research studies. If the calculation of the pressure drop is less than half of the pressure available from the pump, then the pressure drop calculation should serve as a good indicator of whether or not the heat exchanger will work with the pump arrangement.

The general trend that the equivalent diameter gives is that the heat transfer and the pressure drop increase as the equivalent diameter decreases and the area of foil decreases as the equivalent diameter increases. Since all changes but the pressure drops are desirable effects, then sizing of the heat exchanger may be preformed by comparing the pressure drop with the acceptable pressure drop of $6.895\text{x}10^{3}$ Pa (1psi).

The equivalent diameters and foil areas were determined to be $9\text{x}10^{-5}$ m, 0.01048m^{2} and $2\text{x}10^{-4}$ m, $1.05\text{x}10^{-2}$ m^{2} for the air and LA and air and oxygen heat exchangers respectively. The foil areas were determined by adding multiplying the area of each fin by the number of fins in the heat exchanger.

5.5 Insulation

For this design two forms of insulation will be used to bring the high operating temperature inside the device down to a cool face temperature that is safe for the consumer. The insulation types are radiation heat shielding on the interior wall of the membrane stack and vacuum panel insulation on the external membrane housing.

The radiation heat shielding will prevent all radiation produced from the Nichrome heating element from penetrating the wall of the membrane stack. This works more as a safety precaution. It is unknown the amount radiation emitted by the heaters, if any. A small metal sheet adds virtually no weight or volume to the system. Its presence is not detrimental to the design. In addition, this will ensure the smallest thickness of vacuum insulation possible. The radiation insulation is a thin sheet that works to reflect the electromagnetic radiation waves from penetration into the material and causing a rise in temperature. This can be accomplished with a highly polished, thin metallic sheet. These sheets are commercially available in many varieties and usability limits.

A Dewar type arrangement will be used Vacuum panel insulation comes in many varieties and use limits. Of the products commercially available; Porextherm Insulpor© is chosen for this application because of its high use temperature and low thermal conductivity value across its usable temperature range[12]. Porextherm also provides Vacupor© vacuum pack insulation, however, this type of material only has a constant use temperature of 500°C. This temperature is lower than the hot face temperature of the insulation adjacent to the membrane stack. The Insulpor© insulation can be used at temperatures up to 1000°C. The thickness of insulation needed to bring the hot face temperature down to a value of 77°C is 2.52 in. This insulation is placed on each side of the cell stack. This brings the membrane stack dimensions to 12.1 in. in height and 9.4 in. in width. When performing a 3-D heat transfer model, assuming a cylindrical arrangement, and including the conductivity of MgO, the insulation thickness change is negligible. This is primarily due to the fact that in the previous calculations, MgO was not considered.

The vacuum panels were selected on the basis of a low thermal conductivity value and a negligible thermal expansion coefficient. The thermal expansion is approximated to be less than 1% at a temperature of 800°C. This will allow enough expansion such that the components bonded with it will not be subjected to additional strain imposed by the expansion of the insulating material.   More on thermal expansion is discussed in the final design section.

5.5.1 Additional Temperature Reduction Methods Considered

There are other methods to reduce the cold face temperature of the device. One such method that was investigated is to insert a pump into the casing of the device to pull a vacuum inside the device. This method however, is not as feasible to the design as the insulation. An additional pump with the capacity necessary to reduce the amount of molecules in the casing to nearly zero would add an additional weight that is more detrimental to the design of the device than the additional 5 in. added by the insulation materials. There is also an additional cost associated with the installation of an additional pump that will force the selling price of the unit to increase to an undesirable level. Other insulation was examined, however, there is not economically feasible choice that has as good of insulating qualities as the Insulpor© vacuum insulation. It has low thermal conductivity, high operating temperatures, and light weight. Similar products, such as the Vacupor© mentioned above, may be able to provide a couple of the qualities but not all.

5.6 Pumps

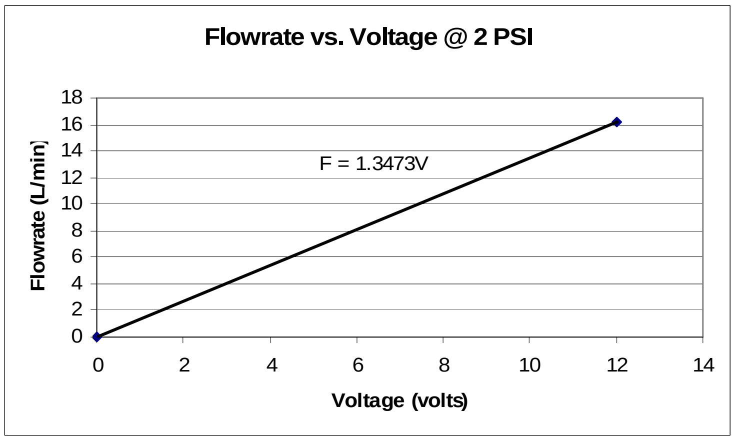
A pair of Thomas rotary air compressors[15] model G12-07N will be used to provide air supply to the system. Each pump requires 2.3 W and 12 V to run at a maximum flow rate output of 20 L/min and an outlet pressure of 0 PSIA. The pumps are also oil-less so there is no possibility that the air stream will be contaminated. In addition the pumps are pulsation free, so there will be fewer sharp changes in the operating pressure. Below is data obtained from medibix.com[16], an online component database.

Table 2: Pump flow rates at various pressures

Compressor Performance LPM @ PSI	**0**	**1**	**1.5**	**3**	**5**
50316	20	18.5	17	14.5	4.5
Maximum Pressure (PSI)	***Continuous***	***Intermittent***	***Restart***		
50316	4.4	11.6	0		
Vacuum Performance LPM @ In. Hg.	**0**	**1.5**	**3**	**5**	
50316	20	13	7	1	

From the table it is apparent that there is some variation in the flow rate at the maximum pressure for each pumping cycle, but for simplification purposes, it will be assumed that the flow rate is constant over time.

In the system each pump was run at 2 PSI with a flow rate of 14.875 L/min, for a total of 29.75 L/min. This the required flow rate to produce a pressure of about 3 PSI, which is needed to overcome the pressure drop in the heat exchangers, while still conforming to the required 5 L/min of pure oxygen. The voltage and the power requirement at 14.875 L/min are close to that at the maximum flow rate. However, it is helpful to model the flow rate as a function of voltage to obtain a more accurate estimate. This model is shown in Figure 7.



The model assumes that the voltage across the system will be zero when the flow rate is zero, and equal to a value of 12 V when the flow rate is 16.167 L/min. Since no data was available for the pumps at 2 PSI, but instead only 1.5 PSI and 3 PSI extrapolation had to be performed on the data presented in table 1, in the previous page.

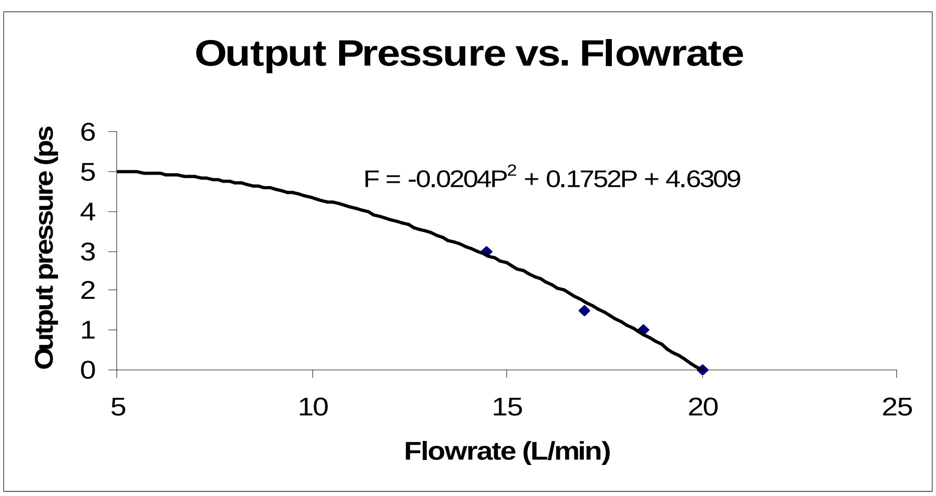


Figure 10. Output Pressure vs. Flow Rate

The pumps are 4.45 inches long high, and range from 2 inches to 1.68 inches and have a 2.25 inch diameter. Because the dimensions of each pump are small, it can easily be fit into the unit and still allow it to remain compact. In addition, the pumps only weigh 1.10 lbs, so their weight will add little to the overall weight of the system.

Two pumps are used instead of one to allow for the possibility of pump failure. If only one pump was used and it failed, the user of the product would be unable to receive oxygen. Lack of oxygen could pose a serious health threat to the user, or possibly even death.

5.6.1 Sound Proofing

The pumps operate at a maximum RPM of 5400. This RPM can be correlated to a frequency. It was assumed that it is the same frequency of the sound it produces. This was determined to be 3553 Hz, and, as determined from Appendix B, which is a chart given on the Acoustiblok website, this corresponds to 43 dB.

An Acoustiblok sound proofing insulation was included at a thickness of 0.11 inches and a weight of 1 pound.[26] This reduced the noise produced by the pumps by about 30 dB. With the insulation, the final decibel output of the unit is 13 dB. Due to the importance of noise reduction to the consumer, as modeled in the happiness function, the decrease in the decibels far outweighed the increase in size.

5.7 External Casing

The outer casing of the device must be able to withstand a reasonable amount of wear and tear from everyday use. This implies that a resilient, durable, and lightweight material be used for this purpose. The material chosen for this purpose is Acrylonitrile Butadiene Styrene, ABS. ABS is a thermoplastic polymer with high strength and mechanical properties[17]. The tensile strength of this material is 6000 PSI, which is a relatively large value for this property, equating to approximately 10% of the strength of steel. This material is also relatively inexpensive and readily available.

5.7.1 Additional External Casings Considered

Alternatives to ABS were explored; however, none combined the durable exterior with the ability to absorb shock like Acrylonitrile Butadiene Styrene. Materials such as polyvinyl chloride, low density polyethylene, and high density polyethylene were all rejected. The only other material with the desired properties was polypropylene. It essentially came down to which was cheaper, and ABS is a more economical choice than polypropylene.

5.8 Sealant

To maintain separation of the air, oxygen, and lean air streams, a sealant is needed. The sealant used in this design must meet certain criteria in order to be considered for use. The sealant must be able to function at the high operating temperatures inside the membrane cell stack, possess the desired thermal and mechanical properties, have a thermal expansion coefficient matching other components and be safe for the customer. For this application several sealants were inspected, however, few have the combination of properties and safety required.

The sealants selected for this application were the Durabond© 900 line of Cotronics ceramic epoxies[16]. All of the epoxies in this series have high bond strength which, unlike other sealants, increases with an increase in temperature. The following figure shows the bond strength as a function of the operating temperature.

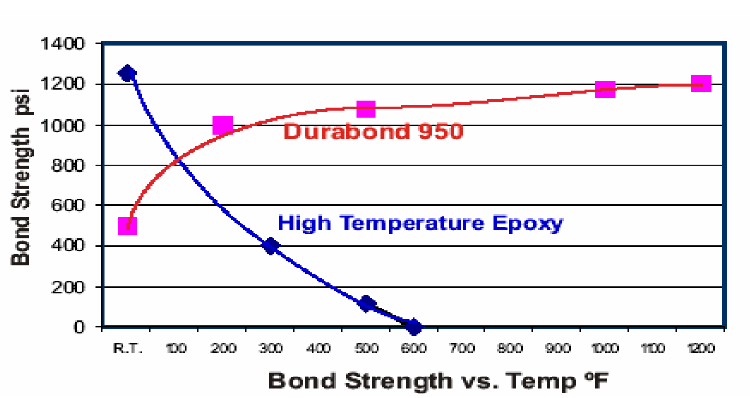


Figure 11: Bond Strength of Cotronics Sealant 950[18]

Durabond 950 is an aluminum based epoxy resin with a use temperature up to 1200°F and bond strength of approximately 1100 PSI at the use temperature. The other sealants in the series have a higher use temperature, however, there is a potential health risk associated with their use. The thermal expansion coefficient of this sealant is $10x10^{-6}/°C$. This is in good agreement with the values of materials used for the membrane stack and the inner case housing.

5.8.1 Additional Sealants Considered

Durabond 952 and 954, the other sealants in the series, contain nickel and chromium components in their formula. Nickel and chromium have been shown to be carcinogenic to animals in laboratory tests[19]. Their occurrence in the sealant does not imply that the sealant will cause cancer, but removing the risk provides a higher degree of safety for the consumer. The aluminum component in Durabond 950 has not been shown to cause risks to health. According to the MSDS on Durabond 950[19], once annealed, the epoxy resin has no vapor pressure. Since there is not a vapor pressure from this sealant, there is a low probability that components locked in the epoxy matrix will diffuse out and come in contact with the consumer.

6.0 Electrical System

The unit is designed to run off of cigarette lighter adapter, or any other 12 volt power source. In Figure 12 an overall electrical schematic of the system is shown. The electrical system consists of two 12V Thomas pumps labeled as P1 and P2, a flow controller labeled as R5, a Bicuvox membrane labeled as M, an on-off switch labeled as 2, a nichrome wire labeled as R2, thermocouples to measure the temperature flow and electrical controllers labeled as R3, an additional resistor labeled as R1 to dissipate voltage to allow for the steady state current in the nichrome wire, a resistor labeled R4 to allow for a complete 12V voltage drop over the membrane current loop, and a switch labeled as 2 to allow for resistor R2 to be switched on or off.

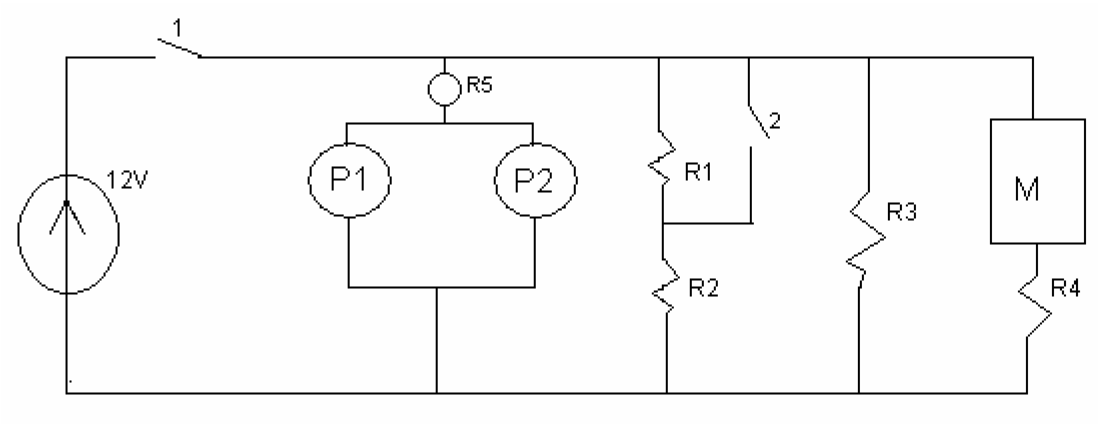


Figure 12: Electrical System Schematic

The power requirements of each unit are as follows:

	Power Requirement	Voltage	Current	Resistance
R5	varies	Varies	Varies	varies
P1	max 2.3W	Max 12V	Varies	62.6 ohms
P2	max 2.3W	Max 12V	Varies	62.6 ohms
M	1275.8W	2.65V	481.44A	5.708E-3 ohms
R1	164.45W	11.56 V	14.30A	8.09E-1 ohms
R4	4448.51W	9.24 V	481.44A	1.92E-2 ohms
R2 steady state	6.095E-1W	4E-2V	14.30	2.98E-2 ohms
R2 unsteady state	29325.4W	9.35V	3136A	2.98E-2 ohms
Total at steady state	5894W	N/A, always 12V drop	N/A, different For each wire	Not Necessary
Total at unsteady state	35218.76W	N/A, always 12V drop	N/A, different For each wire	Not Necessary

7.0 Start-up Calculations

The membrane stack must reach a temperature of 550°C before oxygen begins to permeate through the membrane material. Therefore it is imperative to determine the amount of time for the device to heat up because the consumer will be without oxygen during this period. A reasonable estimate for the start-up period is within 10 minutes of device operation. The power required to heat the material is determined by calculating the heat needed to raise the temperature of the Bicuvox.10 membranes to operation by the following equation:

$$Q = mC_p \Delta T \tag{4}$$

Where C_p is the molar heat capacity of $ZrTiO_4$[20], a Perovskite ceramic with a molecular weight similar to that of Bicuvox.10, m is the amount of material in moles and ΔT is the change in temperature.

Once the heat is determined, the power requirement can be determined by dividing the heat needed by the elapsed time. The power available from the Iconel electrodes is determined by multiplying the current and the voltage drop across the membrane stack and multiplying by the total number of cells. The power available from the electrodes is found to be 26.9 W. The additional power will come from the nichrome heating elements. The resistance of nichrome at the 950 K operating temperature is calculated to be 899 μΩ as predicted by Meier[21]. Since all other parameters are known, the voltage drop across the wire is found to be 0.5 V using the power equation below:

$$V = \sqrt{R \cdot P} \tag{5}$$

This approach assumes that the pumps do not operate until the use temperature is reached. This will be accomplished be inserting a thermocouple into the membrane stack which will be used to operate an off/on type control that will activate the pumps when the appropriate temperature has been reached inside the membrane housing.

8.0 Safety and Controls

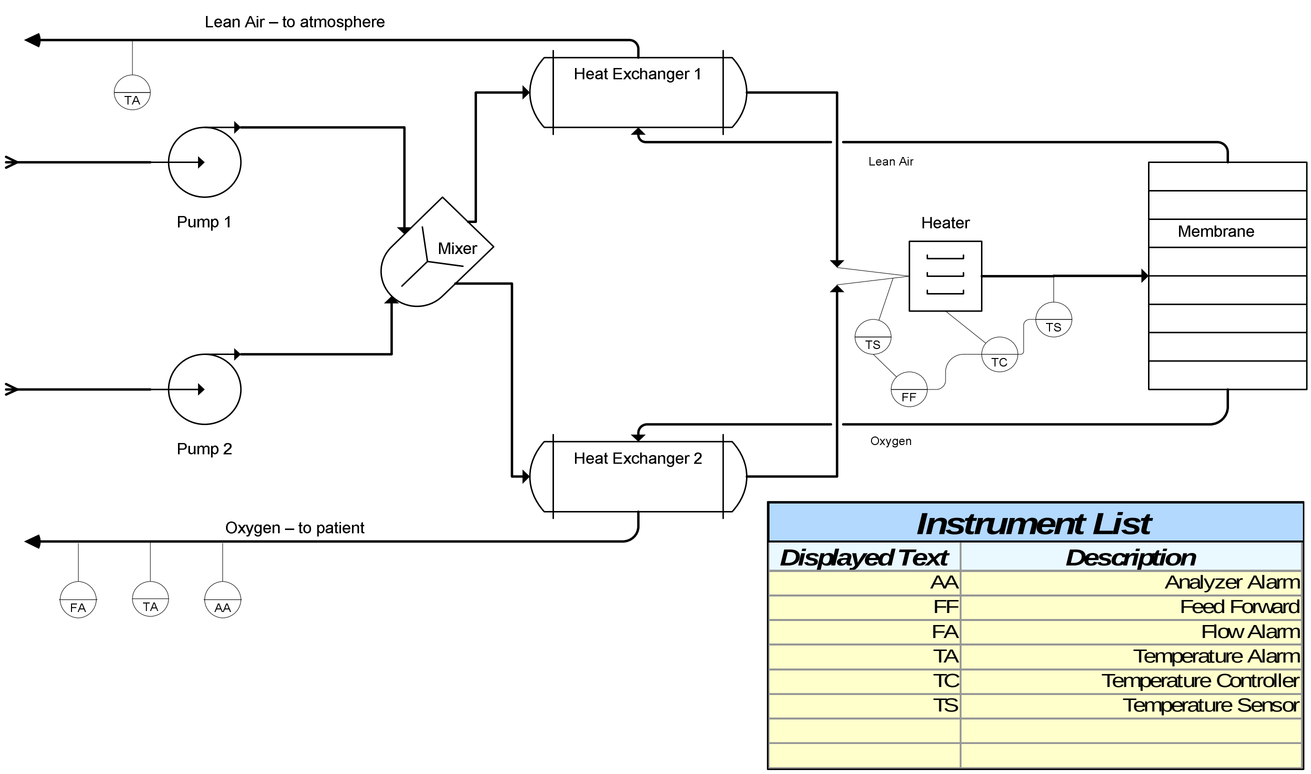
As with any consumer products, safety is of the greatest importance in the design of this device. To ensure the safety of the consumer the following control scheme was designed. The chief safety concerns of the system are temperature, of exit streams and within the membrane, and exit stream composition. Since this is a consumer product, it is necessary to have a control system in place to manage these issues and provide alarms if they are violated. Alarms will sound and be displayed on the front panel to alert the patient of adverse conditions.

8.1 System Piping and Instrumentation Diagram

There are temperature alarms on both exit streams. These are labeled TA, temperature alarm, in figure 13. The oxygen stream has an emergency set point of 82°F; this will allow the pumps enough time to be switched off by the controller before the patient is put at risk of coming in contact with hot oxygen from the membranes. The nitrogen stream has an emergency set point temperature of 90°F. The response of this controller will be identical to that of the oxygen controller except for the heightened temperature before the switch engages. The set point for this stream can afford to be higher since it will not be venting directly in contact with the consumer. However, it is necessary to implement this controller to ensure that hot gasses are not vented in the direction of the patient. In addition, there is a temperature sensor, TS in figure 13, on the oxygen stream that reports to a flow controller, FC in figure 13, which dictates the flow of inlet air through the heat exchangers. In the event that the oxygen stream temperature exceeds 82°F, the flow from the mixer to the oxygen-side heat exchanger will increase to drop the temperature. This will likely cause the lean air stream temperature to increase, but the oxygen stream is more important due to direct contact with the patient. The final control on the oxygen stream is a flow analyzer, FA in figure 13. It will alarm the user if the oxygen flow rate drops below what is specified for their particular oxygen regimen.

The analyzer alarm will shut down the pumps and send a signal to the front display in the event that the oxygen concentration drops below 85%. This is not only to ensure that the patient is receiving the appropriate concentrations of oxygen, but to ensure that the patient is not ingesting contaminants that may be present in the stream due to leaks or other malfunctions in the system. Until the problem has been checked and the controller reset; the device will not operate. This may be an inconvenience for the customer; however, the control lock will work to keep them safe in the event of contamination. The analyzer alarm is labeled AA in figure 13.

The final component of the control system is around the nichrome heating wires. There is a temperature controller, TC in figure 13, connected to a network of temperature sensors. The first sensor is in a feedforward loop, FF. The temperature of the combined streams exiting the heat exchangers is sent to the temperature controller. This allows the heating element to increase or decrease heat output dependent upon the inlet air compositions, which can change dependent upon the ambient air temperature outside the system. By taking into account the inlet stream to the membrane, it is possible to somewhat predict the temperature of the membrane. This allows for fewer fluctuations in system exit temperatures, allows for greater efficiency of the membrane and heat exchangers by designing for smaller temperature intervals. This also prevents runaway heating that could damage the system.



Instrument List	
Displayed Text	Description
AA	Analyzer Alarm
FF	Feed Forward
FA	Flow Alarm
TA	Temperature Alarm
TC	Temperature Controller
TS	Temperature Sensor

Figure 13: System P&ID

5.8.1 Additional Controls

There will also be a temperature controller nested inside the membrane housing that will activate the pumps once the cell temperature has risen to the operating temperature. This will ensure that the membranes are ready to be used before the air is allowed to flow in. This arrangement hastens the start-up period by only having to heat the cells without heating the surrounding air.

Besides the typical safety controls, there will be a valve placed on the exiting oxygen stream that can be adjusted according to the patients prescribed flow rate by adjusting the dial on the front panel display. The valve will be electrically activated and fail open to ensure that the patient still receives an oxygen flow rate in the event of valve failure.

9.0 Design Results & Conclusions

This design of the oxygen generation unit took into account only Iongen One and Airsep Lifestyle as competition. This correlates to a Beta of 0.75. As discussed in the economic section at the end of the report, this design does not consider a third competitor, Airsep Freestyle. With the third competitor included, the Beta value increased to 0.78. A different design would need to be developed to be competitive in this market.

9.1 Final Design

The final design specifications can be seen in the table below. The final size is not a sum of the pieces but the actual size of the membrane when the components are in their respective positions. The membrane stack dimensions include the inner casing, insulation, and the membrane itself. The pumps will also have a sound proofing insulation of 0.2 inches surrounding them. This is represented in the total width, as is the additional weight of this insulation – 1 lb. An additional 0.1 inch was included for thermal expansion of the membrane and inner casing. The largest expansion of both components in any direction was calculated to be 0.075 inches.

Table 3. Unit Dimensions and Weight

Sizes (in inches & pounds)				
Component	**Height**	**Width/Diameter**	**Length**	**Weight**
Membrane Stack	12.1	9.4	12.1	2.4
Pump 1		2.25	4.45	0.55
Pump 2		2.25	4.45	0.55
Heat Exchanger – O2	2.756	0.1005	2.756	0.22
Heat Exchanger - LA	2.756	0.0918	2.756	0.22
Battery	2.75	2	9.5	5
Final Size	***15.2***	***9.5***	***12.2***	***9.94***

The cross-sectional view of the unit, figure 14, shows how the pieces listed in table 2 fit, and how they work together to form the smallest and most convenient arrangement. The arrangement was played with to get the optimal size based on the happiness of the consumer. With this in mind, the width was kept smallest. The height being the largest dimension was based on two main characteristics. First, most of the time the unit will be setting next to the user, this allows easier access to the control panel and handle for picking it up. Second, the unit is large enough that it will be necessary to pull on a cart. The sizes are shown in more detail in figure 15, the three dimensional representation.

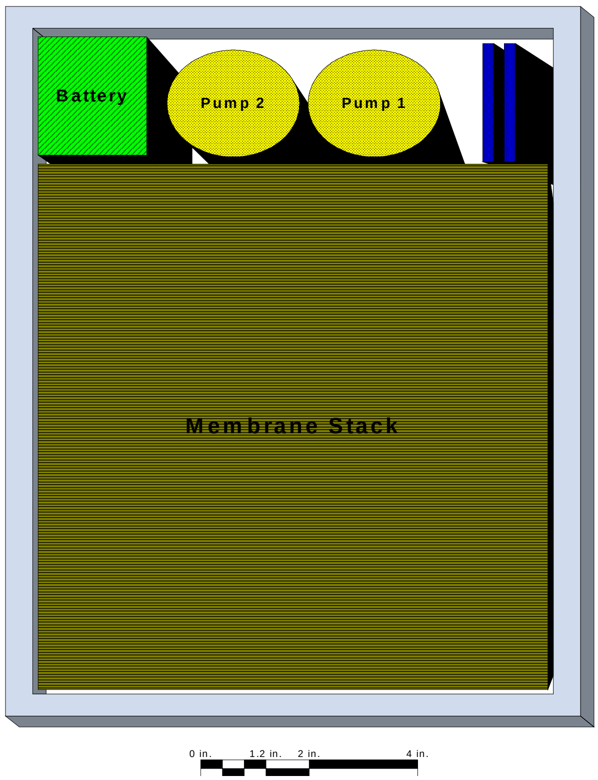


Figure 14. Cross-Sectional View of the Unit

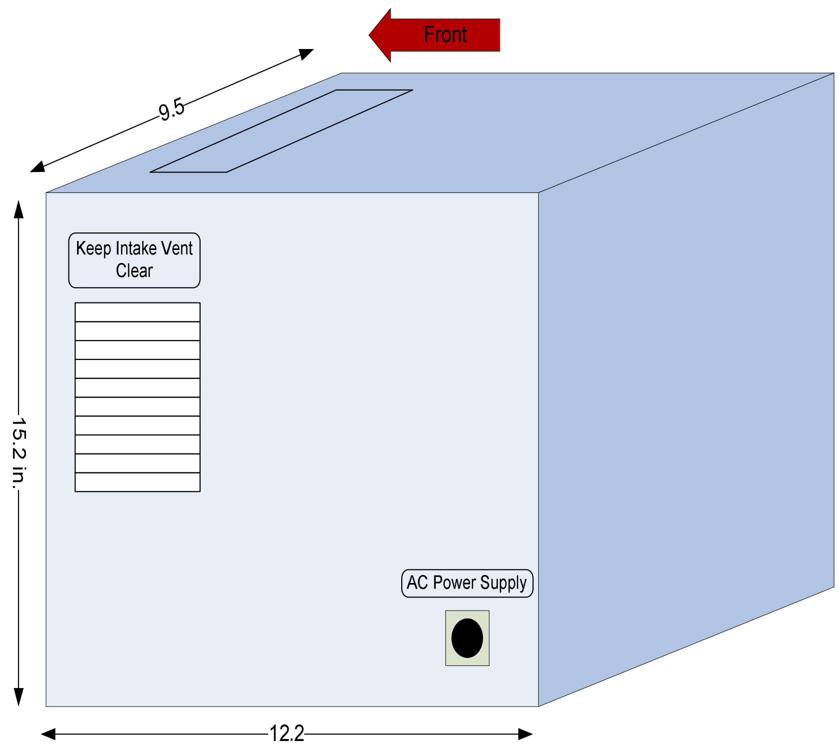


Figure 15. 3-D View of the Unit

The view of the panel, shown in the 3-D model on the top of the unit, can be seen in figure 15. There were several ideas that went into this design. First, there is a necessity to have warning lights for the control system to alert the patient of potential hazards. This is also the purpose of the microphone warning. It is a last resort warning if the user has not noticed the illuminated warning lights. Second, the battery meter allows the user the autonomy movement without the worry of power loss. These two systems prevent the patient from unexpected complications. The only operation necessary is the power button. The general oxygen therapy patient is an older, technology adverse individual. This system requires a single button start-up. The lights next to the power button alert the individual when the system is warming up or ready for use. The final portion is the connection for the nasal cannula.

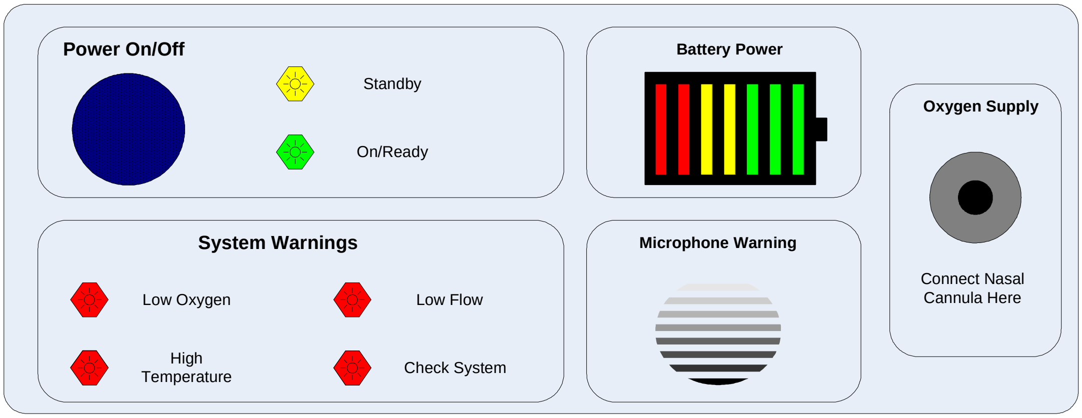


Figure 16. Unit Control Panel

10.0 Business Plan

10.1 Description of Business

The proposed business is intent on the design, manufacture, and distribution of devices used in the aide of patients suffering from pulmonary diseases requiring the use of oxygen therapy.
Our business will begin as a partnership between Justin Brady and Brent Shambaugh. As we gain more laborers to fulfill our production capacity, as well as medical experts that understand the industry, we hope to maintain an employee owned company. We intend on providing a majority of the start-up funding for our company. For additional funding, we will seek private investment.
We predict that there is an even demographic distribution of oxygen users, so the location of our facility will primarily be a function of property taxes. Due to shipping expenses, it would likely be most profitable if we were centrally located. The location that we have chosen is Denver, Colorado. It one of the lowest tax rates of any city in the United States due to the Taxpayer's Bill of Rights that was approved in Colorado a decade ago, as well as due to a restriction in Denver county forbidding tax increases [x].

10.1.1 Objective

The following business plan illustrates marketing principles that affect the Net Present Worth of the project. Principle things that affect the Net Present Worth are the selling price of the product, the product's demand, as well as the Total Product Cost and the Fixed Capital Investment.

10.2 Marketing

The intent of our company is to become a major market holder in our sector. To accomplish this task the company must be known by the consumer base and become visible in the market. In making our presence known in the oxygen therapy and larger medicinal fields, we will actively promote the company in various forms of advertisements. The majority of our customers will be elderly and therefore, the company will advertise in areas with a high population of elderly citizenry. The intent of the company is to become known by our customers but not to flood the marketplace with our advertising media. It is the belief of the company that too much advertising actually has adverse effects on the customer population.

In the field of oxygen concentration and distribution equipment, there are established and emerging companies vying for their sector of the market. To ensure that this company establishes itself in the market, a system better than currently being offered by the competition must be designed and manufactured.

10.2.1 Description of Competition

We will be in direct competition with businesses that produce portable oxygen concentrators that yield 5 L/min of oxygen. These competitors are the Lifestyle and the Freestyle made by Airsep, and the Inogen One made by Inogen. A technical description of each unit, along with the final design of our product is provided in the table below.

	AirSep Lifestyle	AirSep FreeStyle	Inogen One	Our Product
Avg. Noise (Db)	55	55	40	10
Power (watts)	35	72	38	341
weight (lb)	9.75	4.4	9.7	9.8
length (ft)	1.36	0.3	0.97	1.017
width (ft)	0.60	0.51	0.50	0.95
height (ft)	0.46	0.72	1.03	1.034
cost $	3899	4697 (estimate)	5495	5500

Source: Portable Oxygen[27,28]

All three of the competitors have units that are oxygen concentrators, and all of them are pulse flow units. No mention was made of any of them using a solid oxide membrane to separate oxygen. The solid oxide membrane has an advantage in that it provides purer oxygen than any of the competitors, nearly 100%. The AirSep Lifestyle and FreeStyle produce oxygen at 90% purity*(airsepmedical). The purity of oxygen from the Inogen One was not available.
To perform the economic analysis, we considered three different scenarios.

10.2.2 Demand and Selling Price based on Happiness

The demand and selling price of our product, for three different scenarios, was deduced from a happiness analysis based on supposed physical and subjective constraints. Actual happiness functions would be found by surveying patients that may use our product. Their feelings about the product specification would then be fit to quantitative data to give a range of happiness levels. However, due to time constraints this was not possible. Therefore, educated guesses were made concerning what magnitudes of each attribute correlated to specific happiness levels.

Scenario 1:

The unit is placed in a car. The battery size will not matter since the power source comes from the car. The unit will be able to be placed in the trunk, so it will not create an obstacle for any passengers in the car. The size and the weight will less of an issue since it is not likely that the unit will be moved around. The noise that the unit makes will not be a great issue either, because the trunk will likely muffle the sound produced by the unit. The main thing affecting happiness will be the amount of trunk space the unit takes up. The purity of oxygen will not be regarded as affecting happiness. A purity of 85% is regarded as the minimum prescribeable purity. It will be assumed that all of the units satisfy this requirement.

The following happiness functions were constructed:

A happiness function considering the height of the unit was constructed. It is assumed that the height should be no greater than the average clearance in the trunk of a car. An estimate is 1.5 ft.

A happiness function considering the width of the unit was constructed. It is assumed that as the unit takes up a greater percentage of trunk width, the happiness of the patient decreases. Since the trunk width varies, the width of a trunk in a very small car will be considered. A mini has a trunk width of about 4 ft.

A happiness function considering the length of the unit was constructed. The patient will be likely be very unhappy if the unit is longer than the trunk length. A very small car will be chosen as the limiting case. A mini has a trunk length of about 1 ft.

Scenario 2:

The unit is placed in a home. The battery size will not matter since the power source comes from the home. The size and the weight will less of an issue since it is not likely that the unit will be moved around. The noise that the unit makes will be an issue since it will likely be right by the user with no barrier between it and the user. The noise will likely be the most important issue. The purity of oxygen will not affect happiness for reasons given in scenario 1.

The following happiness functions were constructed:

A happiness function considering the noise was constructed considering 60db to be the highest acceptable noise level for the consumer. According to josaka.com, this noise level is comparable to speech interference in an office. At this noise level, the oxygen user would constantly be reminded of the sound that the unit produces throughout the work day. It was assumed that the customer would be the happiest at a noise rating of 0db.

Scenario 3:

The unit is portable. It is placed on a cart. The weight will be an issue because the user will occasionally have to lift the unit when going up a staircase. The height should not be greater than the persons shoulder's; otherwise, the person will be very unhappy. The width is more flexible, but a unit that is too wide could prove to be annoying due to its bulkiness. The battery size will be a significant issue since it will largely affect the weight of the unit, and will also affect its volume. The noise that the unit produces will also be significant because the unit will be right by the user. The purity of oxygen will not affect happiness for reasons given in scenario 1.

The following happiness functions were constructed:

A happiness function considering the noise level was constructed, and was the same as the one used for scenario 2.

A happiness function considering the weight of the unit was constructed assuming that any unit below 5lbs would give the customer 100% happiness. Around a weight of 32lbs it was assumed that the customer would have 0% happiness. Around a weight of 15lbs, the customer would have 20% happiness. It is assumed that women are less willing to lift heavy objects than men are, but to accommodate both sexes the happiness function will be constructed based on women's preferences. This model will not fit men as well, but it is expected that they will be much happier than women, which could be regarded as a bonus for the product.

A happiness function considering the height of the unit will be considered. It is assumed that a unit that is 2 ft tall will produce 100% happiness and a unit that is 3 ft tall will produce 50% happiness. A unit that is 4 ft tall will produce 20% happiness, and a unit that is 5 ft tall will produce 0% happiness.

A happiness function considering the width of a unit will be considered. Any unit that is less than 8 in. wide will produce 100% happiness. A unit that is 18 in. wide will produce 10% happiness. Any unit that is 24 in. wide will produce 0% happiness since it will not fit well in the seats.

A happiness function considering the length of the unit will be considered. It is assumed that happiness will be zero at a length greater than 1 ft. Beyond this length, the user is likely to be torqued out by the cart; making handling difficult.

Out of these three scenarios, we feel that it is appropriate to pursue the third scenario involving a portable unit. The third scenario will provide us with the least competition, but also allow us to pursue a higher selling cost due to the higher average cost for the competitors as compared to the in-home unit. No competitors exist in the market for an in-car unit, but it is assumed that this market would not be very lucrative do to the lack of flexibility in use of such a unit. Therefore, the rest of the focus of the economic plan will be on the third scenario.

10.2.3 Constructing a Happiness Function

The first step in determining demand is to construct a happiness function. The happiness function is based on how happy a customer feels at certain magnitudes of a particular variable. Happiness ranges from 0 to 100%. For simplicity in our analysis, we normalized the happiness function such that it ranges from 0 to 1. As discussed above, the happiness model would be developed in an ideal case by first finding a qualitative description of how a customer feels for various magnitudes of a particular variable and then relating the qualitative description to quantitative values of the variable for each magnitude (e.g. fuzzy logic). An example of a fully developed happiness function from Scenario 3 is presented below:

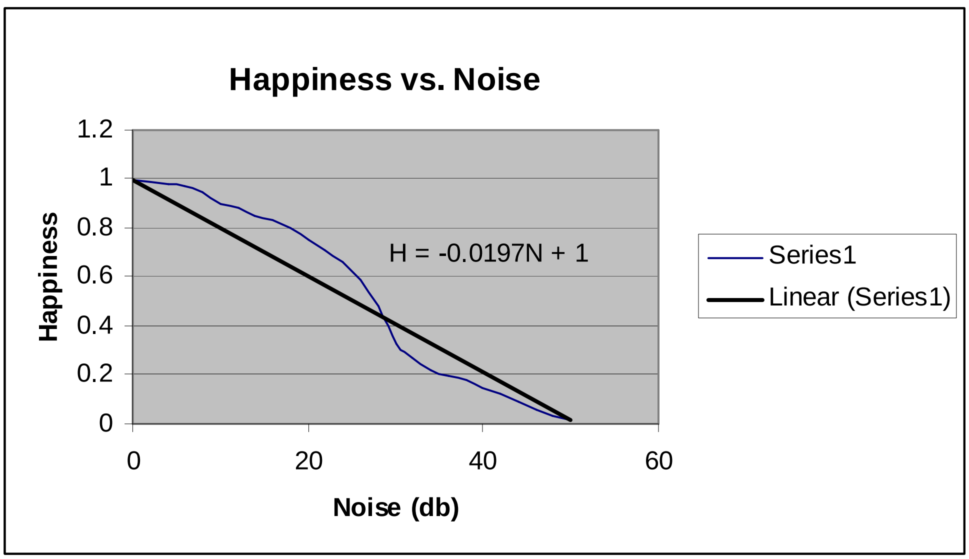


Figure 17. Happiness vs. Noise of Unit

The blue line on the graph above is the happiness function. As shown above, it may be approximated linearly to produce an equation for happiness as a function of decibel level.
For a particular scenario, the graphs produced for all variables may be joined together to form a single expression for the happiness. Some variables are considered more important than others, so they will be appropriately weighted as a fraction of a whole. That is if there were three happiness functions, and one variable was twice as important as the other two, the weights would be 0.5 for the most important variable, and 0.25 for the two remaining variables. The overall

happiness function is taken as the sum of the weighted happiness functions. In scenario 3, the following happiness functions were considered important:

For noise: $H_N = -0.197N + 1$

For power: $H_p = -0.0008P + 1$

For weight: $H_w = -0.0304W + 1$

For height: $H_h = -0.1829h + 1$

For width: $H_w = -0.4886W + 1$

For length: $H_l = -0.3735l + 1$

These happiness functions were weighted accordingly:

Noise = 0.3, Power = 0.05, Weight = 0.3, Length = 0.15, Width = 0.1, Height = 0.1

It was thought that the oxygen user would be most bothered by the weight of the unit and the noise produced by the unit. Of second greatest importance is the bulkiness of the unit caused by its size. Lastly, the oxygen user would likely not want the unit to use a high level of power so that battery life is longer.

10.2.4 Determining Demand with the Happiness Function

A beta function is determined by evaluating the ratio of the overall average happiness (utility) of the competitor's products and the overall happiness of the product being sold. The beta function is under the constraint 0 < β < 1.

$$\beta = \frac{H_c}{H_I} \tag{6}$$

Where:

H_c = the happiness of the competitor's product
H_I = the happiness of the product being sold

The lower the happiness ratio, the more likely the consumer is to purchase the designed product over that designed by the competition. The beta function plays a vital role in determining the demand of the designed product; it also can be used to develop the product if utilities are known before beginning the design. The value β can also be used to alter an existing product to make it more desirable to the public. The lower the β value, the higher the demand will be for the product. On occasion, the beta value may be larger than 1, but in order for the product to sell the product should be cheaper than the competition so that there is some demand.

With this beta function in conjunction with an alpha function, or consumer awareness function, which is dependant on advertising, the demands for the competitor's and the product being sold may be determined. The alpha function is under a constraint that is identical to the one on the beta function. That is $0 < \alpha < 1$. The alpha function specifically is how aware the consumer is of your product compared to that of the competition.

The alpha and beta function may be substituted into two simultaneous equations to solve for the demand.

The first equation is given by:

$$\beta p_1 d_1 = \alpha p_2 d_2 \left(\frac{d_1^{\alpha}}{d_2^{\beta}} \right) \quad (7)$$

Where:

- p_1 = the price of product being sold
- p_2 = the average price of the competitor's product
- d_1 = the demand of the product being sold
- d_2 = the total demand of the competitor's product

For our analysis, the average price of the competitor's product is known. In addition, the price of the product being sold is set as a parameter leaving only the demands unknown. The selling price of the product may be varied in order to capture the sector of the market while still maintaining a competitive price as compared to the competition.

The second equation is given by:

$$p_1 d_1 + p_2 d_2 = Y \quad (8)$$

Where:

Y = the amount of money available in the market of interest.

It is convenient to solve equation 8 for d2 and substitute it into equation 7, and then solve equation 7 for d1. Doing this gives d1 as a function of d1.

This gives:

$$d_1 = \left(\frac{\alpha p_2 \left(\frac{Y - p_1 d_1}{p_2} \right)^{1-\beta}}{\beta p_1} \right)^{\frac{1}{1-\alpha}} \quad (9)$$

or $d_1 = \phi(d_1)$ (10)

Choosing a second function, $d_1 = f(d_1)$, where d_1 is always equal to itself allows for the demand d1 to be solved for iteratively in Excel. This numerical method of direct substitution is equivalent to finding the intersection of the two functions on a graph of d_1 vs. $F(d_1)$.

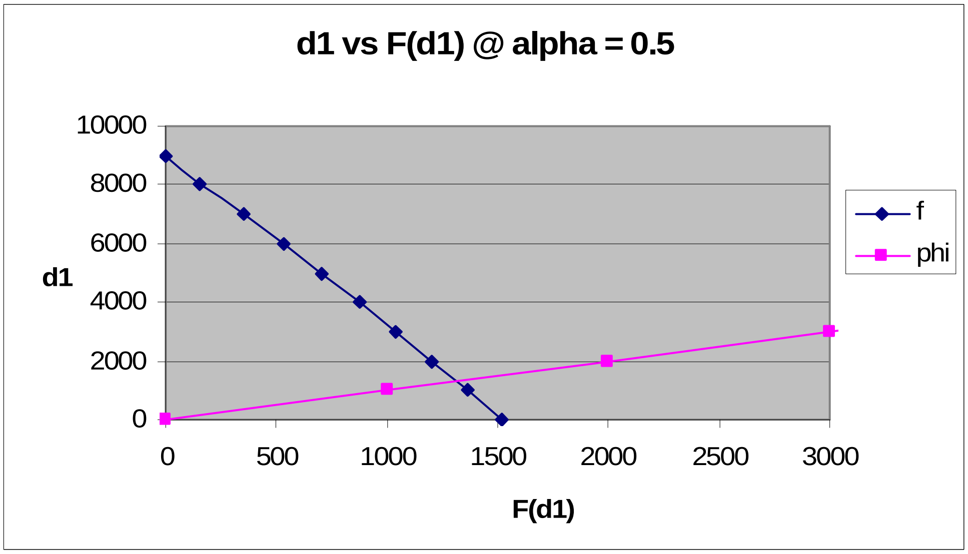


Figure 18. Graphical Demand Estimate

The demand may be determined for different values of α and β. Assuming that the customer base for this type of device is captivated, or required, to buy a product in the domain of the designed product, there will be an overall demand for the product that will be the sum of the demands of all competitors' demands, as follows.

$$D = d_1 + d_2 \tag{11}$$

Where:

D = the total demand the market will allow

According to the American Lung Association[2] there are 90,000 American people that develop Chronic Obstructive Pulmonary Diseases (COPD) each year. It is estimated that approximately 15% of these people will develop the need for oxygen production and delivery equipment, which produces a total demand of approximately 14,000 people each year.

In the case where the total demand is greater than what the market will allow, a different set of equations need to be used. Equation 8 remains the same, but instead of using equation 7, the following equation is used:

$$d_1 = \left(\frac{\beta}{\alpha}\right)^{1-\alpha} \left(D - d_1\right)^{\frac{1-\beta}{1-\alpha}} \tag{12}$$

10.2.5 Graphical Method for Determining Demand

Demand may also be determined by rearranging equations 7 and 8 for d_1 and plotting both equations on a graph of d_1 verses d_2.

When different values of d_2 are selected, a graph such as the following is produced from scenario 3:

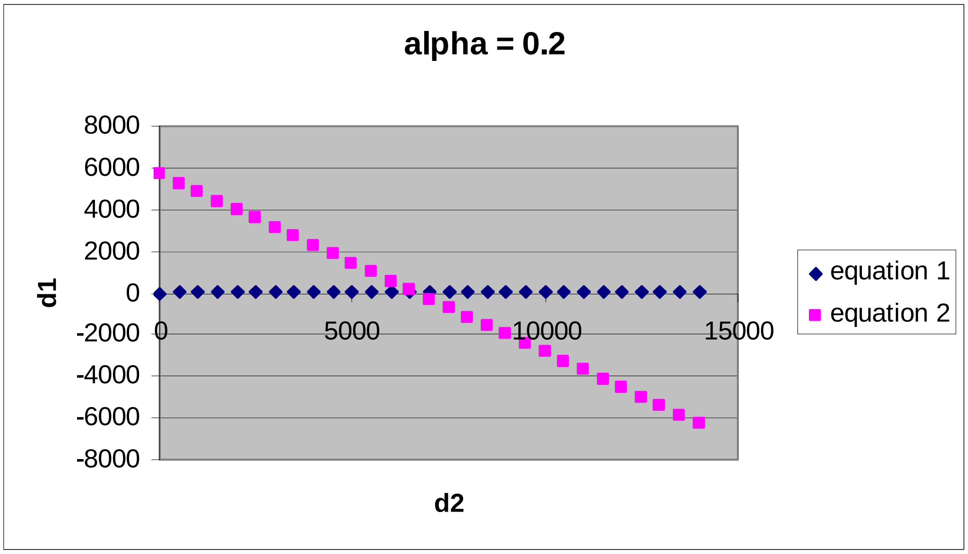


Figure 19. Graphical Demand Estimate

In this case, equation 1 is the rearranged form of equation 7, and equation 2 is the rearranged form of equation 8. By changing the scale and the number of points plotted, the root is able to be located to whatever accuracy is desired. A value of α equal to 0.2 is set as a parameter in the graph above, but α may be whatever value is desired between 0 and 1. It is often convenient due to its simplicity to use values of alpha that are a tenth of a unit apart (0.1, 02,…, 0.9). The graph above was produced using a constant β value, and a constant selling price for the product being sold, p_1. The variables not mentioned, namely Y and p2, are not controllable.

If the sum of the demand of the competitor's product and the product being sold is greater than the total demand of the market, D, equation 12 should be used in place of equation 7, but the analysis remains the same.

10.2.6 Comparison of Graphical and Numerical Methods

The graphical method does produce some deviations from the method of direct substitution, but the graphical method will more likely give values for the demand at higher α values than the substitution method. When the method of direct substitution does not diverge, the error between direct substitution and the graphical method is quite large, occasionally about several thousand percent. However, part of this may be due to the direct substitution's inability to obtain a rational trend due to its persnickety convergence behavior. That is, direct substitution is very sensitive to the initial guess for the demands. If the wrong guess is chosen, it is likely to converge to an undesirable value, or not converge at all. Both predictions for the demand as a function of α are shown below in Figure 20.

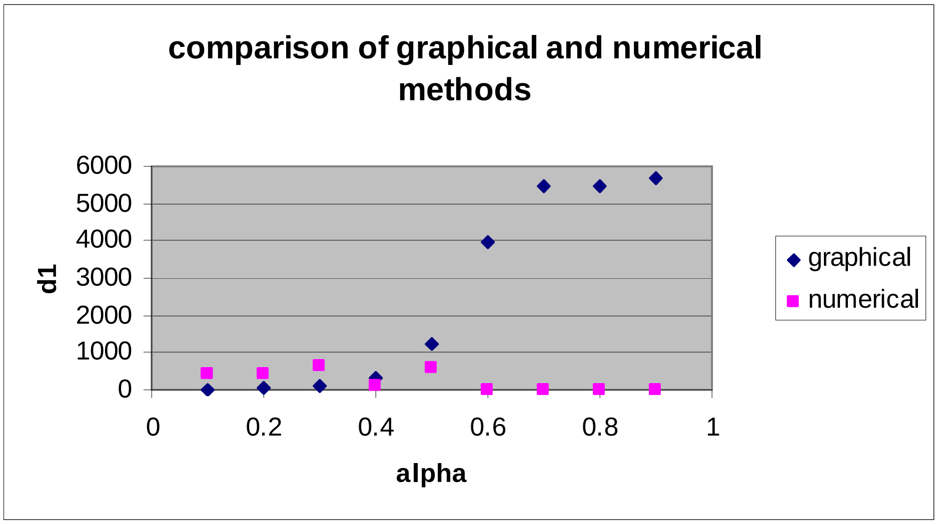


Figure 20. Graphical vs. Numerical Demand Estimation

It is obvious that the graphical method produces a clear-cut trend, while the numerical method does not. In the graphical method, the demand is low for small values of α, but as alpha increases the demand increases exponentially. Eventually as the market becomes saturated at high values of α, the demand experiences a negligible increase. This behavior makes sense because it would take awhile for consumers to become aware of the product, but when they did, demand would increase rapidly. As an even larger percentage of consumers become aware of the product, the demand would likely reach a steady value due to a balance between people that were not interested in buying the product, and people that are.

Figure 20 uses the results from development of scenario 1 as an example. As the β value increases, the steepness of the curve from the graphical method tends to increase, while the numerical method produces a line with little increase of the demand with alpha. For low values of alpha, the behavior of the numerical solution is due to predicted market behavior, whereas at higher alpha values, typically between 0.3 and 0.6, the behavior is due to lack of convergence of the numerical method. The behavior of a higher β value is evident from the same type of plot produced for the choice scenario, scenario 3. It is evident that the higher beta value prevents consumers from buying the product in great quantities at low values of alpha.

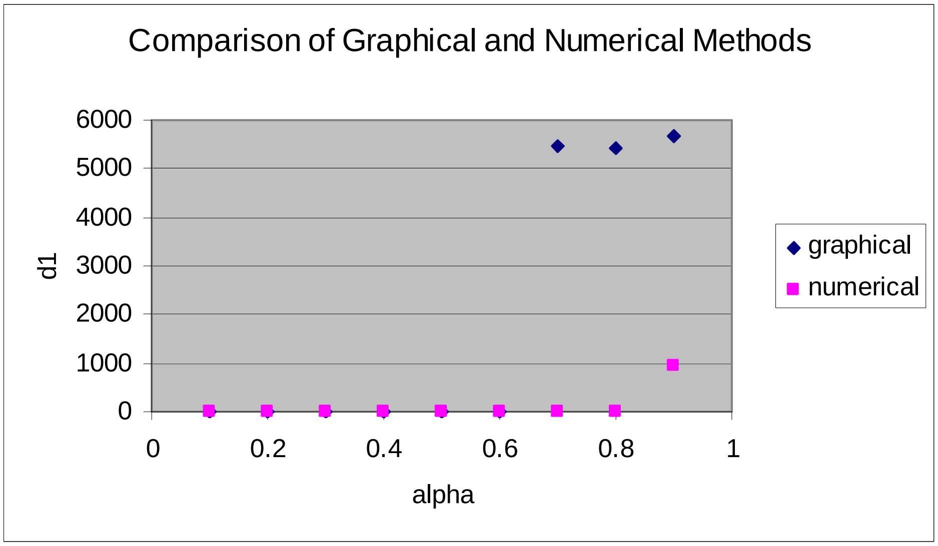


Figure 21. Graphical and Numerical Comparison

For the instant, all other variables besides the beta function are kept constant between the two scenarios. The β value for scenario 1 was 0.554, while the β value for scenario 3 was 0.702. Due to its superiority in predicting a logical trend, final analysis of scenario 3 made use of the graphical method. The major limitation of using this model is its lack of flexibility. Other numerical methods such as fixed-point iteration and the Newton-Rahpson method were also examined, but they produced similar results to the substitution method. For completeness, the demand model equations should be better understood, so that convergence of the numerical methods will become more favorable.

10.3 Variables Affecting the Demand Model

10.3.1 Relating Time to Alpha

The consumer awareness for the product of interest over time at a constant beta may be determined by relating the α for a particular demand to the time that this α would occur. This is accomplished with the following equation:

$$\alpha = \frac{yt}{1+yt} \tag{13}$$

Where:

y = the rate of advertising

Below is a graph of the variance of α over time for three different values of y. The low case is when y = 1, the medium case is when y = 3, and the high case is when y = 5.

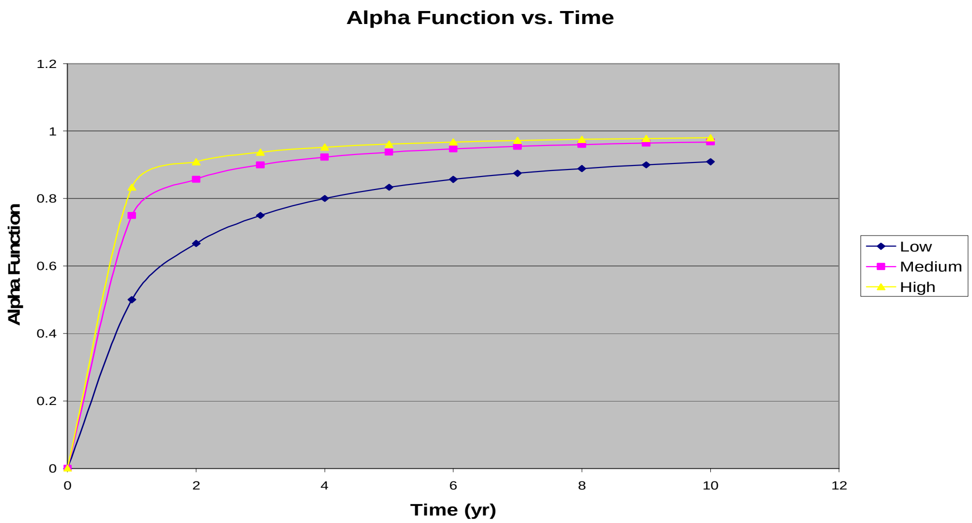


Figure 22. Alpha vs. Time

It is apparent from the graph that as time increases the value of α increases exponentially and then levels off. For higher values of y, the rate of initial increase is higher. This means that the consumers exponentially become aware of the product, but the rate of awareness happens faster at higher advertising rates. It can be predicted from the behavior of the plot that as the rate of advertising increases, the rate of change of the alpha function varies inversely. It is worth restating that the alpha function cannot be greater than 1, so an infinitely larger advertising rate would not produce a consumer awareness greater than 1, that is 100%. At an infinitely large advertising rate, all of the consumers would be aware of the product immediately. Unfortunately, the quantitative values (i.e. dollar figures) corresponding to the advertising rate are not known.

10.3.2 Relating Demand to Time

When the relation between α and time is known, and the relation between consumer demand for the product of interest and α is known, a relationship between demand and time may be deduced. This may be accomplished by substituting values of α determined for desired times into the desired demand method (graphical or numerical), or by interpolating between demand values determined at specific values of α.

When the relation between demand and time is known, plots of demand verses time may be developed using scenario 1 for various advertising rates:

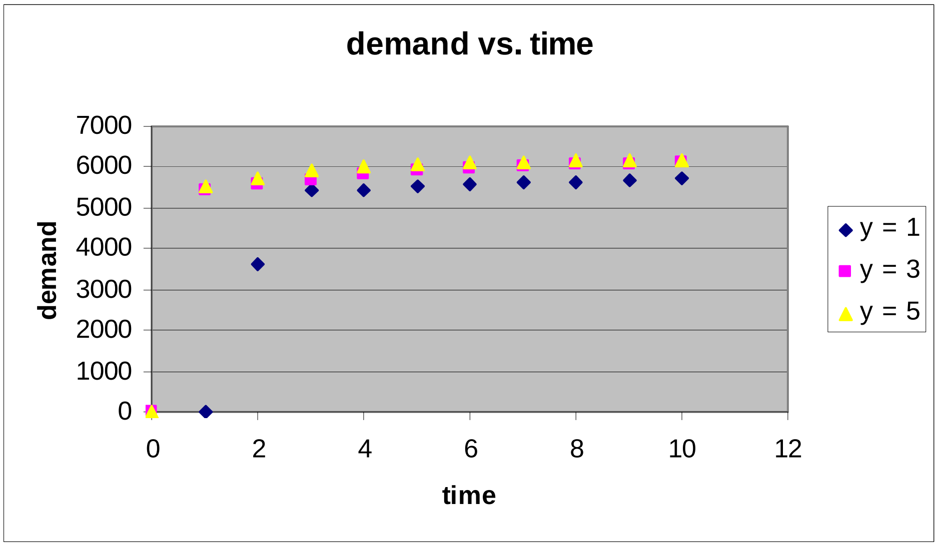


Figure 23. Demand vs. Time

This figure shows the change in demand with time for three different rates of advertising for scenario 3. From the figure, it is apparent that as the advertising rate y increases the demand reaches a steady state in a shorter time period.

10.3.3 The Beta Value Revisited

In figure 24, demand was plotted against α for different β values, at a constant selling price of $5500.

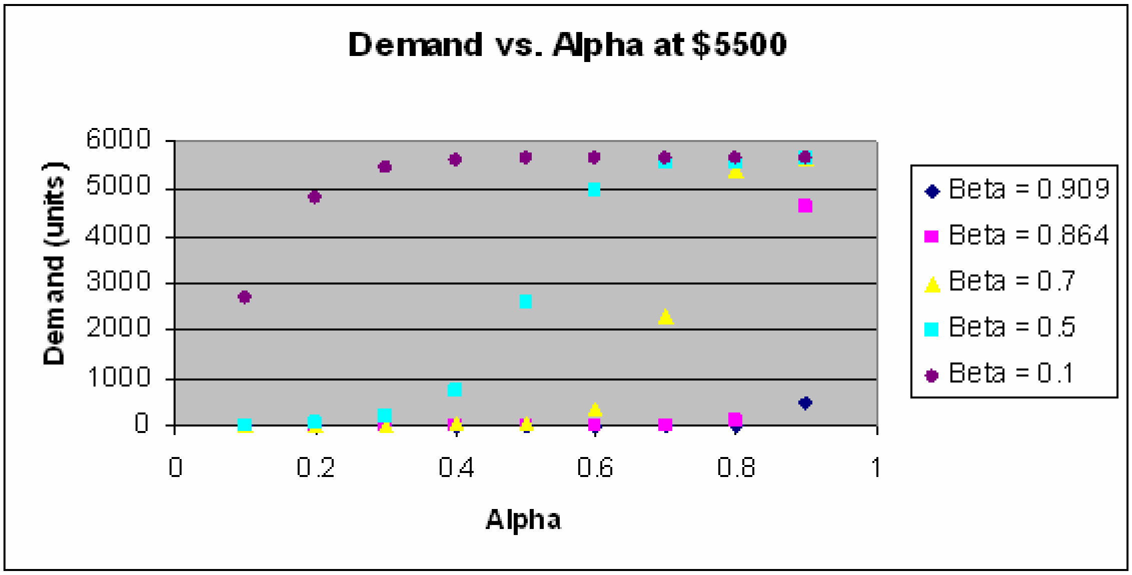


Figure 24. Demand vs. Alpha at $5500

As the β value decreases, the curves become steeper. That is, at high β values the product becomes so popular compared to the competition that only a few people have to be aware of the product for the product to be purchased. For our project, we would like to have a lower β value so that we are able to reach high demand level quickly, and therefore have sufficient demand to make a profit during our ten year project life.

10.3.4 Relating Demand to Alpha at Different Selling Prices

In figure 25, demand is related to α with the different selling prices as a parameter. A value of β = 0.865 was chosen which correlates to the design that was used before the addition of the Acoustiblock insulation.

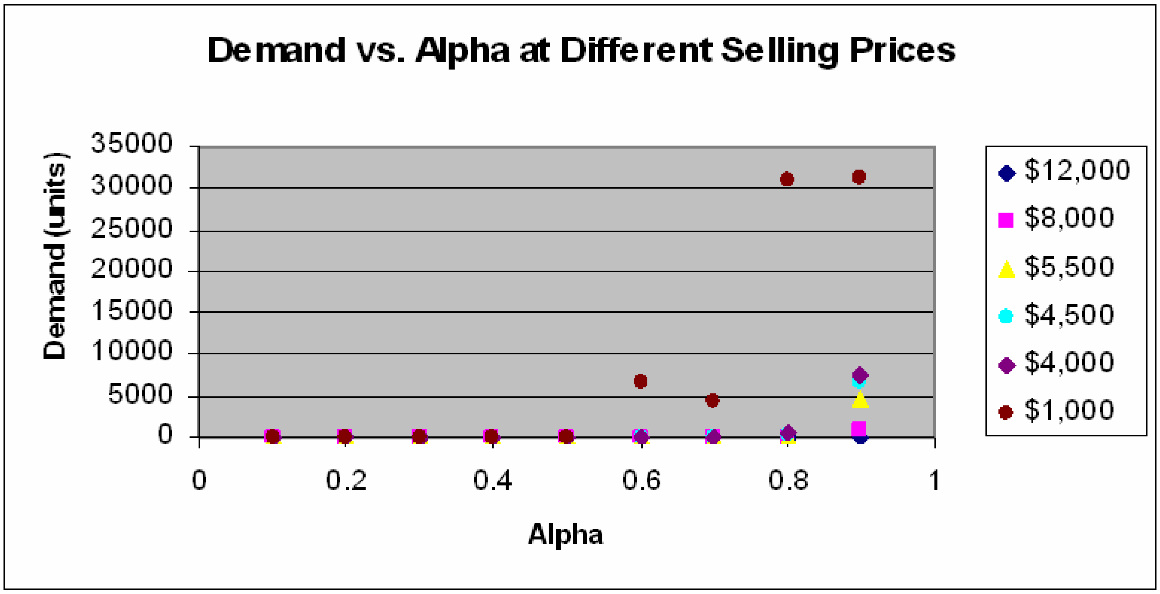


Figure 25. Demand vs. Alpha at Multiple Selling Prices

After the addition of Acoustiblock insulation, the Beta value was reduced to a value of 0.75. A plot with a Beta of 0.72 is shown, which should be a reasonable approximation.

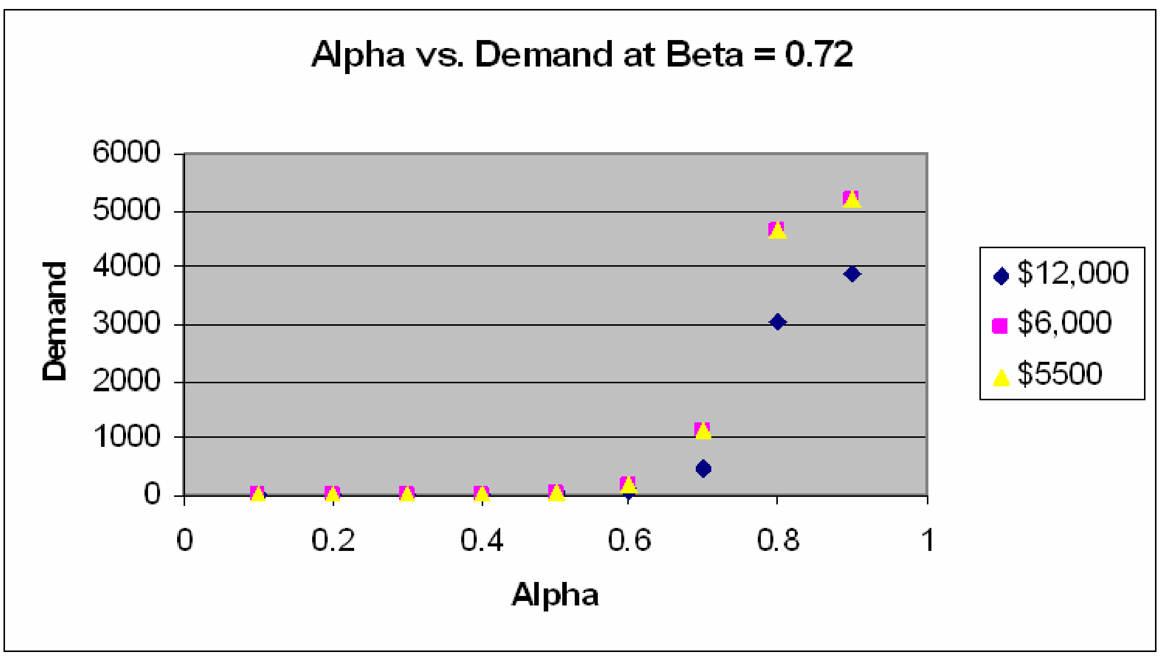


Figure 26. Alpha vs. Demand at Beta=0.72

It is apparent that as the selling price increases, the demand increases at a slower rate with increasing α. The behavior of this graph is similar to the demand verses alpha graph with beta as a parameter. A certain level of demand needs to be reached during the project life such that the process will become profitable. At $6000, this breakeven point is about 4000 units/yr, and will be discussed later in the report.

10.3.5 Relating NPW to Beta at Different Advertising Rates

In figure 27, demand is related to alpha with different advertising rates as a parameter.

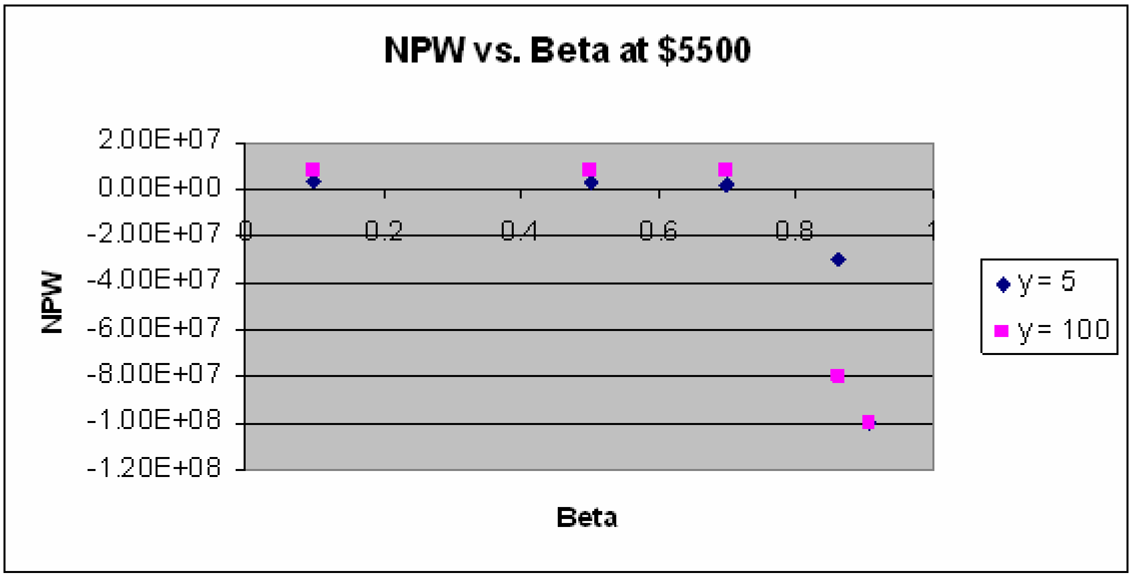


Figure 27. NPW vs. Beta at $5500

When the advertising rate y is changed, higher values of NPW can be reached, but crossover point of profitability remains nearly constant near a value of 0.7. Therefore, for the product to be profitable, a beta value near 0.7 needs to be achieved.

10.3.6 Effect of Changing the Selling Price on Demand with Changing Alpha Values

The effect of changing the selling price may be examined when considering the β value that was arrived at when considering the addition of the Acoustiblok.

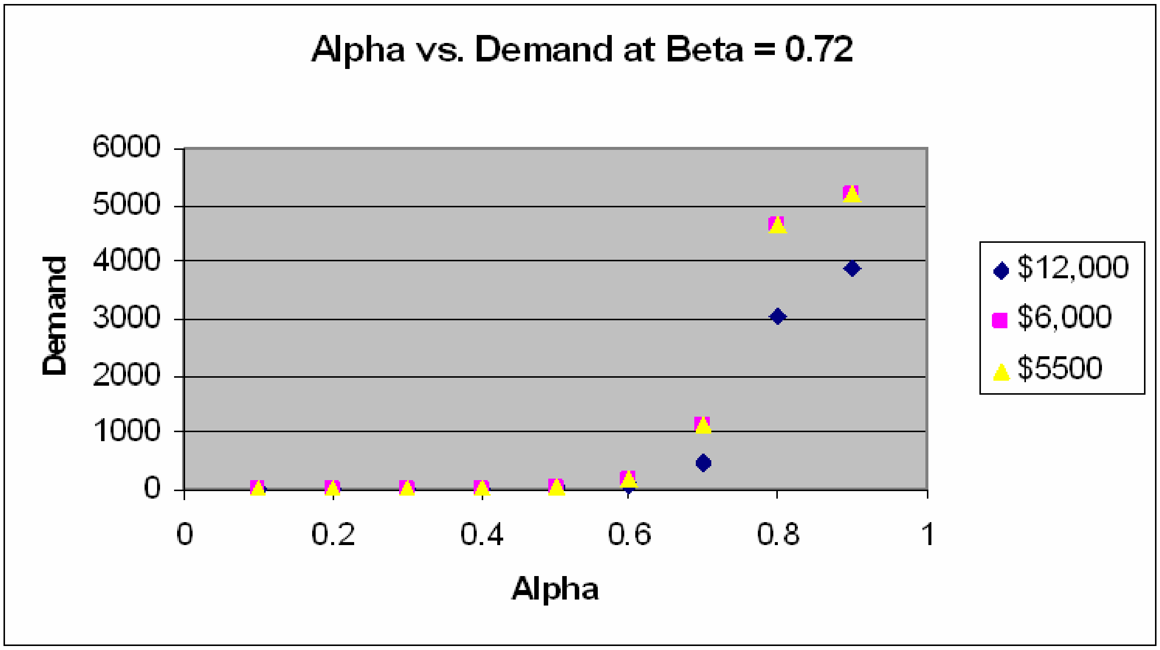


Figure 28. Alpha vs. Demand at Beta=0.72

It is apparent that as the selling price increases, the rate of increase of the demand with α decreases. However, pursing any of these projects will give a demand at alpha = 0.9 that breakeven point according to the Breakeven vs. Selling Price Chart (Figure 9).

10.4 Financial Data

This section describes the financial stability as well as the expected earnings and loans for the start-up and daily operation of our facilities. A breakeven analysis, lists of capital equipment and a cumulative cash position chart are also included in this section for scenario 3.

10.4.1 Determining Net Present Worth

To determine the net present worth (NPW) for this project, the TCI was determined using table 6-9 from Peters and Timmerhaus[22] that have been adjusted to reflect actual levels of expected costs. This table is based on a percentage of purchased equipment cost that was determined by pricing equipment that was large enough to handle the maximum available capacity for the plant. The table considers direct costs of infrastructure, and indirect costs of things such as engineering work and legal fees. From the table, the fixed capital investment (FCI) and the working capital (WC) were calculated. The sum of the FCI and the WC is the TCI.

Once the TCI, FCI, and WC were found, the total product cost (TPC) was determined based on raw material prices and tables from Peters and Timmerhaus. The TPC was determined as a function of the demand and was calculated for each of the operating years. The TPC was then used to determine the total costs associated with the process for the 10 years of operation.

The NPW was then found considering all of these variables in addition to demand, depreciation and taxes. The following table shows the NPW for manufacturing everything in-house, cash flows, and costs determined for the design of this product under scenario 3 with the design described earlier in the report.

Table 4. NPW and Cost Calculations

						P2=	2.16E+03	P1=	7.E+03		
Manufacturing Heat exchangers only						D=	1.40E+04	i=	8.00E-02	y	3.00E+00
Year	**β(t,H)**	**α(y,t)**	**Demand**	**Sales**	**Product Cost**	**Gross Earnings**	**Depreciation**	**Taxes**	**Net Profit**	**Cash Flow**	**$Cf_i/(1+i)^k$**
1	0.76	0.83	4.E+03	2.36E+07	**1.87E+07**	4.87E+06	5.55E+06	1.70E+06	-2.38E+06	3.17E+06	2.93E+06
2	0.76	0.91	5.E+03	3.13E+07	1.96E+07	1.17E+07	5.55E+06	4.08E+06	2.04E+06	7.58E+06	6.50E+06
3	0.76	0.94	5.E+03	3.22E+07	1.97E+07	1.25E+07	5.55E+06	4.38E+06	2.60E+06	8.14E+06	6.46E+06
4	0.76	0.95	5.E+03	3.27E+07	1.98E+07	1.30E+07	5.55E+06	4.54E+06	2.89E+06	8.43E+06	6.20E+06
5	0.76	0.96	5.E+03	3.31E+07	1.98E+07	1.33E+07	5.55E+06	4.64E+06	3.07E+06	8.62E+06	5.86E+06
6	0.76	0.97	5.E+03	3.33E+07	1.98E+07	1.34E+07	5.55E+06	4.70E+06	3.19E+06	8.74E+06	5.51E+06
7	0.76	0.97	5.E+03	3.34E+07	1.98E+07	1.36E+07	5.55E+06	4.75E+06	3.28E+06	8.83E+06	5.15E+06
8	0.76	0.98	5.E+03	3.35E+07	1.99E+07	1.37E+07	5.55E+06	4.79E+06	3.35E+06	8.89E+06	4.80E+06
9	0.76	0.98	5.E+03	3.36E+07	1.99E+07	1.38E+07	5.55E+06	4.82E+06	3.40E+06	8.95E+06	4.47E+06
10	0.76	0.98	5.E+03	3.37E+07	1.99E+07	1.38E+07	5.55E+06	4.84E+06	3.44E+06	8.99E+06	4.16E+06
										NPW=	1.E+06

10.4.2 Determination of the Total Product Cost

The total product cost was determined by considering the TCI and the FCI. One of the first things that needs to be known to determine the FCI, is the purchased equipment cost.

The following table lists the capital equipment needed to begin operation of our facility. The expected price of each item is also shown.

Table 5: Equipment prices

Equipment	Use	Size	Price

Storage Tank	Bismuth Oxide	50 m^3	33373
Storage Tank	Vanadium Oxide	50 m^3	33373
Storage Tank	Magnesium Oxide	50 m^3	33373
Conveyor System	Plant Automation	200 m, .4 m width	254627
Roller Conveyor	Finished Product	21 m, .5 m width	6180
Mixer, high solids	Bismuth Vanadate	1.5 m^3	12361
Mixer, high solids	MgO Slurry	1 m^3	12361
Welder/ Brazing Equipment	Heat Exchanger		1483265
High Temperature Press	Membrane Sintering	2000 kW, 100 Mpa	741633
High Temperature Press	Mgo Sintering	2000 kW, 100 Mpa	741633
High precision cutter	Copper Cutting	Rotary cutter 10kg/s	2224898
Oven	Sealant Annealing	1m^3	61803
Grinder 100 mesh	Uniform Particle Size	1.3 kg/s	282202
Automation Equipment	Plant Automation		7416327
		Equipment Price	13337409

Using the following table given as table 6-9 in Peters and Timmerhaus, the Purchased Equipment Cost may be substituted to calculate the TCI.

Table 6. Total Capital Investment

Costs Based on Solids Processing Plant

Manufacture Everything

Cost Item	Measurement Criteria	Amount
Direct Costs		
Purchased equipment	100	13337409
Installation	45	6001834
Instrumentation (installed)	18	2400734
Piping	16	2133985
Electrical systems (installed)	10	1333741
Buildings (including services)	68	9069438
Yard improvements	15	2000611
Service facilities	40	5334964
Total Direct Cost		41612717
Indirect Costs		
Engineering and Supervision	33	4401345
Construction expenses	39	5201590
Legal expenses	4	533496
Contractor's fee	17	2267360
Contingency	35	4668093
Total Indirect Cost		17071884

FCI	440	58684600
Working Capital (15% of TCI)	78	10356106
TCI	518	69040706

The TCI is simply the sum of the FCI and the working capital, where the working capital is taken to be 15% of the TCI. The FCI is the sum of all direct and indirect costs. The ratio factor of the building cost was increased from a value of 25 in Peters and Timmerhaus to 68 to account for the fact that buildings will play a larger part since the facility will largely be indoors rather that mainly outdoors in the case of a solid processing plant.

The total product cost considers the raw material costs, labor costs, utilities, overhead costs, and general expenses. This was calculated for each year using the annual demand.

The following table (Table 6-7) in Peters and Timmerhaus, shows the calculation for the TPC for the case where everything is manufactured in-house:

Cost Item	Basis of Estimate	Amount	
Raw material	Dealer quotes where applicable		
Copper	$9.50/lb allfoils	**.061 lb**	3200.25
Vanadium Oxide	$3.75/lb (15 year average)	**1.38 lb**	28578.59
Bismuth Oxide	$3.33/lb (USGS 5 yr average)	**7.83 lb**	143991.4
Vacupor insulation	$50/unit estimate		276121.7
Magnesium oxide	$2/lb estimate	**4.62 lb**	51027.28
Sealant	$10/gal estimate	**.02 gal**	1104.487
Operating labor	Brazing/welding, Sealant application,		
Skilled	3 hrs. for each unit needed for skilled workers, $30/hr		497019
Unskilled	5 general laborers/shift, 300 days/yr $20/hr		720000
Operating supervision	15% of operating labor		182553
Utilities			
Electricity	Brazing equipment, furnaces and facility power	**2.31*demand**	12757
Cooling water		**$500 estimate**	500
Process water		**.5*demand**	2761
Maintenance and repair	7% of FCI		4107922
Operating supplies	15% of maintenance and repair		616188
Laboratory charges	11% of operating labor		133872
Royalties (not on lump sum)	5% of total product cost		1073194
Taxes (property)	2% of FCI		1173692
Financing (interest)	5.5% of TCI		3797239
Insurance	1% of FCI		586846
Overhead Costs	60% of maintenance, labor, and supervision		3304496
General Expenses			
Administrative costs	20%of operating labor		243404
Distribution and marketing	15% of total product cost		3219582
Research and Development	6% of total product cost		1287833
	Total Product Cost		21463882

The NPW two other scenarios was also considered. These were manufacturing only the BICUVOX membranes and buying everything else off the shelf, and manufacturing only the heat exchangers and buying everything else off the self.

10.4.3 Relating NPW to Selling Price

Net Present Worth may be related to selling price while holding the β value constant. The α value by necessity was not constant since it changed with demand in the calculation of the net present worth. This is shown below in figure 8.

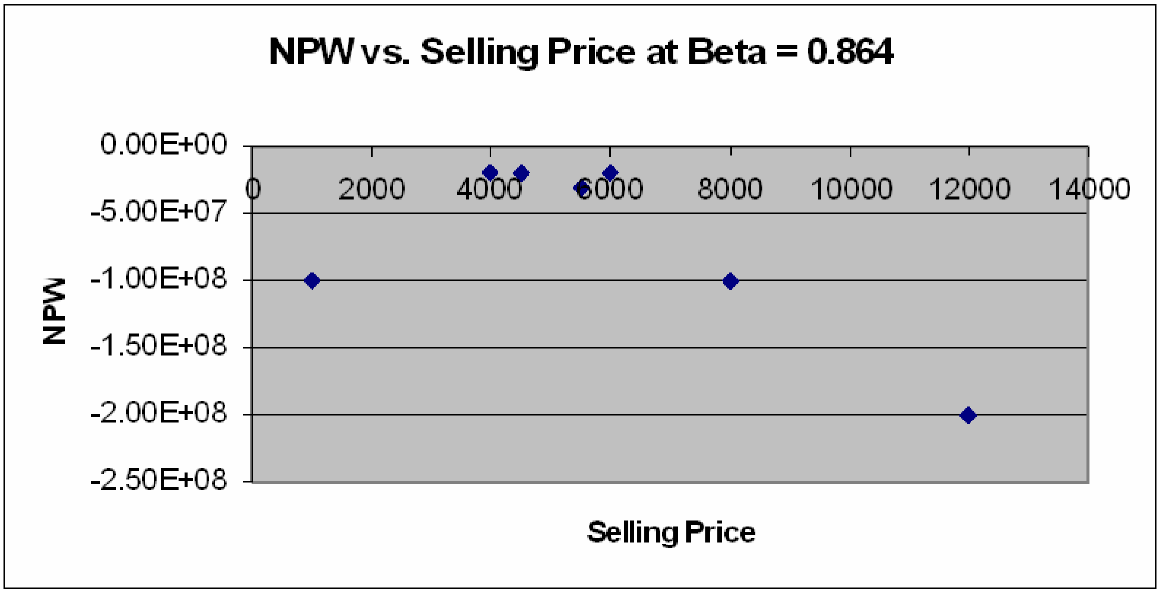


Figure 29. NPW vs. Price at Beta=0.864

The process is never profitable for a beta value of 0.864. This can be expected when considering the NPW verses beta plot given earlier in the report. From this, it may be predicted that a plot of NPW verses selling price would yield positive values of NPW if a value of β less than approximately 0.7 was chosen. When soundproofing was added to the system, the value of beta changed from 0.864 to 0.75. This change was sufficient to increase the NPW such that it had a positive value for prices around $6000. However, this number failed to consider the Airsep FreeStyle in the Happiness Function. As a result, the Beta Function was increased to a value of 0.78. This puts the beta function above the threshold of profitability. The behavior of NPW with selling price for a beta value of 0.78 is shown below. The easiest solution is to lower the beta function.

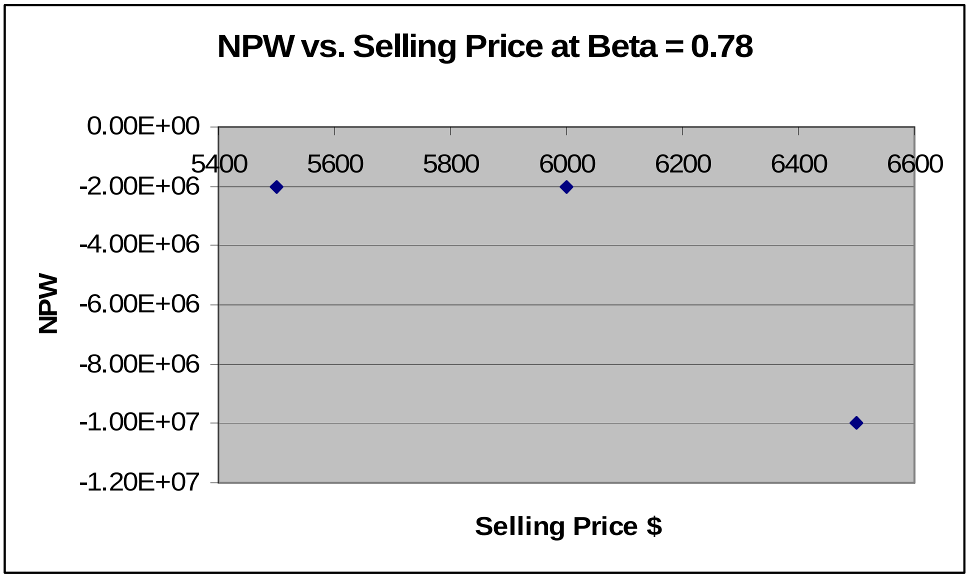


Figure 30. NPW vs. Price at Beta=0.78

10.4.4 The Effect of Advertising on the Net Present Worth

Changes in the NPW with advertising were examined for four different selling prices.

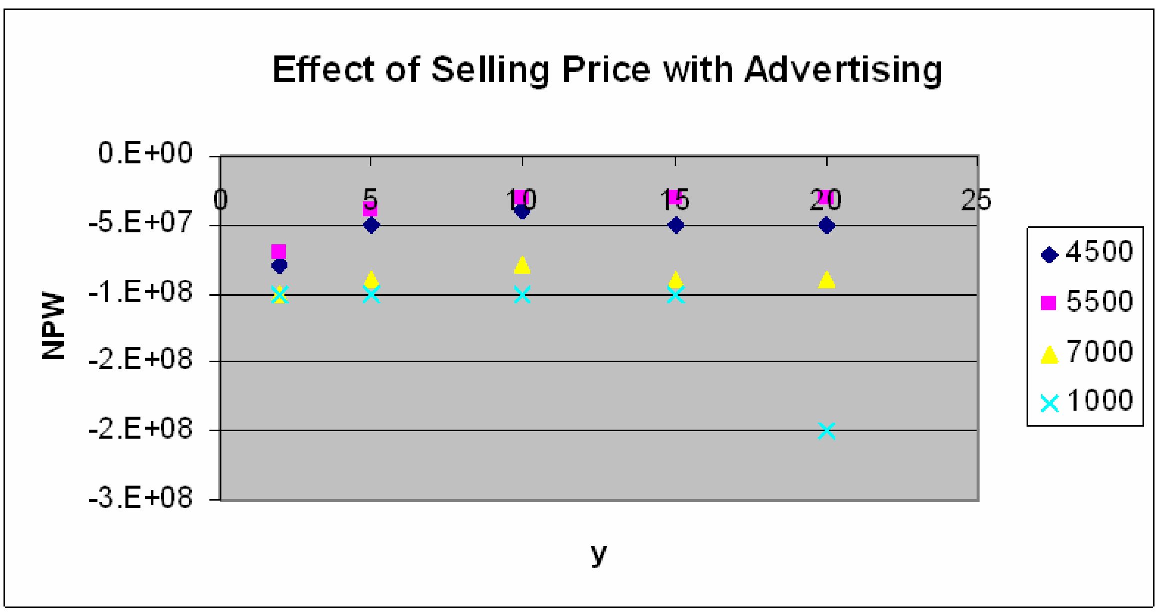


Figure 31. Effect of Selling Price with Advertising

For this model, the change in the NPW with the advertising rate was determined by assuming the product cost followed the following expression:

$$Cost = TPC + \left(\frac{y}{100}\right) * TPC \tag{14}$$

It is apparent that modest rates of advertising, between values of 5 and 10, generally help increase the NPW, while increasing the rates of advertising beyond 10 generally cause a decrease in NPW. The curves for a low price of $1000 and a high price of $7000 nearly match for advertising rates less than 15. Low selling prices generate high sales, but money is lost with each unit since the Total Product Cost for our unit is greater than the selling price. At high selling prices, the demand is lower since many people are unwilling to pay for the unit. The demand at $7000 is likely less than the 4000 units needed to breakeven at $5500. If a specific number of units are sold at a certain price other than $5500, with a different quantity than 4000, the profit may differ from that in the breakeven analysis. The breakeven analysis therefore is price specific. It can be predicted that the demand at the breakeven point at $7000 was not met, but for verification an additional breakeven analysis at $7000 will be included.

10.4.5 Effect of Changing the Selling Price on Demand with Changing Alpha Values

The effect of changing the selling price may be examined when considering the β value that was arrived at when considering the addition of the Acoustiblok.

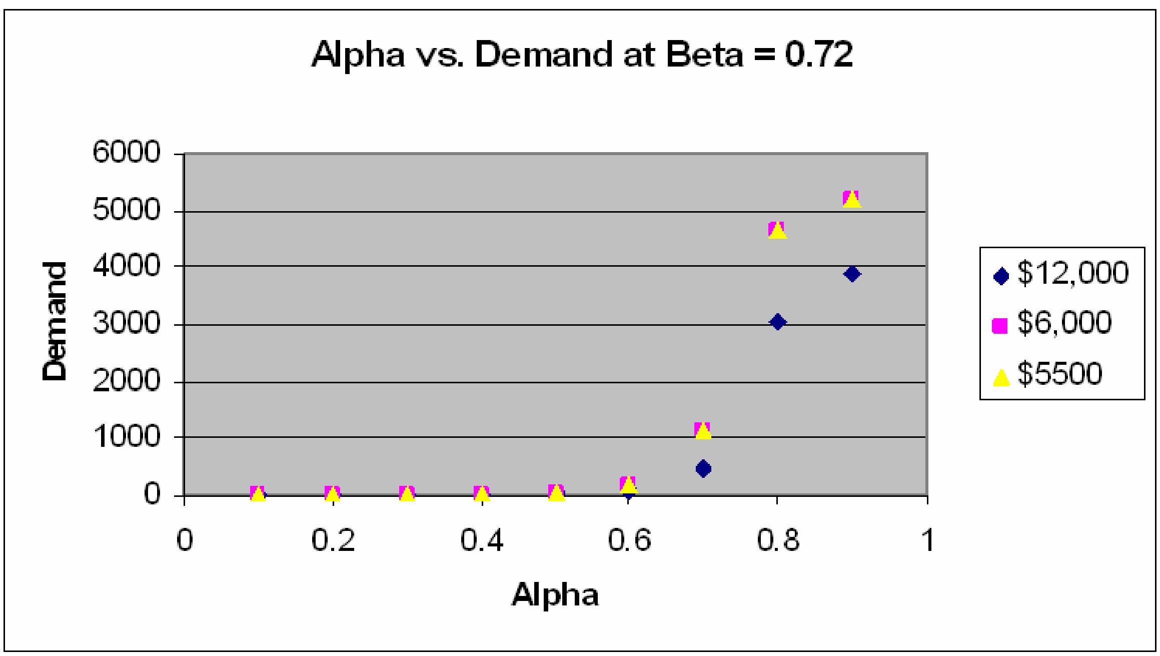


Figure 32. Alpha vs. Demand at Beta=0.72

It is apparent that as the selling price increases, the rate of increase of the demand with α decreases. This trend is not unique, for we know from the plot of demand vs. alpha chart at various selling prices; the final demand that is reached is lower at higher selling prices. However, just because the demand is low, it doesn't mean that the process will not be profitable. In fact, a positive NPW was reached at a selling price of $12,000. Further examination using breakeven analysis will show various selling prices and their corresponding demands to become profitable.

10.4.6 Failures of the Economic Model

The graphical model that was chosen is very difficult to manipulate. It typically takes 20 minutes to manipulate the model for alpha values ranging from 0.1 to 0.9. As discussed before, values of Y, β, p_1, p_2, d_1, and d_2 are held constant. In order to make the graphs above, 28 simulations were run for selling prices ranging from $12000 to $1000. Beta values ranged from 0.909 to 0.1. Estimations had to be made on the little data that could be obtained in the time available. When developed to determine the NPW, which will be discussed later, the model did not include what the selling price of the Acoustiblock soundproofing was, but it is assumed that the price is low. In addition, only an estimate could be given for the welding equipment.

10.4.7 Breakeven Analysis

It is important to know the capacity of the plant to breakeven. The following figure shows the TPC and the sales as a function of the plant capacity. The model shows that in order to break even at a selling price of $5500, a demand of at least 4000 units/yr must exist. If the demand drops below 4000 units/yr, the costs of production will outweigh the income generated from sales.

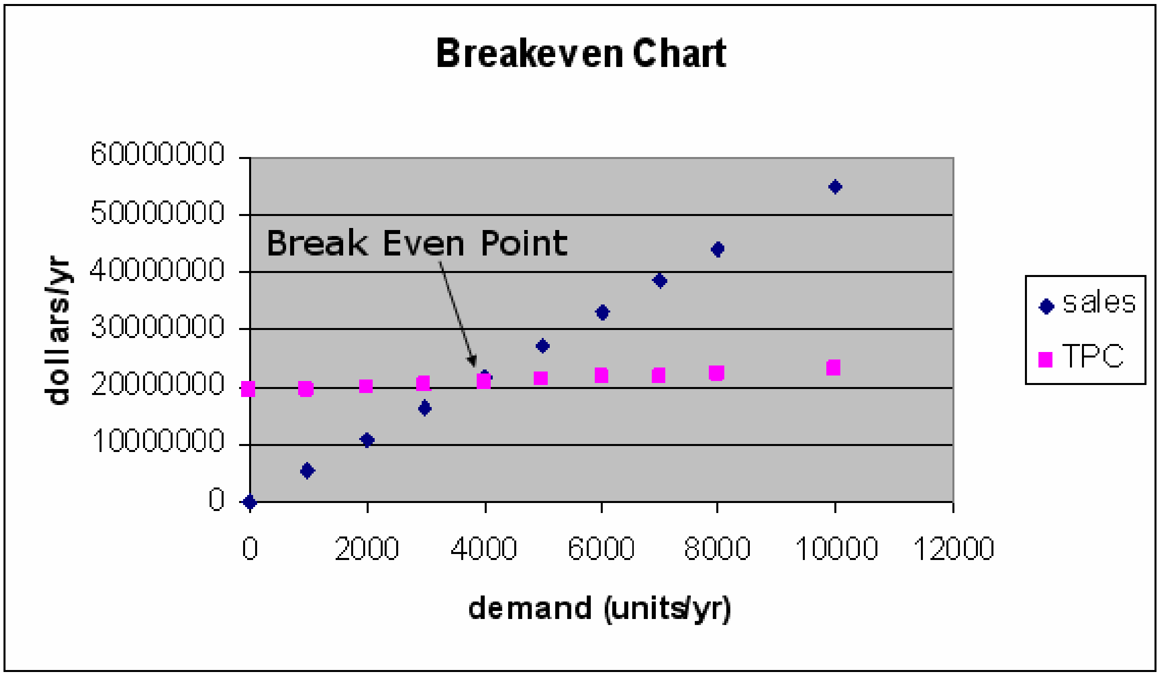


Figure 33: Breakeven Analysis

A second graph shows the break-even point for a selling price of $7000.

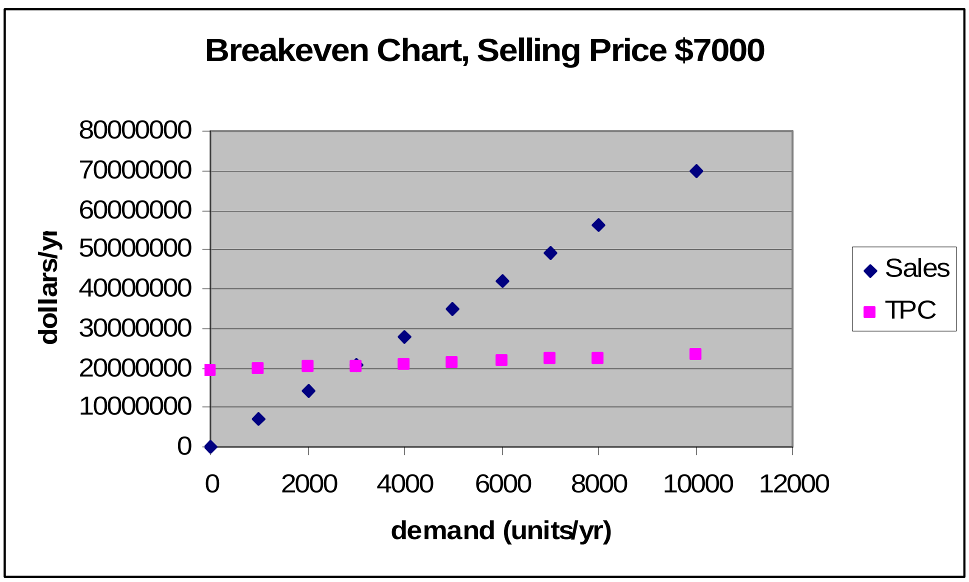


Figure 34. Break Even Analysis

As expected, the demand is different for a different selling price. It makes sense that the breakeven point is at a lower demand than for a selling price of $5500. However, the breakeven point occurs at the same selling price. This makes sense since the TPC is not a function of the selling price, and is not a strong function of the demand. Shown in figure 35 is a plot of the breakeven point as a function of selling price.

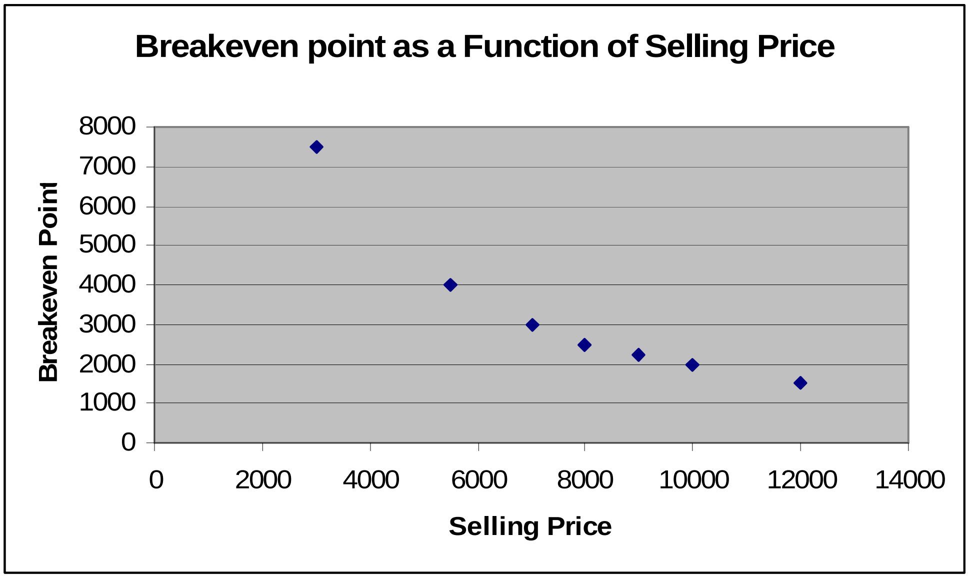


Figure 35. Break Even with Respect to Price

10.4.8 Economic Life of Project

The life of this venture is estimated to be at least ten years. The following graph shows the expected cumulative cash position for each year of the project in the case that a beta of 0.75 was reached.

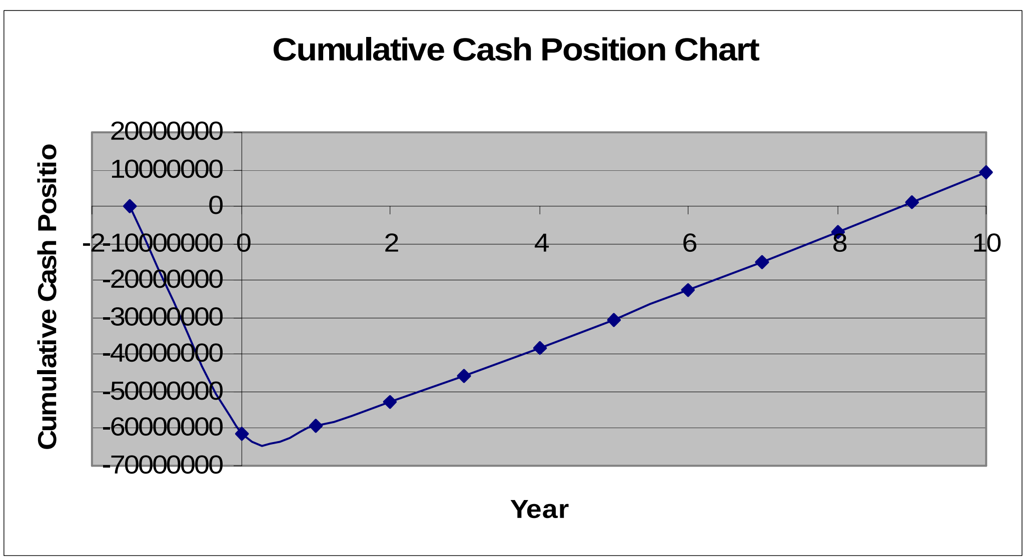


Figure 36: Cumulative Cash Position

According to the figure above, it will take approximately 8.3 years to pay back the loans for the total capital investment at a selling price of $6500. Although it may take a bit of time to start repayment of loans, by the end of the expected life of the project, the company will have generated approximately 12.4 million in net profits. The NPW is not positive for a selling price of $5500, but it is positive for a selling price of $6000 and a beta value of 0.75. This price is still reasonably close to the selling price of the Inogen One. In order for the product to be affordable to the average consumer we have chosen this selling price. A further look into the risk associated with the investment will provide a more thorough evaluation of the expected earning potential of this project.

10.4.9 Risk Analysis

To determine the feasibility of this project, a risk analysis was conducted for manufacturing the heat exchangers in house. A complete cost and profit evaluation was conducted keeping the first level decisions of selling price ($6000), equipment specifications and constant. While keeping these components constant, the prices of raw materials were varied by 20% on a normal distribution. Using the software program @Risk, a probability distribution of NPW was found as reported on the following figure.

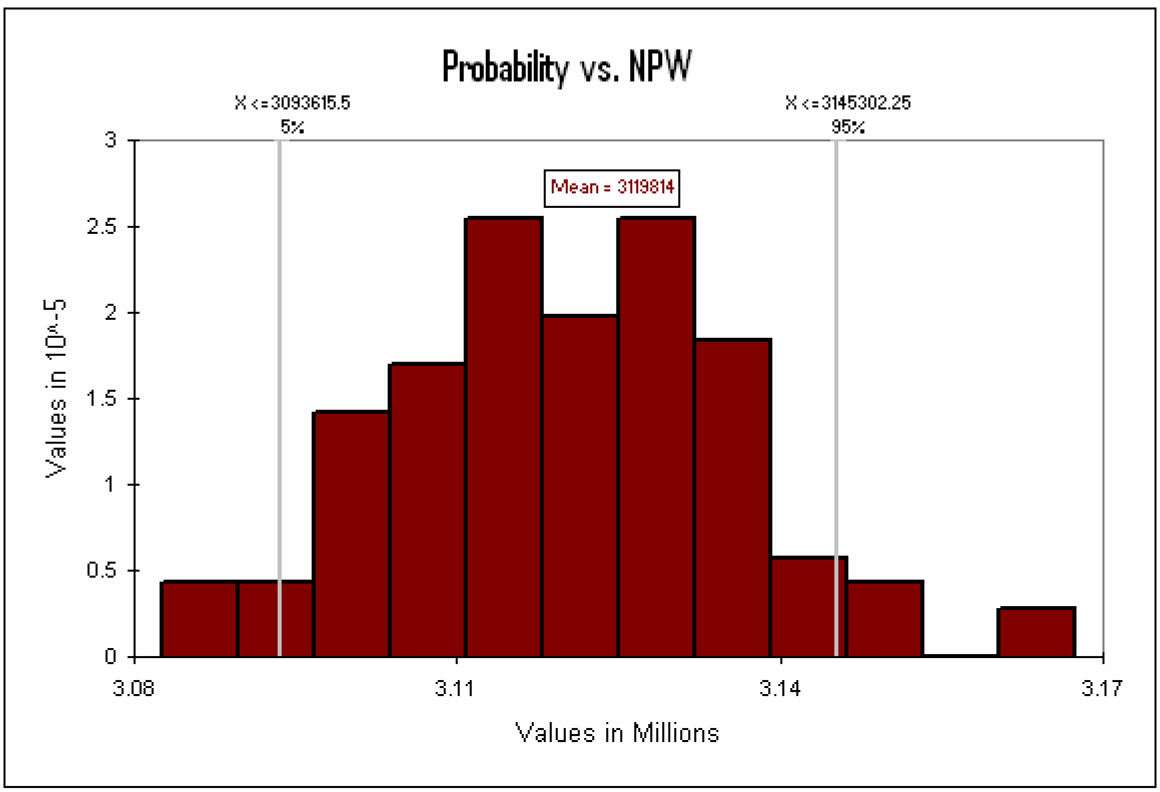


Figure 37: NPW Probability Distribution

The figure above shows the distribution of possibility for the new device to generate a positive NPW. This, however, is not a definitive method for determining the probability of the project's success. The following figure shows the cumulative probability distribution for the project, and the total likelihood of making money for the heat exchanger only scenario.

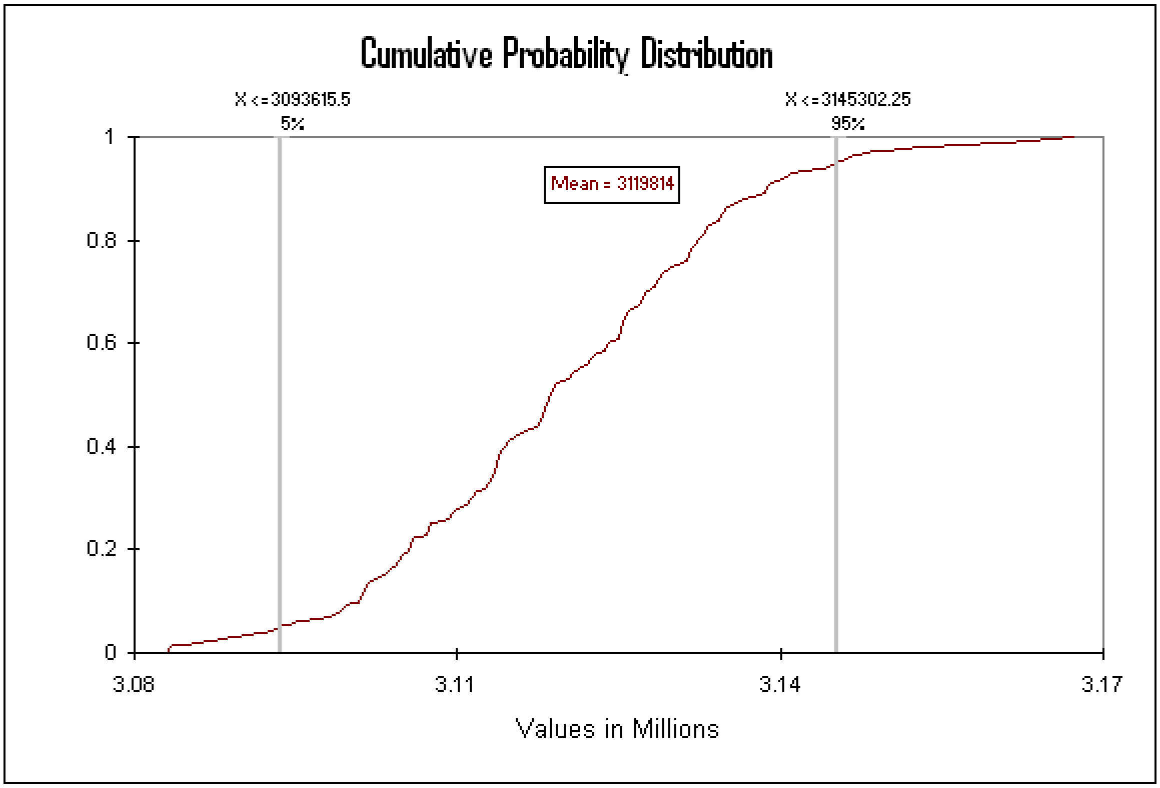


Figure 38: Cumulative Probability Distribution

The figure above shows the likelihood of each of the processes making or losing money. As depicted above, the process that involves fabrication of all device components in house is the superior choice for this project venture. This scenario has about a 50% likelihood of loosing money. A more thorough investigation into the probability distributions of raw materials cost could lower this probability and increase the chances of profit from this process.

11.0 Conclusions and Recommendations

The membrane oxygen separator has an advantage in the market given that it only needs a supply of power to provide an unlimited supply of oxygen. However, the manufacturing of an ionic membrane oxygen separator proves to have a negative Net Present Worth over a ten year period. As a result, it would be worthwhile to investigate the project further.

If a β value of 0.75 was reached, as in the case before the AirSep Freestyle was considered, a selling price of $6000 could be decided upon so that the product would be profitable for the consumer. A positive value of NPW of $3x10^6$ was determined at this selling price. The return of investment for the project was 5.64% for the 10 year lifetime. A risk assessment using @Risk indicated that the investment has a 50% chance of loosing money. Such a high percentage implies that going into the market would be very risky. Having the business start out at a partnership is favorable at this Risk level, since a partnership does not require many people to be pleased.

With final analysis a beta value of 0.78 was reached when considering the AirSep FreeStyle. In order to make the process profitable, the soundproofing needs to be reexamined. Perhaps a thicker layer of soundproofing needs to be used. More soundproofing however adds more weight, which makes the consumer less happy and raises the beta function. There clearly is a tradeoff when trying to reduce the noise. Since the happiness functions and weights of happiness functions were not based on a survey of actual oxygen users, it is possible that the β value is not realistic. Therefore it is possible that the product could be found to be profitable with its current design if more accurate happiness model were found. Another possible problem could be the way that length, width, and height are defined for each of the competitor's products. If these dimensions were confused then the beta function would be altered. One possible ways of decreasing the volume, and therefore decreasing the β value and making the process profitable, would be to find a way to resize the membrane. This would involve looking deeper into the literature to find more about BICUVOX. As it is, sufficient information could not be found that would allow for further optimization of the membrane size. It appears that little is known, at least compared to other perskovite-like materials, about BICUVOX.

The power consumption is related to the weight of the unit through the battery. If the system could be made more efficient, then a smaller battery could be used. This would mean a lighter unit, and a smaller beta value.

One thing that wasn't considered was the fact that Acoustiblok soundproofing is a good insulator. This means that if it is wrapped around, or near the pumps it may cause them to overheat. To reduce the noise effectively, the soundproofing should be placed near the pumps.

To increase heat loss from the pumps, some of the inlet air could be rerouted in a sheath around the pumps to cool them. The flow-rate necessary for this would need to be calculated, as it is not known. The heat loss from the pumps into air stream in the case without the sheaths would need to be known so that the air temperature at the entrance to the sheath may be determined.

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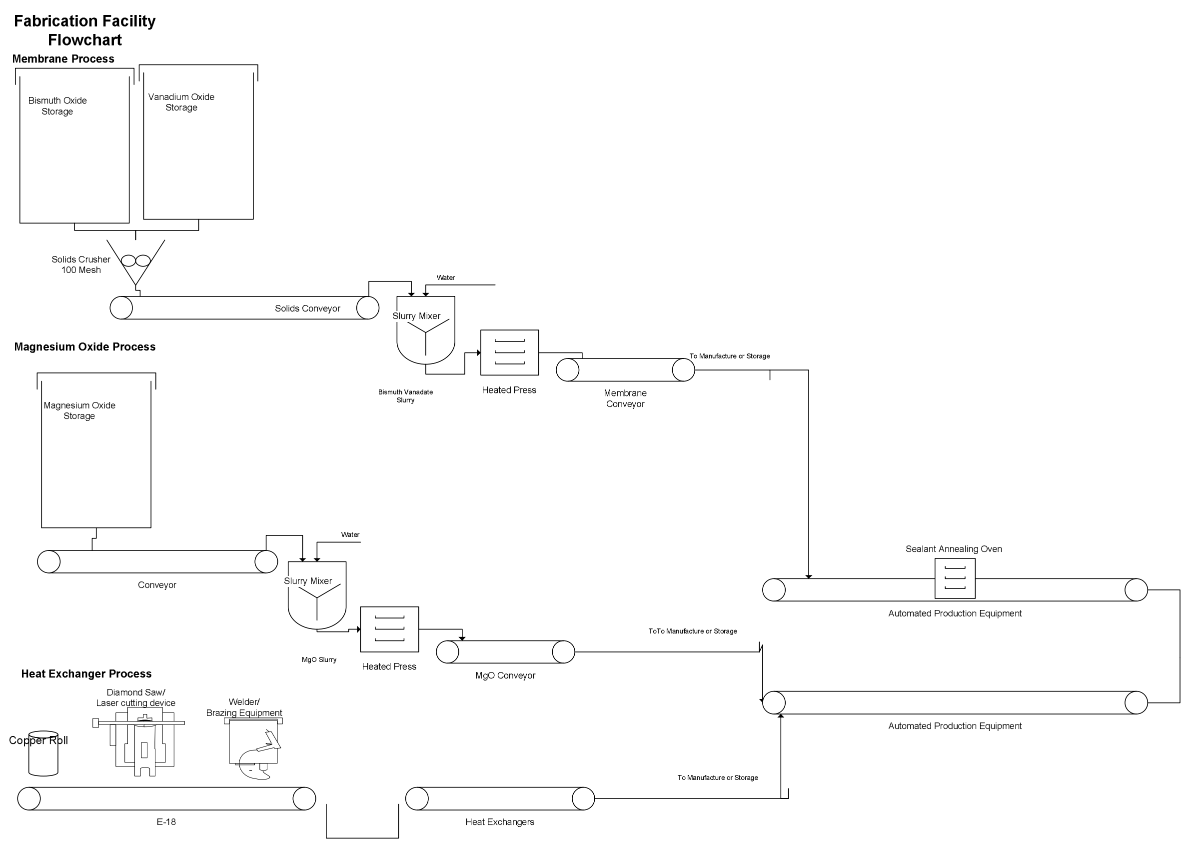
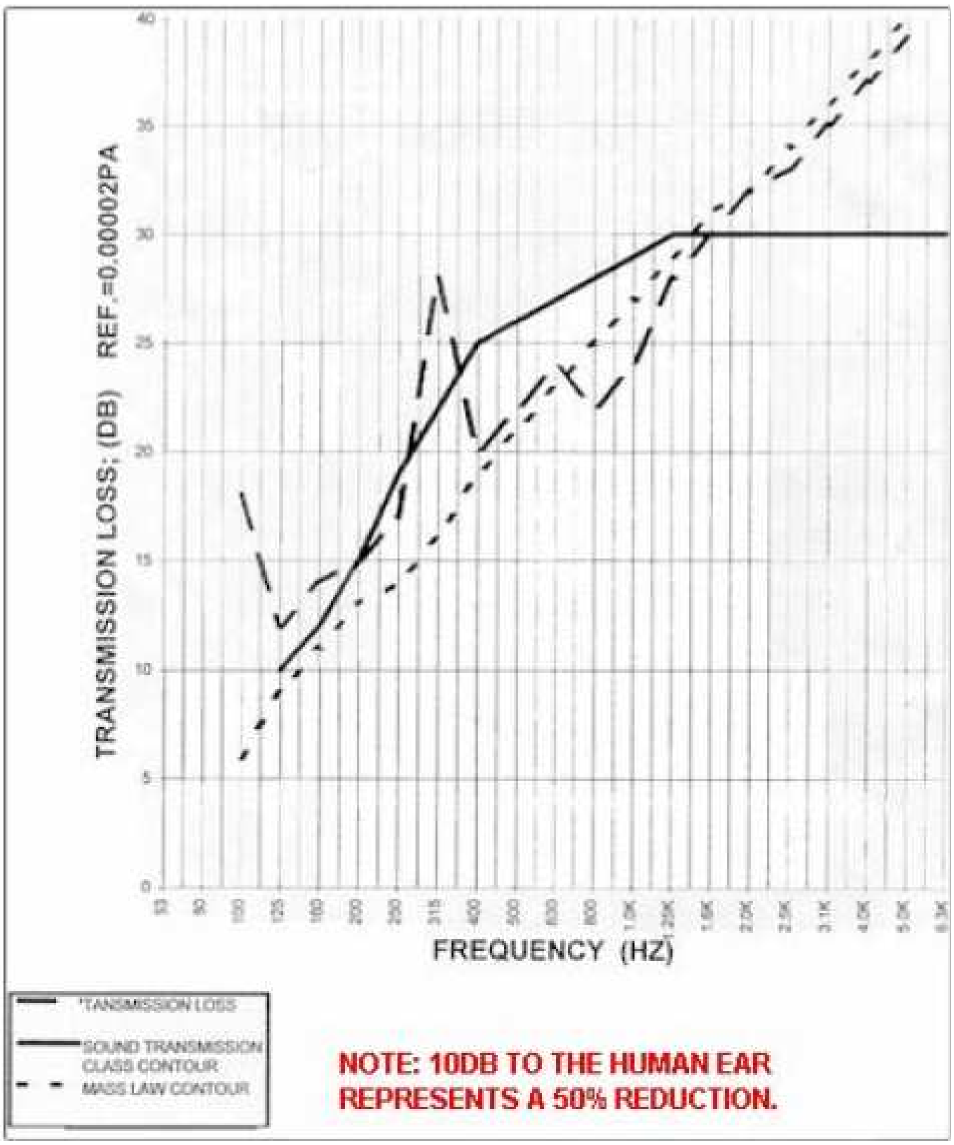
Appendix A

A.1 Plant Layout



Appendix B


TRANSMISSION LOSS; (DB) REF.=0.00002PA
40
35
30
25
20
15
10
5
0
FREQUENCY (HZ)
TANSMISSION LOSS
SOUND TRANSMISSION CLASS CONTOUR
MASS LAW CONTOUR
NOTE: 10DB TO THE HUMAN EAR
REPRESENTS A 50% REDUCTION.