Oxygen Production with Silver Zeolites and Pressure Swing Adsorption: Portable and Hospital Oxygen Concentrator Unit Designs with Economic Analysis

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Capstone Advanced Design Project: Spring 2007

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May 3, 2007

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Executive Summary

The objective of this project is to determine whether or not it is feasible to build an oxygen supply device using silver zeolites to separate nitrogen and argon from oxygen for >99% purity. The goal is to introduce a design into different markets to determine profitability over time.

Two consumers were focused on during the stint of the project. This produced two designs, a portable unit for individuals and a stationary unit for hospitals. Both designs incorporate the use of Pressure Swing Adsorption (PSA) with silver zeolites as the adsorbents.

A portable unit that can sustain a constant flowrate of 5 L/min at 99% purity was determined to be obtainable. Preliminary estimates have shown the portable unit will cost approximately $4,200 and weigh 20.5 pounds. Future investigation is required to determine consumer preference and the economics of this device.

The hospital unit utilizes a PSA system and is successful of producing >99% oxygen with a split bed silver zeolites LiAgX and AgA. The product is designed for 350 large hospitals in the United States consisting of 500 beds or more with the ability to sustain 5 L/min of 99% O_2 for 300 users.

A consumer utility maximization equation was used to determine an optimal unit price of $250,000 for the hospital project with an estimated net present value (NPV) of $2.8 million. The return on investment (ROI) was determined to be 12000% at a maximum consumer demand and preference over a period of 5 years. The ROI for the first year of operation is projected to be 5200% with an NPV of $1.3 million. The ROI is large, because the FCI is low and the calculated profit is large in comparison. Another reason is because the ROI and NPV were calculated assuming no copycat competition enters the market, consumers bought on impulse, and liquid oxygen kept prices constant. The fixed capital investment is $23,612, and the total product cost for the first year is approximately $1.57 million.

Using high advertisement expenditures, revenue peaks at $6.3 million around the second year of operation and slowly declines until the 5th year of operation. After the 5th year of the lifetime of the unit it will need to be replaced and the revenue will climb again when consumers purchase another unit.

A preliminary risk analysis on the hospital oxygen concentrator was necessary to determine the NPV, ROI, demand, and revenue over time assuming the demand calculated with consumer utility maximization equation was less than expected due to copycat or different competition. It was found that the hospital design is still profitable if the actual demand is above 25% of the demand calculated under perfect conditions.

The average expenditure on liquid oxygen in a large hospital is $170,000. Over 5 years it is estimated a large hospital will save $350,000 with an average annual savings of $70,000 with the hospital design. Since the price of the unit is $250,000 and greater than the annual budget of a large hospital, it is recommended that the producer of such a product allow for a 2 year payment plant of $125,000 payments each. This would allow a hospital to stay under their yearly budget and would make the hospital design more desirable.

The project is highly recommended due to the high NPV, ROI, and revenue values that have been determined. Since the market in the United States is limited to 350 large hospitals, it is recommended that other markets be investigated such as middle sized hospital and international markets. Future work needs to be put into further economic analysis of the portable device.

Table of Contents

INTRODUCTION **8**

Introduction to Oxygen Uses 8
Oxygen in hospitals *8*
Oxygen for individual use *8*
Oxygen Uses in Healthcare 9

MARKET ANALYSIS **10**

AIR SEPARATION METHODS **11**

Membranes 11
Cryogenic Air Separation 12
Pressure Swing Adsorption 13

METHODS OF PRESSURE SWING ADSORPTION **17**

Equilibrium Adsorption 17
Kinetic Adsorption 18

ADSORBENTS FOR PRESSURE SWING ADSORPTION **19**

Silica Gel 19
Nanotubes 19
Zeolites 21
Ion Exchange *21*
LiAgX Zeolite *22*
AgA Zeolite *23*
Nitrogen and Argon Adsorption 24

PROPOSED USE OF TECHNOLOGY **25**

Design 1: LiAgX Zeolite 25
Design 2: AgA Zeolite 26
Design 3: Mixed Ratio of Zeolites LiAgX and AgA 26
Design 4: LiAgX and AgA Zeolites Separated 27
Adsorbent Design Recommendation 27
PSA Process Flow 28

HOSPITAL OXYGEN CONCENTRATOR DESIGN **30**

Inlet Flow Rate and Mass of Silver Zeolites Calculations 30
Adsorption Column Design 32
Compressor for Hospital Unit 32
Silica Gel Air Drying Column Design 32
Outlet Compressor and High Pressure Storage Tank Design Specifications 33

PORTABLE OXYGEN CONCENTRATOR DESIGN **34**

Inlet Air Flow/ Zeolite/ Column Calculations and Design 35
Adsorption Column Design 35
Silica Gel Column, Feed Compressor, and Low Pressure Storage Tank Design 36
Portable Concentrator Conclusion and Recommendation 37

CONSUMER UTILITY AND PREFERENCE **38**

Consumer Preference Evaluation 40
Weights *41*
Yi (% Preference) Determination *42*
Characteristic Utilities and Consumer Preference Evaluation 43
Appearance *43*

Manipulation of Hospital Oxygen Concentrator for Appearance Characteristic 45
Noise... *48*
Manipulation of Hospital Oxygen Concentrator for Noise Characteristic...52
Ease of Use *55*
Manipulation of Hospital Oxygen Concentrator for Ease of Use Characteristic 57
Reliability *58*
Manipulation of Hospital Oxygen Concentrator for Reliability Characteristic..61
Durability *65*
Manipulation of Hospital Oxygen Concentrator for Durability Characteristic...68
Frequency of Maintenance 68
Manipulation of Hospital Oxygen Concentrator for Frequency of Maintenance Characteristic 71
CONCLUSION OF CONSUMER UTILITY AND PREFERENCE SECTION 71

BUSINESS MODEL.. 72

INTEGRATION OF CONSUMER SATISFACTION MODEL 74
FIXED CAPITAL INVESTMENT 76
Total Equipment Costs *77*
Total Product Costs.. *77*
Total Raw Materials Cost *77*
Total Variable Production Costs.. *78*
Fixed Charges... *79*
Total Administrative Costs... *79*
Distribution and Marketing Expenses *80*
OPTIMAL BETA VALUE AND NPV 83
RETURN ON INVESTMENT.. 85
Varying α with Time *86*
PRELIMINARY RISK ESTIMATES FOR THE HOSPITAL OXYGEN CONCENTRATOR 92
Brief Financial Analysis for Hospitals Purchasing Concentrators *95*

CONCLUSIONS 95

FUTURE WORK/RECOMMENDATIONS.. 96

REFERENCES.. 98

Table of Figures

Figure 1. Composition of Air 11
Figure 2. Membrane types [5] 12
Figure 3. Cryogenic Air Separation Plant [6] 13
Figure 4. Pressure Swing Adsorption Unit [7] 14
Figure 5. PSA Stage 1[8] 15
Figure 6. PSA Stage 2[8] 15
Figure 7. PSA Stage 3[8] 16
Figure 8. PSA Stage 4[8] 16
Figure 9. Air components through adsorbent bed 17
Figure 10. Carbon Nanotube [14] 20
Figure 11. PSA with Nanotubes 20
Figure 12. Zeolite structure [16] 21
Figure 13. Zeolite A with Silver Ion [19] 22
Figure 14. Zeolite X structure [21] 22
Figure 15. Zeolite A structure [21] 23
Figure 16. Adsorption Isotherm at 288.2 K [17] 24
Figure 17. LiAgX Zeolite in Adsorption Column 25
Figure 18. AgA Zeolite in Adsorption Column 26
Figure 19. LiAgX and AgA Zeolites in Adsorption Column 26
Figure 20. LiAgX and AgA Zeolites Separated in Adsorption Column 27
Figure 21. PSA Process Flow Diagram 29
Figure 22. Consumer perference as a function appearance 43
Figure 23. Appearance versus Color and Texture Options 44
Figure 24. Consumer preference plot as a function of appearance 45
Figure 25. Example of vinyl siding[33][34] 46
Figure 26. Example of aluminum siding[35][36] 47
Figure 27. Examples of veneer with artificial stone[31] 48
Figure 28. Plot of %preference versus noise 49
Figure 29. Physical representation of the noise characteristic versus everyday noises 50
Figure 30. Plot of %preference versus noise 51
Figure 31. Quit Barrier Foam [39] Figure 32. Ultra Barrier Foam[39] 53
Figure 33. Soundproof Foam [39] Figure 34. Econo Barrier Foam [39] 53
Figure 35. Noise characteristic versus type of sound adsorbing layer 54
Figure 36. Consumer preference as a function of ease of use 55
Figure 37. Ease of use versus amount of training 56
Figure 38. Consumer %preference toward the amount of training 57
Figure 39. Percent preference versus reliability 58
Figure 40. Reliability verse MTBF 60
Figure 41. Percent preference versus MTBF 61
Figure 42. Estimate of reliability versus time for a typical PSA system 63
Figure 43. Two PSA systems[42] 64
Figure 44. Consumer preference as a function of durability 65
Figure 45. Durability versus Time to Complete Revamp 67
Figure 46. Consumer Preference versus Time to Revamp 67
Figure 47. Percent Perference versus Frequency of Maintenance 69
Figure 48. Frequency of Maintenance versus Maintenance Visits per Year 69
Figure 49. Consumer Preference versus Maintenance per Year 70
Figure 50. Warehouse Facility[52] 79
Figure 51. NPV versus Price with varying beta values 83
Figure 52. Demand versus Price with varying Beta values 84
Figure 53. Return on Investment % versus Unit Price for varying consumer preference values. 86
Figure 54. alpha versus time with different levels of advertising. 87
Figure 55. Revenue versus Time with high advertising and variable alpha. 88
Figure 56. Demand versus Time with variable alpha. 89

Figure 57. Estimated NPV versus Time in years over 10 years 90
Figure 58. ROI versus time for hospital oxygen concentrator 91
Figure 59. Revenue versus Time with varying percentages of demand of perfect conditions 93
Figure 60. Demand versus Time with varying percentages of demand of perfect conditions 93
Figure 61. NPV versus Time with varying percentages of demand of perfect conditions 94
Figure 62. ROI % versus Time with varying percentages of demand of perfect conditions 94

Table of Tables

TABLE 1. ZEOLITE DESIGN PARAMETERS 28
TABLE 2. DETERMINATION OF INLET FLOW RATE NECESSARY USING TOTAL RECOVERY OF OXYGEN. 31
TABLE 3. PRODUCT THROUGHPUTS AND MASS OF ZEOLITES. 31
TABLE 4. COLUMN SPECIFICATIONS FOR HOSPITAL OXYGEN CONCENTRATOR 32
TABLE 5. COMPRESSOR SPECIFICATIONS FOR HOSPITAL DESIGN 32
TABLE 6. SPECIFICATIONS FOR SILICA GEL COLUMN 33
TABLE 7. SPECIFICATIONS FOR HIGH PRESSURE STORAGE TANK AND COMPRESSOR. 34
TABLE 8. INLET FLOW FOR PORTABLE OXYGEN CONCENTRATOR. 35
TABLE 9. MASS OF ZEOLITES FOR PORTABLE OXYGEN CONCENTRATOR. 35
TABLE 10. COLUMN SPECIFICATIONS FOR HOSPITAL OXYGEN CONCENTRATOR 36
TABLE 11. COMPRESSOR AND SILICA GEL COLUMN DESIGNS 36
TABLE 12. COMPLETE DESIGN SPECS AND PRICE FOR PORTABLE OXYGEN CONCENTRATOR 37
TABLE 13. ASSIGNED CHARACTERISTICS TABLE WITH ASSOCIATED VALUES FOR WEIGHTS. 41
TABLE 14. NORMALIZED WEIGHTS 42
TABLE 15. TYPES OF MATERIALS WITH ASSOCIATED COSTS FOR OXYGEN CONCENTRATION SYSTEM 46
TABLE 16. NOISE CHARACTERISTICS IN RELATION TO SOUND ENVIRONMENT, LEVEL, AND RELATIVITY TO CONVERSATION[38] 50
TABLE 17. NOISE BARRIERS CHARACTERISTICS[39] 52
TABLE 18. SOUND ADSORBING MATERIALS WITH ASSOCIATED NOISE LEVEL CHANGE AND COSTS[39] 54
TABLE 19. EXAMPLE OF RELIABILITY CALCULATION FOR YEAR 1 62
TABLE 20. ESTIMATED RELIABILITIES FOR EACH YEAR OVER 10 YEARS FOR HOSPITAL UNIT 62
TABLE 21. SERVICE LIFE EXPECTANCIES OF PARTS 66
TABLE 22. TOTAL PREFERENCE OF LIQUID OXYGEN PRODUCT 74
TABLE 23. BEST HOSPITAL DESIGN WITH ASSOCIATED CHARACTERISTICS, % PREFERENCES, PREFERENCE VALUE H_1 AND ASSOCIATED BETA VALUE. 74
TABLE 24. CONCENTRATOR DESIGN WITH ASSOCIATED CHARACTERISTICS, % PREFERENCES, PREFERENCE VALUE H_1 AND ASSOCIATED BETA VALUE. 75
TABLE 25. EXAMPLES DESIGNS WITH ASSOCIATED BETA VALUES. 75
TABLE 26. PRICES AND DEMANDS FROM CONSUMER UTILITY MAXIMIZATION EQUATION WHEN BETA=0.85 AND ALPHA=1 76
TABLE 27. FCI ESTIMATION FOR HOSPITAL OXYGEN CONCENTRATOR. 76
TABLE 28. ESTIMATION OF EQUIPMENT COST FOR HOSPITAL UNIT 77
TABLE 29. ESTIMATED RAW MATERIALS COST 78
TABLE 30. ESTIMATED VARIABLE PRODUCTION COSTS FOR HOSPITAL UNIT 78
TABLE 31. ADMINISTRATIVE COSTS 80
TABLE 32. TOTAL ESTIMATED DISTRIBUTION AND MARKETING EXPENSES FOR YEAR 1 81
TABLE 33. ESTIMATED TOTAL PRODUCT COSTS FOR YEAR 1 82
TABLE 34. ESTIMATED ADVERTISING COSTS PER YEAR FOR THE HOSPITAL DESIGN. 87
TABLE 35. PRELIMINARY FINANCIAL ANALYSIS FOR HOSPITALS PURCHASING CONCENTRATOR 95

Introduction

The purpose of this project is to design and evaluate the economics of a device which delivers 99 percent oxygen from a feedstock of atmospheric air. The design will be used for on-site hospital units which are capable of delivering 5 L/min of 99% oxygen simultaneously to 300 patients, and also as a portable unit for individuals suffering from lung diseases, such as Chronic Obstructive Pulmonary Disease (COPD). The device utilizes pressure swing adsorption (PSA) technology and silver zeolite adsorbents. The design is innovative as it is the first of its kind in providing hospitals an on-site unit which is cost effective and will meet the needs of oxygen purity and flow rate demand.

Introduction to Oxygen Uses

Oxygen in hospitals

Oxygen is the most important clinical gas used in health care centers. No modern hospital can manage without medical oxygen. Pure oxygen is an essential resource in the operating room during anesthesia, for the respiration of patients, and in the intensive care or neonatal units. The constant high demand for this gas renders substantial expenses for hospitals. Currently, hospitals buy oxygen with 99% purity in bulk from bulk oxygen manufacturers. The bulk oxygen is bought in both liquid and gaseous form. These sources of oxygen can become an economic burden as large hospitals can spend approximately $170,000 a year on oxygen supply alone [1]. Fortunately, medical oxygen can be generated on-site in any hospital, clinic, or health center in a much more cost effective manner. Using pressure swing adsorption as an air separation technique, oxygen is generated as it is being used, thus enabling a health care center to be self-sufficient in meeting its oxygen demand. The financial savings will allow for increased spending in providing for other areas of health care.

Oxygen for individual use

Oxygen is a drug that can help individuals who suffer from certain lung diseases such as emphysema, sarcoidosis, or chronic obstructive pulmonary disease (COPD) [2]. Since excessive use of oxygen at high purities can be toxic, a prescription is required for individual use [2]. With the consultation of a physician, individuals requiring supplemental oxygen can use portable oxygen concentrators to continue with their daily activities. For many people with end stage lung disease, supplemental oxygen allows their bodies to get the oxygen that they need and may also help them become more active. Supplemental oxygen enables cells in their body get their energy. The energy produced is used to do everything from breathing, to carrying out bodily functions, to going to the grocery store.

Currently, there are no portable systems that can maintain a 5 liter per minute supply of greater than 99 percent oxygen. The best solution on the market is portable containers which are filled via a home oxygen concentrator unit or by oxygen suppliers. These containers exist in several sizes and are typically tanks or cylinders of aluminum or steel [2]. They have the disadvantage of only lasting up to 8 hours. This limited time frame of oxygen supply poses a constraint on an individual's activity outside the home. There are portable oxygen concentrators on the market, but these devices can only supply oxygen with a purity of 85 to 95%. In these devices nitrogen molecules are removed from air leaving both argon and oxygen in the product. Creating a device which is portable and concentrates 99 percent oxygen with a product flow rate of 5 liters per minute from air is ideal. A possible design is discussed within this report.

Oxygen Uses in Healthcare

Using medical oxygen in healthcare is widely practiced throughout the world. Oxygen is used in numerous scenarios in the healthcare industry. Medical oxygen is used in the following instances [3]:

- Inhalation therapy
- During surgery to maintain tissue oxygenation under anesthesia
- Resuscitation of patients
- Mechanical lung ventilation for treatment of respiratory depression
- The treatment of such diseases as chronic obstructive lung disease pneumoconiosis, pneumonia, myocardial infarction, and pulmonary embolism
- For the newborn experiencing respiratory distress syndrome
- The treatment of respiratory burns or poisoning by carbon monoxide and other chemical substances

A portable oxygen unit which is capable of supplying 99% oxygen at a flow rate of 5 L/min is essential individuals suffering from chronic obstructive pulmonary disease (COPD). COPD is a lung disease in which the lungs are damaged, making it hard to breathe. In COPD, the airway tubes that carry air in and out of your lungs are partly obstructed, making it difficult to get air in and out. Cigarette smoking is the most common cause of COPD, but breathing in other kinds of lung irritants, like pollution, dust, or chemicals, over a long period of time may also cause or contribute to COPD.

This device is in high demand as there are 80 million[2] people suffering from COPD. In 2005 more than 3 million people died from COPD, that's 5% of all deaths globally[2]. According to the World Health Organization, COPD was the fifth leading cause of death in 2002 [2]. By the year 2030, COPD is predicted to advance in being the fourth leading cause of death worldwide[2]. Oxygen therapy is used to treat individuals with chronic obstructive pulmonary disease. Individuals needing treatment can obtain treatment from home and hospitals. Treatment for COPD involves the patient requiring >96% oxygen purity. Currently, there is no portable unit that is able to produce the purity that is required.

Market Analysis

There is an extensive market for oxygen not only in the United States but also internationally. Oxygen is the third most widely used chemical around the world. Currently there is a $9 billion market for the production of oxygen [3].

Cryogenic oxygen plants are the leading producer of bulk oxygen supply worldwide. Healthcare centers acquire medical oxygen in a liquid form from cryogenic plants. Oxygen from these plants is delivered using oxygen cylinders or tanker trucks which fill the central oxygen tank at the healthcare centers. Cryogenic plants are large scale plants and are used for applications that need 100 tons per day of oxygen or more. Pressure swing adsorption is a medium scale unit which is cost effective for meeting and oxygen demand supply up to 60 tons per day requirement. Pressure swing adsorption technology is thus a reasonable application to meet the demand of healthcare facilities.

In the United States alone, there is an estimated 350 large hospitals characterized by having a 500 patient bed capacity [4]. On average these large hospitals spend an estimated $170,000 a year on oxygen [1]. An on-site oxygen producing unit will allow for hospitals to gain independence from cryogenic plants and save money. The solution comprises of having a device that produces oxygen on site which does not require continuous maintenance or any other services from the healthcare facility.

Air Separation Methods

Several methods exist for the process of separating air to produce purified oxygen. Membranes, cryogenic distillation, and pressure swing adsorption are the most common techniques. Atmospheric air is composed of mainly nitrogen, oxygen, and argon. See Figure 1 below for the actual composition.

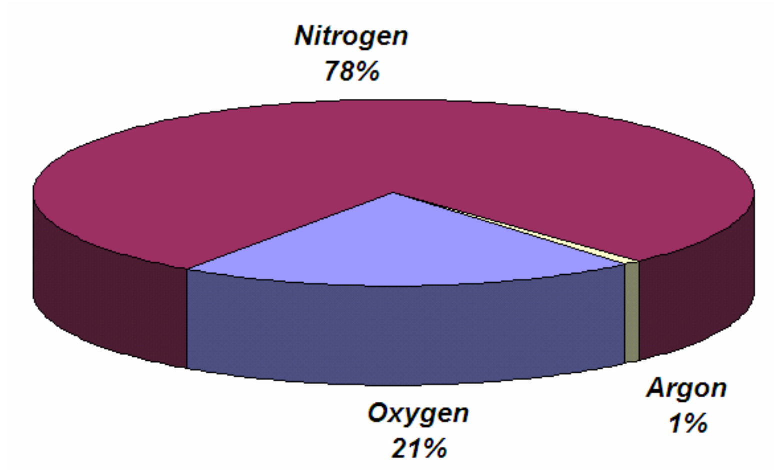

Figure 1. Composition of Air

These separation methods use air as the primary feedstock. Membranes, cryogenic distillation, and pressure swing adsorption techniques are discussed in the application of providing medical oxygen at a purity of 99 percent for hospitals and individual use.

Membranes

Membrane separation uses selective material to separate oxygen from nitrogen and argon. This method allows for a high recovery of oxygen with high selectivity of oxygen. For oxygen purification the membranes are designed to allow the oxygen molecules to pass through while providing a barrier for the nitrogen and argon molecules. This is possible with the use of diffusivity, pressure, or potential gradient as the driving force across the membrane.

Figure 2. Membrane types [5]

Membranes present a simple and less expensive method of producing oxygen compared to other processes. The dilemma associated with membrane separation for oxygen purification is membranes require a large amount of surface area. Certain ceramic membranes allow for separation with a smaller area, but require a high electrical current. This presents a problem of safety with the current and heat that is produced. The equipment used in the separation depends on the type of membrane selected. For example, a membrane that separates using a pressure gradient as the driving force requires equipment consisting of a compressor and equipment that can withstand substantial pressure.

Cryogenic Air Separation

Cryogenic air separation processes are the leading process for producing 99% oxygen in bulk supply. Distillation technology is used in this process as atmospheric air is cooled to a liquid phase and distilled to separate the oxygen, nitrogen, and argon components of air. Cryogenic process is the preferred technology for large to medium oxygen production plants.

Figure 3. Cryogenic Air Separation Plant [6]

An advantage of this process is the separated air components can be sold in a liquid form. One liter of liquid oxygen is equivalent to 860 liters of gaseous oxygen at standard conditions of 293 K and 1 atm. This characteristic is the primary reason why cryogenic air separation is one of the leading producers of purified oxygen.

This process is not ideal for an on-site hospital unit, because it uses large bulky equipment and has safety hazards associated with the distillation operations. Cryogenic distillation units for air separation are not energy efficient in comparison with other methods when the required supply of purified oxygen is less than 60 tons per day.

Pressure Swing Adsorption

Pressure Swing Adsorption (PSA) is one of the most common non-cryogenic processes on the market. PSA methods are capable of producing oxygen in medium capacity. This is ideal for an on-site hospital unit, because it is a safe process with reasonable energy and area requirements.

Figure 4. Pressure Swing Adsorption Unit [7]

The process operates by using adsorbents to separate air components. The main equipment required in PSA is a compressor, a silica gel bed, two adsorption columns, and a storage tank. A compressor is required to supply the required volume of atmospheric air to produce the desired purity and output flow rate of oxygen. A silica gel bed is used to remove water vapor and impurities such as carbon dioxide and carbon monoxide. Two adsorption columns are used to allow for a semi-continuous supply of product. A storage tank allows for product storage for later use.

The two columns operate semi-continuously in four stages to supply the desired purity and flow rate of oxygen. Adsorbents are selectively chosen to provide for the most beneficial design. The PSA stage operation is described in Figures 5-8.

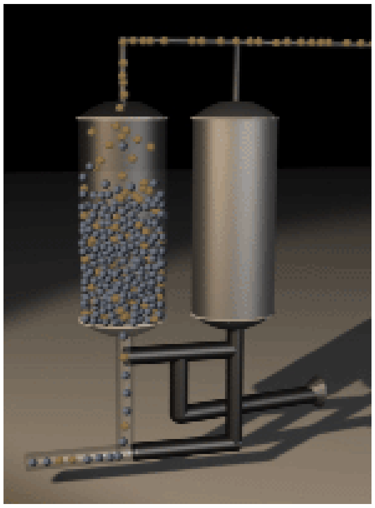

Figure 5. PSA Stage 1[8]

Stage 1: Compressed air is fed into the first bed. Nitrogen and argon molecules are trapped, while oxygen is allowed to flow through.

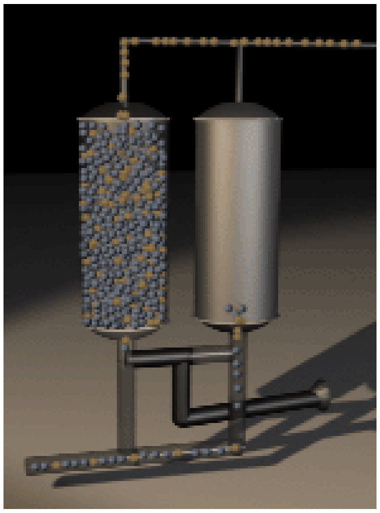

Figure 6. PSA Stage 2[8]

Stage 2: When the adsorbent in the first bed becomes saturated with nitrogen and argon, the airflow feed is directed into the second bed.

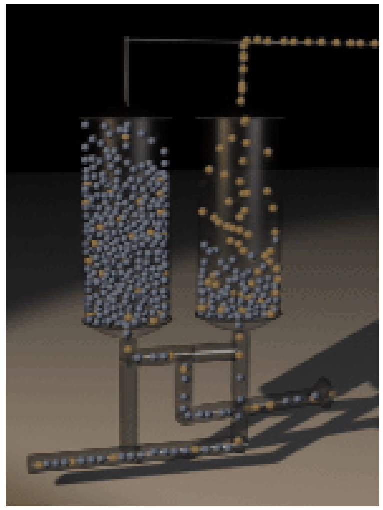

Figure 7. PSA Stage 3[8]

Stage 3: The adsorbent adsorbs nitrogen and argon in the second bed. The first bed is depressurized allowing argon and nitrogen to be purged out of the system and released to the atmosphere.

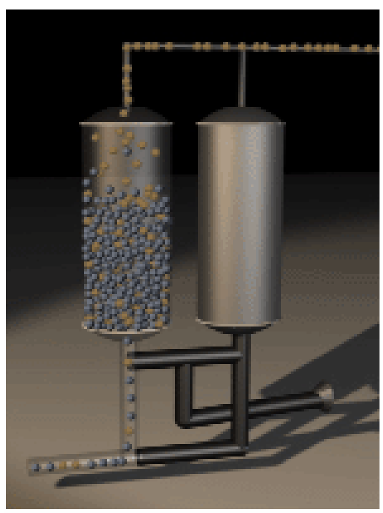

Figure 8. PSA Stage 4[8]

Stage 4: The process starts over. Compressed air is once again fed into the first bed. The second bed is depressurized releasing argon and nitrogen molecules to the atmosphere. The process is repeated continuously producing a constant flow of purified oxygen.

Methods of Pressure Swing Adsorption

Equilibrium Adsorption

Air comprises of three primary components: nitrogen, oxygen, and argon. The theory of multi-component adsorption equilibria involving the competition between the different molecules on the adsorbent is required for designing purposes. Langmuirian Multi-component Theory is used [9]. The fractional loading contributed by each component *i*, Θ_i is given by:

$$\theta_i = \frac{b_i P_i}{1 + \sum_{j=1}^{N} b_j P_j}$$

Equation 1

Where: b_i and b_j is the ratio of the rate constant for adsorption to that for desorption for component *i* and component *j*, respectively.
P_i and P_j is the partial pressure of component *i* and component *j*, respectively.
N is the number of species.

Equation 1 gives the amount adsorbed of species *i* on the adsorbent in the multi-component system.

The selectivity describes how selective one species is to bind to the adsorbent over another species. The selectivity of a species *i* in relation to species *j* is give as [9]:

$$S_{i,j} = \frac{b_i}{b_j}$$

Equation 2

A transport phenomenon is studied to determine how each species is adsorbed in the adsorbent bed. Material balance equations are used to determine these parameters.

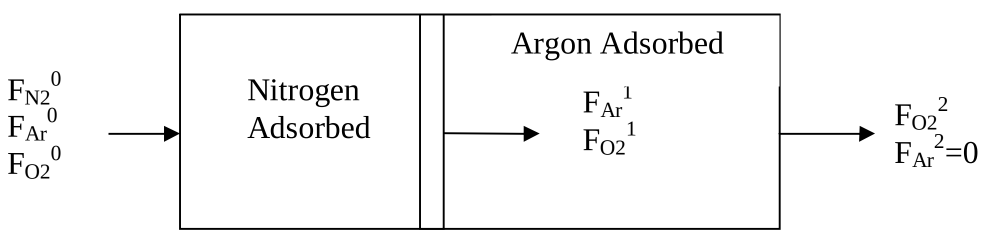

Figure 9. Air components through adsorbent bed

Material balances are performed for the components in each section of the adsorbent bed:

Nitrogen:

$$F_{N2}^{0}\Delta t = \Delta L_1 A N_{N2}^{1} = \nu_1 A N_{N2}^{1}$$

Equation 3

Oxygen:

$$F_{O2}^{1} = F_{O2}^{0} + (N_{O2}^{2} - N_{O2}^{1})A\nu_1$$

Equation 4

Argon:

$$F_{Ar}^{1} = F_{Ar}^{0} + (N_{Ar}^{2} - N_{Ar}^{1})A\nu_1$$

Equation 5

$$F_{Ar}^{2} = 0 = F_{Ar}^{1} + N_{Ar}^{2}A\nu_2$$

Equation 6

Where: F is the volumetric flowrate
Δt is the cycle time
ΔL is the length of the bed
A is the area
N is the loading
ν is the front velocity

To ensure the two concentration fronts do not collapse the ratio of the velocity of the argon front must be greater than that of the nitrogen front.

$$\frac{\nu_2}{\nu_1} = \frac{\frac{F_{Ar}^{0}}{F_{N2}^{0}} + (N_{Ar}^{2} - N_{Ar}^{1})}{N_{Ar}^{2}} > 1$$

Equation 7

Nitrogen molecules have a stronger electrostatic interaction with the adsorbents than do oxygen and argon molecules. The velocity of the nitrogen front is the velocity the front moves as a function of the rate of adsorption and desorption of the molecules on the adsorbent sites. Nitrogen there for has a slower rate of desorption than oxygen or argon because of its stronger interaction forces. Thus, the ratio of the velocity front of argon to nitrogen is greater than one in the PSA design.

Kinetic Adsorption

Pressure swing adsorption can easily separate nitrogen from and atmospheric air feed. Argon and oxygen have similar properties which makes it more difficult to separate the two components. Kinetic separation of oxygen and argon using molecular sieve carbon (MSC) adsorbents using pressure swing adsorption technique has been shown to adsorb oxygen almost 30 times faster than argon [10]. This is a very good separation and would lead to high purity and recovery of oxygen.

Oxygen being adsorbed on the MSCs in this process leads to a problem in design. To recover the oxygen adsorbed on the adsorbent the oxygen would be collected in the purge cycle of the pressure swing adsorption stage. This factor results in the need for two PSA processes. The cost associated with an additional PSA system outweighs the advantages in of the achievable separation between oxygen and argon.

Adsorbents for Pressure Swing Adsorption

Silica Gel

Silica gel is used in a pretreatment bed to remove water vapor and impurities such as carbon dioxide and carbon monoxide before the air feed stream enters the adsorbent beds. Water strongly adheres to the cation sites within each zeolite rendering them useless and ineffective [11]. Silica gel beds are necessary to remove water vapor from the air. Air at 100% humidity has approximately 3% of water vapor [12]. Once the bed is saturated with water, the bed is heated with a heating coil to evaporate the water from the silica gel.

Nanotubes

Carbon nanotubes are sheets of carbon atoms rolled into tubes of varying diameters. They exhibit extraordinary strength and have a potential use in many industries including adsorption. Nanotubes have little interaction with nitrogen at high temperatures due to oxygen's higher packing efficiency and smaller diameter. Research has shown that single walled carbon nanotubes (SWCN) of 12.53Å have a selectivity of O2/N2 of 100:1 at 10 bar [13]. Argon can also be separated from oxygen using nanotubes.

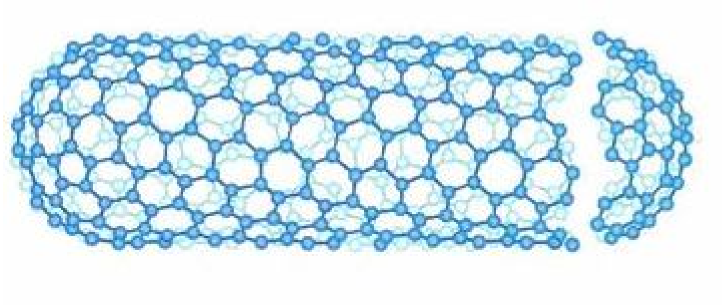

Figure 10. Carbon Nanotube [14]

Nanotubes are very efficient in the separation of the components of air. In fact, nanotubes are so efficient, their volume for separation of air is much smaller than the volume of air needed to be separated. The size of the nanotubes creates a problem for separation. Nanotubes are microscopic; thus the surface area is not large enough to react with the volume of air required for oxygen supply in medicine. Currently, no way exists to disperse nanotubes effectively for PSA separation. The figure below demonstrates this concept.

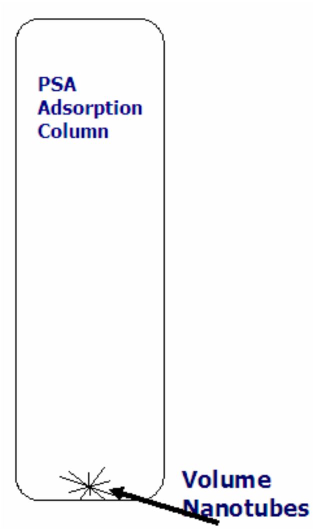

Figure 11. PSA with Nanotubes

Nanotubes are expensive the current price is $325-500 per gram [15]. In the on-site hospital oxygen concentrator unit, it was calculated that 670 kg of nanotubes would be required required. The cost for the nanotubes alone in the PSA system amounts to approximately $335 million.

Zeolites

Zeolites are microporous crystalline structures[16] that govern the molecules that are adsorbed during the PSA process. The shape-selective properties of zeolites are the basis for their use in molecular adsorption [16]. The different structures of the zeolite indicate the type of molecules that the zeolite will adsorb.

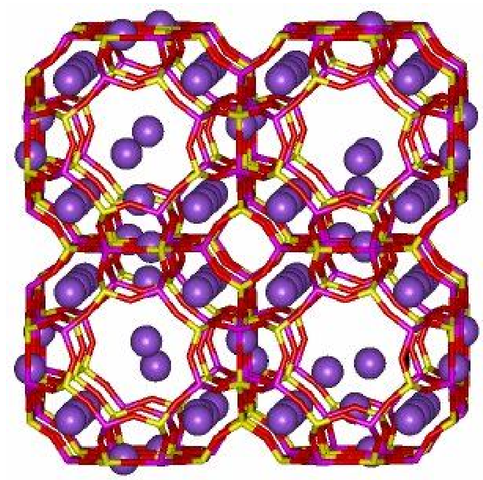

Figure 12. Zeolite structure [16]

Zeolites have various ways of controlling adsorption. The size and shape of pores can control access into the zeolite. In another case different types of molecule enter the zeolite, but some diffuse through the channels more quickly while others are left behind and do not pass through. Cation-containing zeolites, such as silver zeolites, are extensively used in gas separation processes. These cations are indicated as the purple spheres in Figure 12. Molecules are differentiated on the basis of their electrostatic interactions with the metal ions. Zeolites can thus separate molecules based on differences of size, shape and polarity.

Ion Exchange

Ion exchange is another aspect of zeolites that aids in the separation process. Ion exchange involves adding metal cations to the structure of the zeolite to attract certain molecules. Calcium is the most common metal cation exchanged in zeolites, but new studies have found silver exchanged zeolites to be more effective in air separation [17].

For zeolites to be affective, metal cations must be bound to the structure such as calcium, sodium, and in our case silver. Silver exchanged zeolites are a relatively new type of zeolite used in separation. The silver metal cation is placed in the structure of the zeolite structure as shown in Figure 13. Zeolite structure types of A, X, and Y are the dominant types used in commercial use for adsorption and ion exchange [18].

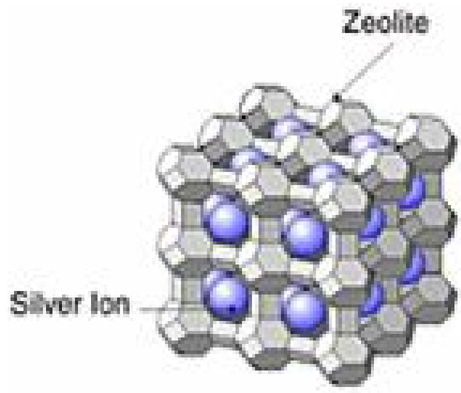

Figure 13. Zeolite A with Silver Ion [19]

With this type of arrangement nitrogen and argon are attracted to the silver ion by electrostatic forces because of their polarization properties.

LiAgX Zeolite

Research over of air separation using PSA shows zeolite LiAgX currently has the best performance of removing nitrogen in air separation processes. At atmospheric pressure, the PSA process had an oxygen purity of 96.42% and recovery of oxygen from the feed stream of 62.74%[20]. The product throughput used to calculate the amount of LiAgX zeolites required to attain this separation is 0.054 kg O_2/H/kg adsorbent at 2.5 minute cycles [20]. The LiAgX has structure type X which is shown in Figure 14.

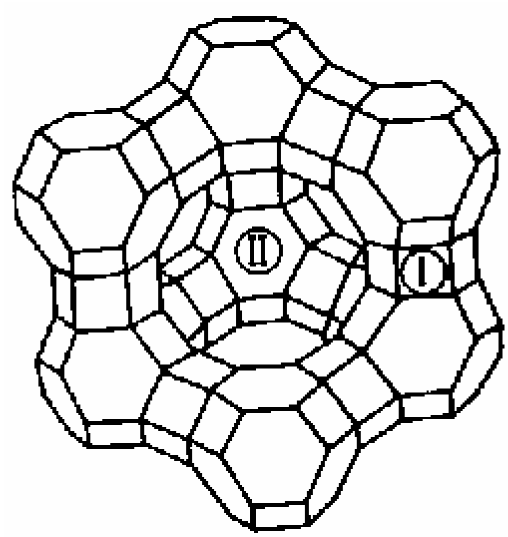

Figure 14. Zeolite X structure [21]

AgA Zeolite

Silver-exchanged zeolite A shows a strong adsorption of nitrogen as well as argon. For the separation of oxygen from nitrogen and argon, the zeolite structure A is the best structure. It allows for the best interaction between the ion in the zeolite and the nitrogen and argon molecules.

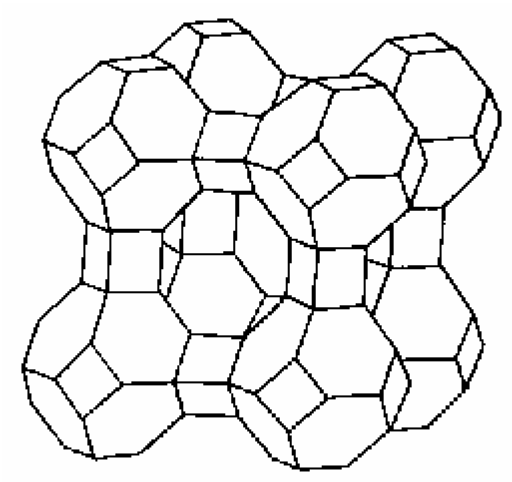

Figure 15. Zeolite A structure [21]

AgA zeolite has a selectivity of argon to oxygen as 1.63 to 1 at atmospheric pressure [17]. Nitrogen to oxygen selectivity is lower at 5.1 to 1 in this AgA zeolite when compared to the LiAgX zeolite previously discussed. From the adsorption isotherm data approximately 7 cm^3/g of argon is adsorbed on the AgA zeolite.

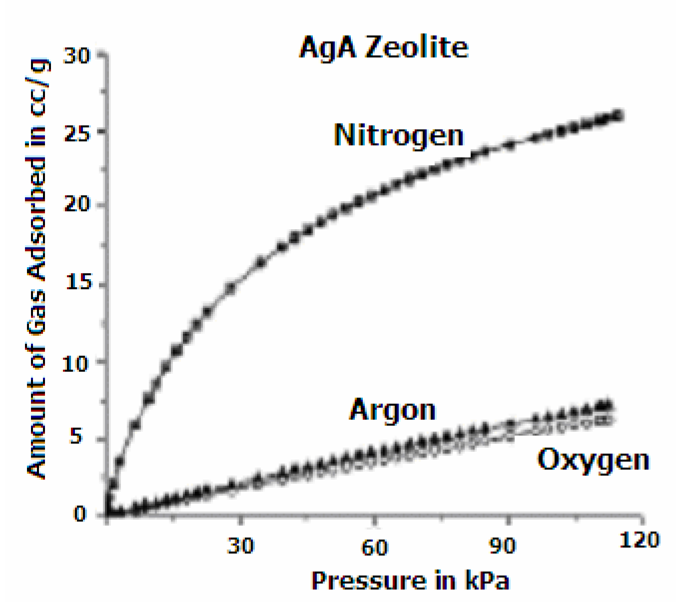

Figure 16. Adsorption Isotherm at 288.2 K [17]

Nitrogen and Argon Adsorption

Nitrogen and argon are capable of being adsorbed on zeolite adsorbents in PSA. Nitrogen has been shown to have a high absorbance while argon is just slightly more adsorbed than oxygen. How much of each component is adsorbed to zeolite is a function of the component's polarization properties. Polarization is the tendency of a molecule's electrons to be deformed by an applied electric field. The silver cation ions on the zeolites cause an electrostatic interaction with the elements electron field [17].

Nitrogen is strongly adsorbed in several silver zeolites. Nitrogen molecules have higher electrostatic interactions with the zeolite extraframework cations than oxygen and argon molecules due to nitrogen's higher quadrupole moment [17]. This is the primary reason why nitrogen has a much higher selectivity than argon and oxygen in silver zeolites.

Argon and oxygen have many similar physical properties making it more difficult to separate the two molecules in air purification methods. Argon typically adsorbs on silver zeolites with the same selectivity as oxygen or at a slightly higher rate depending on the zeolite structure. Because argon is a noble gas, it is slightly more polar than oxygen. Nitrogen's polarizability is 17.60×10^{-25} cm^3, argon is 16.41×10^{-25} cm^3, and oxygen is slightly less at 16.00×10^{-25} cm^3 [11]. In the AgA zeolite, argon's polarization properties allow its selectivity to be slightly greater than oxygen with a ratio of 1.63 to 1.

Proposed Use of Technology

Pressure Swing Adsorption (PSA) was chosen to be used in the design based on its medium product capacity, safety, energy efficiency, and associated costs. Four adsorbent designs consisting of the arrangement of zeolites in the adsorption column were analysized. The four designs studied used zeolites LiAgX and AgA were:

- Design 1: Only LiAgX zeolite
- Design 2: Only AgA zeolite
- Design 3: Mixed ratio of zeolites LiAgX and AgA
- Design 4: Both LiAgX and AgA zeolites separating them for different sections

The best design was determined using a fixed column diameter and cycle time. The required length of the bed varied determining on the product recovery. The outlet flow of oxygen must be at least 1,500 L/min in the hospital design and 5 L/min in the portable design. In both designs, the purity of oxygen from air must be at least 99 percent.

Design 1: LiAgX Zeolite

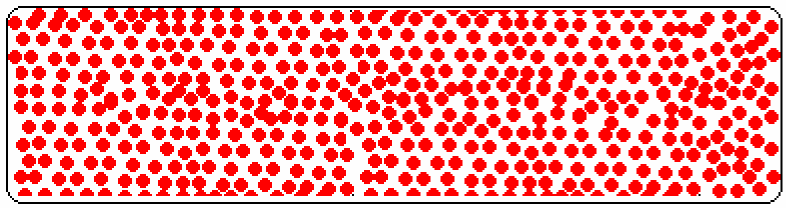

Figure 17. LiAgX Zeolite in Adsorption Column

A design over the length of the bed to achieve 99% oxygen was performed using purely zeolite LiAgX as the adsorbent. Since argon is not as selective to adsorb on LiAgX as it is on AgA the more zeolites are required to achieve the set product purity. The major concern of this option is the large amount of added volume in order to accomplish the separation,. This increased volume increases the cost of the equipment as a large compressor and columns are required. In addition, it increases the amount of zeolite needed thus the zeolite cost.

Design 2: AgA Zeolite

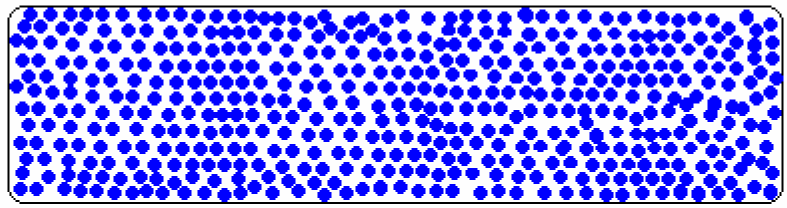

Figure 18. AgA Zeolite in Adsorption Column

Using zeolite AgA as the adsorbent creates the same dilemma as the previous design. In this case nitrogen molecules are not as highly adsorbed to the AgA zeolite used as they are to the LiAgX zeolite. Argon, however, is more favorable to adsorb on this zeolite. This design does not minimize the costs associated with size and capacity of the device.

Design 3: Mixed Ratio of Zeolites LiAgX and AgA

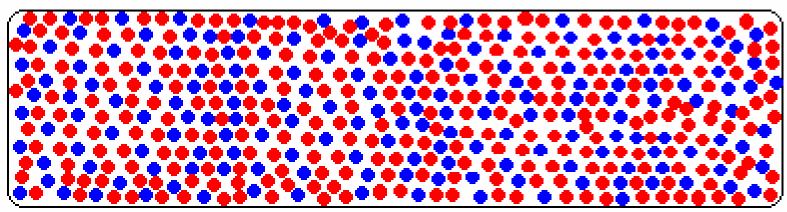

Figure 19. LiAgX and AgA Zeolites in Adsorption Column

As shown in the figure above the design of the mixed adsorbents has a selected ratio 1:1 of zeolite LiAgX (red) and zeolite AgA (blue).

Nitrogen has a higher loading capacity on zeolite LiAgX at a selectivity of nitrogen to oxygen of 12 to 1. In the AgA zeolite the selectivity of nitrogen to oxygen is about 5 to 1. Nitrogen is more strongly absorbed on both zeolites than argon. Thus, when argon is absorbed the remaining nitrogen molecules left to absorb will selectively replace the argon molecules. Since the selectivity of the nitrogen adsorbance is lower in zeolite AgA than LiAgX the presence of zeolite AgA will require a longer column length the remove the nitrogen. Argon's selectivity in zeolite AgA is 1.63 to 1 argon to oxygen and in zeolite LiAgX it is a 1 to 1 ratio. The presence of LiAgX zeolite in the argon removal section requires the length of the column to be longer than if just having AgA zeolite.

In conclusion, the use of zeolite AgA would increase the length of the nitrogen removal section. In the argon section zeolite LiAgX would increase the required length of the section to remove the argon as compared to using purely AgA zeolite.

Design 4: LiAgX and AgA Zeolites Separated

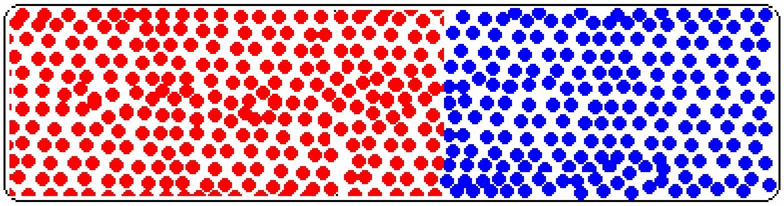

Figure 20. LiAgX and AgA Zeolites Separated in Adsorption Column

The last adsorbent design in the column consists of using zeolite LiAgX in the nitrogen removal section and zeolite AgA in the argon removal section. This was chosen, because zeolite LiAgX has a higher selectivity of nitrogen to argon and oxygen than zeolite AgA. Zeolite AgA was chosen for the argon removal section as its selectivity is 1.63:1 argon to oxygen, which is much greater than zeolite LiAgX. The volume of the column, inlet air, and zeolites required is dramatically lower and would save money on the overall unit. This will be the best option since the zeolites are roughly the same price.

Adsorbent Design Recommendation

Design 4 using a separated zeolite design was determined to be the most cost effective. For the hospital unit, design 4 has 35% recovery of oxygen, column length of 412 cm, and a total mass of zeolites as 2,214 kg. Table 1 shows the calculated parameters for each design of zeolite adsorbents.

Column, Zeolite, and Flow Specifications for PSA Designs			
LiAgX Only		**AgA Only**	
Recovery of Inlet Oxygen	27	Recovery of Inlet Oxygen	20
Inlet Flow Rate (L/s)	1,007	Inlet Flow Rate (L/s)	1,325
Mass of LiAgX Zeolites (kg)	4,342	Mass of LiAgX Zeolites (kg)	5,714
Volume Column (cm^3)	4,058,324	Volume Column (cm^3)	5,339,900
Area Column (cm^2)	5,027	Area Column (cm^2)	5,027
Length Column (cm)	807	Length Column (cm)	1,062
50/50 Mixture		**LiAgx/AgA**	
Recovery of Inlet Oxygen	25	Recovery of Inlet Oxygen	35
Inlet Flow Rate (L/s)	1,060	Inlet Flow Rate (L/s)	362
Mass of LiAgX Zeolites (kg)	2,286	Mass of LiAgX Zeolites (kg)	1,614
Mass of AgA Zeolites (kg)	2,286	Mass of AgA Zeolites (kg)	601
Volume Column (cm^3)	4,271,920	Volume Column (cm^3)	2,069,402
Area Column (cm^2)	5,027	Area Column (cm^2)	5,027
Length Column (cm)	850	Length Column (cm)	412

Table 1. Zeolite Design Parameters

PSA Process Flow

The overall design is shown in Figure 21. The pressure swing adsorption design consists of atmospheric air feed, a compressor, two adsorption columns, a high pressure storage tank, two 3-way valves, and two 2-way valves. The adsorbents used in this design will have the configuration of design 4 discussing in the previous section. This design was determined to be the most cost effective in the both the portable and hospital units.

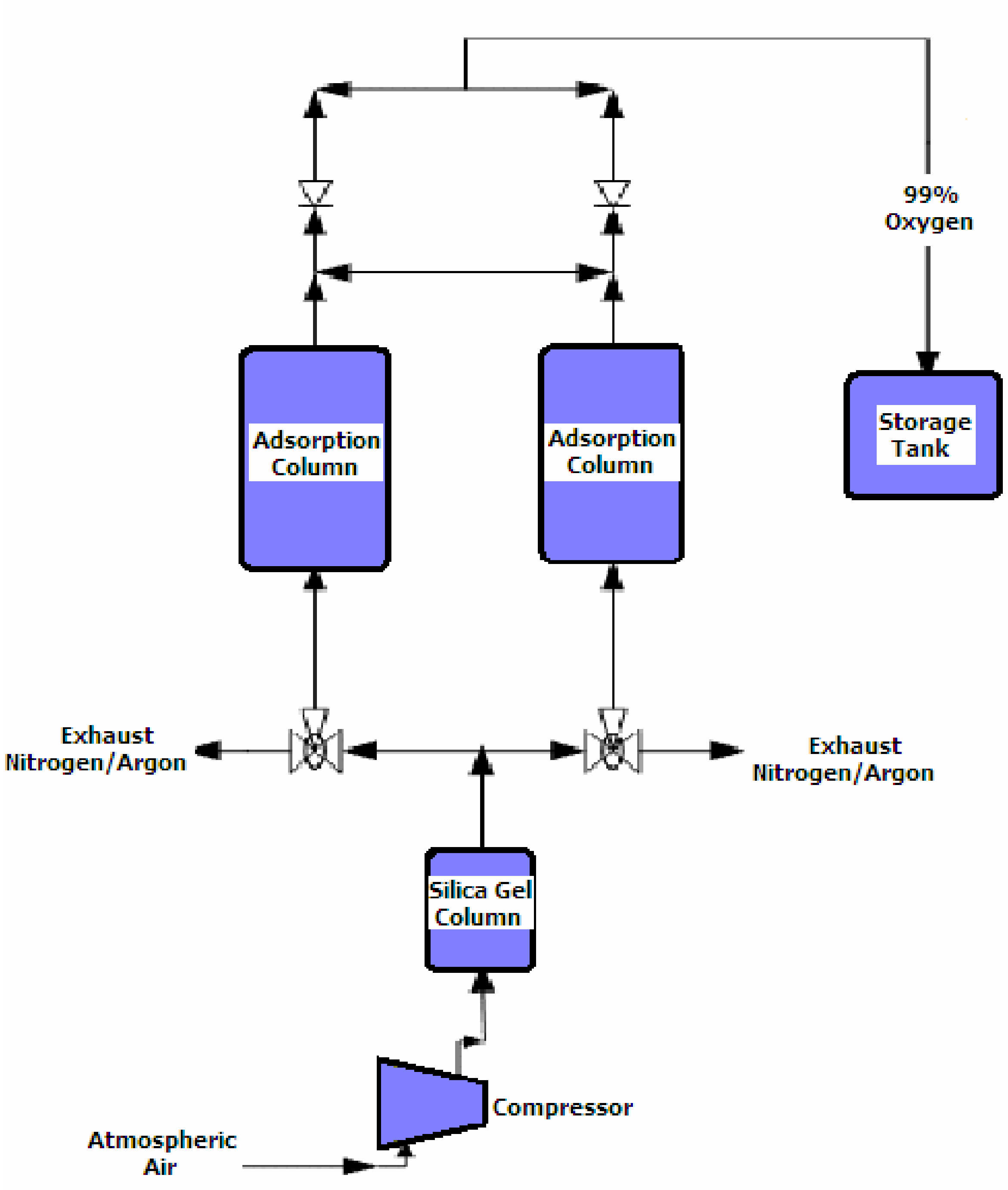

Figure 21. PSA Process Flow Diagram

Hospital Oxygen Concentrator Design

This section introduces the complete design of the hospital oxygen concentrator. As stated before, there are 350 large hospitals in the United States of America. The goal of this design is to use the presented technology of pressure swing adsorption with silver zeolites to produce 99% oxygen that would allow a hospital to be completely self sufficient concerning their oxygen consumption.

Assuming that oxygen is constantly flowing, at any one given time 150 patients in a large hospital are using 5 L/min of oxygen [1]. The basis for the design is to develop the concentrator to produce 1,500 L/min to provide for a maximum 300 users at 5 L/min. The reason for designing the system for this load is because 150 simultaneous users is an average. The real number of users at a given time fluctuates depending on the number of surgeries, emergency situations and surges in patients for one reason or another.

Inlet Flow Rate and Mass of Silver Zeolites Calculations

The different arrangements of silver zeolites were presented in the "Proposed Use of Technology" section using the hospital design as an example. The chosen design that minimized the volume of zeolites and flow rate was the separated LiAgX and AgA design. Thus, this specific arrangement of zeolites was chosen to be included for the final design of the hospital oxygen concentration unit.

In order to determine the amount of zeolites that would be necessary for each column in the pressure swing adsorption system, the inlet air flow rate needed to be calculated. To calculate the inlet flow rate necessary to produce 1,500 L/min of 99% oxygen, the recoveries of oxygen from both the LiAgX section and AgA section of each column. The recovery of oxygen from LiAgX when removing nitrogen was found in literature to be 62.74% [20]. Using available langmuir adsorption data from *Sorption of Nitrogen, Oxygen, and Argon in Silver-Exchanged Zeolties* by Sebastian and Jasra and the introduced material balances, the recovery of oxygen was determined to be 55% when separating just oxygen and argon.

Using the total recovery of oxygen and mass balance equations around the column the total inlet air flow rate was determined. The inlet air mixture along with adsorption of oxygen and recoveries are shown in Table 2.

Calculation of Inlet Flow Rate	
Recovery of Oxygen (LiAgX) (%)	62.7
Recovery of Oxygen (AgA) (%)	55.0
Total Recovery of Oxygen (%)	34.5
Assume 30 second Cycle Time	
Oulet Oxygen needed for 300 users at 5L/min	1500
Oxygen Adsorbed per 2 columns (L)	2850
Inlet Oxygen (L)	4350
Inlet Air Mixture (L)	21750

Table 2. Determination of inlet flow rate necessary using total recovery of oxygen.

The inlet flow in Table 2 is 21,750 L/min. The chosen cycle time for this pressure swing adsorption process is 30 seconds. A cycle is the time it takes to feed and produce a given flow rate of purified oxygen in one column. Using a 30 second cycle time and the assumption that half of the inlet flow volume of 21,750 will go to each column per 30 seconds, the flow rate of air to each column was determined.

Using the inlet flow rate in Table 2, oxygen flow rate out of each section using the recovery and mass balance equations for each silver zeolite section, the product throughputs for each adsorbent was calculated. From these product throughputs of oxygen for each zeolite, the total amount of adsorbent for each section was determined. The air flow rates, throughputs and calculated mass of zeolites are in Table 3.

Adsorbent Results	
Inlet Air Mixture (L)	21750.0
Inlet Air Feed to each column (L)	10875.0
Flow rate air to each column (L/s)	362.5
LiAgX Section of Column	
Product Throughput kg O2/h/kg adsorbent [20]	0.1
Total 96.42% Pure Oxygen from LiAgX (L) [20]	2729.2
Mass of LiAgX Zeolites (kg)	3227.2
AgA Section of Column	
Total Entering O2/Ar mixture (L)	1414.6
Total 99% Pure Oxygen from AgA (L)	749.7
Product Throughput kg O2/h/kg adsorbent	0.2
Mass of AgA Zeolites (kg)	1201.3

Table 3. Product Throughputs and Mass of Zeolites.

The mass of zeolites presented in Table 3 is only for one column. The mass for one pressure swing adsorption system would be double the amount above.

Adsorption Column Design

The mass of total zeolites in Table 3 can now be used to determine the volume of the column. Under the assumption of 30 second cycles and assuming a set diameter, the length and volume of the bed were determined. Table 4 below contains all specifications as well as loading for a single adsorption column.

Column Specifications	
Total Mass of Zeolites per Column (kg)	4429
Total Volume of Zeolites per Column (L)	4139
Column Data	
Volume of Column (L)	4139
Diameter of Column (cm)	80
Height of Column (cm)	412
Total Loading of N2/O2/Ar per Column (kg)	22

Table 4. Column Specifications for Hospital Oxygen Concentrator

Compressor for Hospital Unit

A compressor was needed to supply 362.2 L/s (776 CFM) of inlet flow rate required for the hospital oxygen concentrator. The following compressor chosen for the design is in Table 5. The compressor is an industrial type made by Sullivan-Palatek company [22].

Compressor (Palatek) [22]	
Max Flow of Compressor (CFM)	900
Inlet Flow to be Compressed (CFM)	776
Power Consumption (hP)	200

Table 5. Compressor specifications for Hospital Design.

Silica Gel Air Drying Column Design

It is necessary to remove all water out of the air so that the silver zeolites remain useful and effective. To size the silica gel column, the amount of water vapor in the air needed to be calculated. It was desired to have a silica gel column that would remove all entering water in the air per cycle all the while regenerating the silica gel using a heating coil.

Under the assumption of worst case scenario of 100% humidity, the mass of water to be removed per cycle was determined. At 100% humidity, air has approximately 3% water vapor[12]. The following equation was used to determine the mass and volume of water to be removed.

$$Massofwater = V * \rho$$

Equation 8

Where:

V= volume of air supplied * .03 (.03 is used to take into account water vapor in the air)

ρ= density of water vapor .804 g/L [12]

The final volume of water per cycle is approximately 178 grams. From literature, .75 g H_2O is absorbed per gram of silica gel [23]. Table 6 contains the specifications for silica gel column.

Silica Gel Drying Column	
Mass Water in incoming Air (g)	9131
Grams H20 Adsorbed per gram of silica gel	1
Mass of Silica Gel (kg)	12
Volume of column w/ silica gel (cm^3)	20291
Height (cm)	65
Diameter (cm)	20

Table 6. Specifications for Silica Gel Column

Outlet Compressor and High Pressure Storage Tank Design Specifications

As the purified oxygen comes out of the columns, it will be stored in a high pressure storage tank at approximately 10 atm. The flow coming out of the system is considerably less due to the adsorption, thus a smaller compressor could be used.

The storage tank was designed to contain 60 minutes worth of oxygen. The reasoning behind this design is for the case of an emergency situation that over 300 users would be using oxygen for a short period of time. The tank should provide a safety barrier until the user level declines under 300. It is also assumed that all the rooms in the hospital will directly tap into the tank in order to get the oxygen with flow regulator valves in each room. The designs for both the tank and compressor are in Table 7.

Components Continued	
High Pressure Storage Tank	
Volume to be stored in 60 minutes (L)	92100
Volume of stored air at 10 atm	9210
Compressor for High Pressure Storage (Palatek)	
Inlet Flow to be Compressed (L/min)	1500
Inlet Flow to be Compressed (CFM)	55
Max Flow of Compressor (CFM)	100
Power Consumption (hP)	50

Table 7. Specifications for high pressure storage tank and compressor.

The overall design of the major components of the hospital oxygen concentrator is complete. The hospital unit will contain two pressure swing adsorption systems with the design specifications presented. The reason for designing the whole system this way is for increased reliability and for patient safety. This concept will be presented further in the consumer utility and preference section.

Portable Oxygen Concentrator Design

The portable oxygen concentrator was designed in exactly the same manner as the hospital oxygen concentrator. However, a few requirements for the prototype were considered. Requirements such as:

- Unit must weight less than 30 lbs
- Unit is able to provide 99% oxygen purity and 5 L/min
- Unit has a battery life of at least 6 hours
- Unit is small enough to take on an airplane
- Unit is less than $5,000 and could be covered by medicare

These factors would not only put the product in a competitive market but would also put it ahead of the competition because of the 99% purity that is offered.

Inlet Air Flow/ Zeolite/ Column Calculations and Design

The following tables contain the inlet air specifications.

Calculation of Inlet Flow Rate	
Recovery of Oxygen (LiAgX) (%)	62.7
Recovery of Oxygen (AgA) (%)	55.0
Total Recovery of Oxygen (%)	34.5
Assume 30 second Cycle Time	
Oulet Oxygen needed for 1 users at 5L/min	5
Oxygen Adsorbed per columns (L)	9
Inlet Oxygen (L)	14
Inlet Air Mixture (L)	72

Table 8. Inlet Flow for Portable Oxygen Concentrator.

The chosen cycle time for this pressure swing adsorption process is 10 seconds to reduce overall weight of the zeolites.

Using the inlet flow rate in Table 8, oxygen flow rate out of each section using recovery and the mass balance equations for each silver zeolite section, the product throughputs for each adsorbent were calculated based on the 10 second cycle time. From these product throughputs of oxygen for each zeolite, the total amount of adsorbent for each section was determined. The air flow rates, throughputs and calculated mass of zeolites are in Table 9.

Adsorbent Results	
Inlet Air Mixture (L)	72.5
Inlet Air Feed to each column (L/min)	36.2
Flow rate air to each column (L/s)	3.6
LiAgX Section of Column	
Product Throughput kg O2/h/kg adsorbent	0.1
Total 96.42% Pure Oxygen from LiAgX (kg)	0.3
Mass of LiAgX Zeolites (kg)	2.5
AgA Section of Column	
Total Entering O2/Ar mixture (L)	9.1
Total 99% Pure Oxygen from AgA (kg)	0.1
Product Throughput kg O2/h/kg adsorbent	0.2
Mass of AgA Zeolites (kg)	0.7

Table 9. Mass of Zeolites for Portable Oxygen Concentrator.

Adsorption Column Design

The mass of total zeolites in Table 9 can now be used to determine the volume of the column. Under the assumption of 10 second cycles and assuming a set diameter, the length and volume of the bed were found. The following Table 10 contains all specifications as well as loading for a single adsorption column.

Column Specifications	
Total Mass of Zeolites per Column (kg)	3.2
Total Volume of Zeolites per Column (L)	3.0
Column Data	
Volume of Column (L)	3
Diameter of Column (cm)	10
Height of Column (cm)	38
Total Loading of N2/O2/Ar per Column (kg)	2

Table 10. Column Specifications for Hospital Oxygen Concentrator

Silica Gel Column, Feed Compressor, and Low Pressure Storage Tank Design

Under the assumption of 100% humidity the silica gel specifications are below in Table 11 for 10 second cycles with the specifications for the feed compressor.

Final Components of Design	
Compressor (VIAir 90P) [24]	
Max Flow of Compressor (CFM)	5
Inlet Flow to be Compressed (CFM)	2.6
Power Consumption (Amps)	22
Silica Gel Drying Column	
Mass Water in incoming Air (g)	0.06
Grams H20 Adsorbed per gram of silica gel	0.75
Mass of Silica Gel (kg)	0.08
Volume of column w/ silica gel (cm^3)	135.33
Height (cm)	19.15
Diameter (cm)	3.00

Table 11. Compressor and Silica Gel Column Designs

The low pressure storage tank is necessary in the portable oxygen concentrator was chosen to have a volume of 2 L. The storage tank is necessary to charge before the unit is in operation for continuous flow out. Pressure swing adsorption systems are semi continuous and thus to have a non pulsating system the pressure tank is a necessity. The tank will be filled, but the outlet stream will be steady and continuous despite the pulsating of the PSA system.

The following Table 12 is the complete specifications, price, and estimated weight for the portable oxygen unit.

Oxygen Concentrator					
		Weight			
Parts	#	kg	Price	Basis	Cost
Column and Tanks					
Adsorption Columns (Al) 1.5 liter	2	1.86	$100.00	Estimate	$200.00
Drying Column (Al) 1 liter	1	0.0115	$100.00	Estimate	$100.00
Low Pressure Storage tank (Al) 2 liter	1	1.86	$100.00	Estimate	$50.00
Packing					
LiAgX Zeolites (Adsorbent)		5	$.4/g	Quote Sigma Aldrich	$2,000.00
Silver Zeolite A (Adsorbent)		1.4	$.4/g	Quote Sigma Aldrich	$560.00
Silica Gel (Drying)		0.08	$.05/g	Quote Sigma Aldrich	$4.00
Other items					
Inlet Feed Compressor	1	2.73	$100.00	autoanything.com	$100.00
Nitrogen Exhaust Muffler	1	0.23	$3.00	Ace Hardware [25]	$3.00
3 Way Ball Valve	2	0.09	$100.00	Hanbay Inc [26]	$200.00
2 Way Solenoid Valve	2	0.09	$100.00	Hanbay Inc [26]	$200.00
Battery	3	0.93	$100.00	laptops for less [27]	$300.00
Control Computer	1	0.09	$300.00	NextTag [28]	$300.00
Frame (Aluminum)	1	0.91	$100.00	Estimate	$100.00
Casing (Plastic)	1	0.09	$75.00	Estimate	$75.00
Final Total Weight (kg)		**9.35**	**Total Cost =**		**$4,192.00**
Final Total Weight (lb)		**20.57**			

Table 12. Complete Design Specs and Price for Portable Oxygen Concentrator

Portable Concentrator Conclusion and Recommendation

The following goals were met with the portable oxygen concentrator from the initial estimates in Table 12.

- Purity: 99% oxygen
- Cost: $4200 (under $5000)
- Weight: 21 lbs (under 30 lb)
- Small: Estimated .6ft x 1ft x 1.5 ft

Thus from the above information, it can be see that a competitive/lightweight portable oxygen concentrator with 99% oxygen can be produced. No portable concentrator has yet to be able to produce the same results. It is recommended that extensive design estimates and economic analysis be performed for the portable oxygen concentrator in order to determine profitability and demand. This item is likely to be very profitable, because it has no matched competition other than liquid oxygen for portable oxygen supply at 99% purity.

Consumer Utility and Preference

This section presents the method that was used to determine the relationship between consumer preference and satisfaction when evaluating a hospital oxygen supply system in order to predict product price and demand. By predicting the most important product attributes of an oxygen supply system that hospital management would prefer, the hospital oxygen concentrator could be modified to meet those certain preferences. Modifying the oxygen concentrator design would attract more consumers to the product.

The following method was used to determine the preferences that will later help in the prediction of the product price and approximate demand to be used in the "Business Model" section.

Utility (satisfaction) is based on functions of demand or "satisfaction functions."[29]. The utility function (S) can be quantified with the following equation:

$$u(d1, d2) = (\alpha * d_1{}^{\rho} + \beta * d_2{}^{\rho})^{1-\rho}$$

Equation 9

Where: d_1 and d_2 are the demand of the PSA hospital project and competitor's liquid oxygen cylinders, respectively. The parameter α is the inferiority function which can be described as the knowledge that the consumer possesses about the PSA hospital project. The α value is a function of time depending on the amount and aggressiveness of advertising and ranges between 0 and 1. If α is equal to one then it is assumed that the consumer has perfect knowledge of the current product. The β parameter is named the superiority function and directly deals with the consumer preference of the competition to that of the hospital oxygen concentrator.

The competition for the hospital oxygen supply market will be primarily liquid oxygen manufacturers. Liquid oxygen currently dominates the oxygen market in the case of hospital oxygen supply. Liquid oxygen competition will be used for evaluation and comparison with the hospital oxygen concentration unit in the consumer preference evaluation and extensively in the business model section.

Another important equation is that of the consumer budget[29] Y which is described by the following equation:

$$Y \leq p_1 d_1 + p_2 d_2$$

Equation 10

The parameters of d_1 and d_2 are the same as in the utility function equation. The new parameters of p_1 and p_2 are the price of the hospital project and the liquid oxygen competitor's price, respectively.

Under the above variables and conditions, the solution to consumer utility maximization[29] is given by the following microeconomics equation:

$$\phi(d_1) = p_1 d_1 - \left(\frac{\alpha}{\beta}\right)^{\rho} p_2 \left[\frac{Y - p_1 d_1}{p_2}\right]^{1-\rho} d_1{}^{\rho} = 0$$

Equation 11

All the variables are the same as described above with the addition of the new variable ρ. The parameter ρ is assumed to be equal to .76 [29] as suggested from research.

Once the consumer budget is defined, the β and α values need to be determined. The equation for the superiority function[29] β is as follows:

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

Equation 12

Where: H_2 and H_1 are the consumer preference of the liquid oxygen product to the hospital oxygen concentrator as described before

The values for β typically range between 0 and 1 depending on the consumer preference of the competitor. However, the values can be larger than 1 of the product that is developed has a lower consumer preference than the competition. The lower the value of β the more preferably the hospital oxygen concentrator design is to that of the competition. For example, if the consumer preference for the competition product is .64, then the best β value would be when the hospital project has maximum preference value of 1 or 100% preference of the consumer which in turn gives the value of β to be .64/1=64.

The consumer preferences[29] H_1 and H_2 are directly related to the important characteristics of a product (noise, appearance, etc.) and product attribute scores by the formula below:

$$H_i = \sum w_i y_i$$

Equation 13

Where: w_i are weights based on the proposed importance characteristics of the consumer and are determined through consumer surveys. The values for y_i are based on the % of consumer preference determined from utility functions and range between 0 and 1.

A value of 1 means the consumer is 100% satisfied or has 100% preference toward the product. The y_i values can be manipulated for the hospital oxygen concentrator project in order to determine the maximum preference in accordance to customer specifications. These will be presented in the next section in their entirety.

Consumer Preference Evaluation

Hospital management utilizes several different characteristics in order to evaluate total preference (H_i) and quality of an addition to a hospital as well as a new oxygen supply system. The following characteristics were predicted to be the most valuable to hospital management when evaluating an oxygen supply system:

- Appearance
- Noise
- Ease of Use
- Reliability
- Durability
- Maintenance

Now that the important characteristics were defined, it was possible to determine the weights and % preference or utility (Y_i) values.

Weights

Before the consumer preference value (H_i) for each characteristic can be determined, a system of weights or importance values must be assigned to each one. A set of informal surveys was handed out to a limited number of people within the class. The participants were to assume the position of hospital management in evaluation of an oxygen supply system and rank each of the important characteristics from 1-10 based on how important it was to them. A value of 10 would be extremely important and a value of 1 would be not important at all. From the surveys, the weights were established and are shown below in Table 13.

It is important to note that there is a lot of inaccuracy to the surveys that were conducted. Only a limited number of people were surveyed and do not represent hospital management. The participants were only asked to base their answers as if they were hospital management. This survey was meant to provide insight that would allow for estimation on how hospitals would rank the important characteristics.

Characteristics	Average Importance
Noise	7.5
Ease of Use	6.3
Appearance	4.8
Frequency of Maintenance	7.9
Reliability	8.8
Durability	7.6

Table 13. Assigned characteristics table with associated values for weights.

*This is an estimation only.

The average importance values from the surveys for each characteristic are shown in Table 13. Dividing all the value by their summation gives their normalized weight value between 0 and 1. The summation of these normalized values must be equal to 1 and can be found in Table 14. It is important to note that the values will vary depending on the various hospitals and values of each. The weights in the above table are merely an example based upon estimated average importance values for a large hospital taken from the limited survey.

Characteristics	Weights (wi)
Noise	0.175
Ease of Use	0.147
Appearance	0.112
Frequency of Maintenance	0.184
Reliability	0.205
Durability	0.177

Table 14. Normalized Weights

Yi (% Preference) Determination

The last item to evaluate before the consumer preference (H_i) can be calculated is the y_i, % preference values. The % preference values come directly from utility equations that relate the consumer's % preference to that of a physical attribute that can be modified in a product in order to increase consumer preference. Three expressions must be developed in order to produce a utility equation for each of the characteristics. The following expressions must be developed:

1. An expression must first be developed to relate %preference between each important consumer characteristic and the words used to describe each characteristic by the consumer description.
2. An expression that relates the characteristic with consumer descriptions to physical attributes that can be changed.
3. A combination of the first two expressions to yield a % preference of characteristic versus physical attributes yielding the utility equation.

Once all utility functions have been found from the third expression above, the hospital oxygen concentrator's physical attributes can be modified to yield different % preference values. These % preference values will be multiplied against the weights and summed to produce an overall preference H_i value. The following section evaluates all the characteristics and determines the utility functions of each as well as provides possible manipulations for the hospital oxygen concentrator to increase consumer demand.

Characteristic Utilities and Consumer Preference Evaluation

Appearance

Appearance is an important characteristic for a hospital when evaluating an oxygen concentration system. Appearance can be used by a hospital to show cleanliness, class, and professionalism. By keeping a hospital with a great appearance, a hospital may be able to attract more doctors, specialists, and patients.

The relationship between % preference of appearance and the actual consumer descriptions of appearance is shown in Figure 22. It was estimated that the % preference would stay low until the consumer described it as "good" and then would quickly increase.

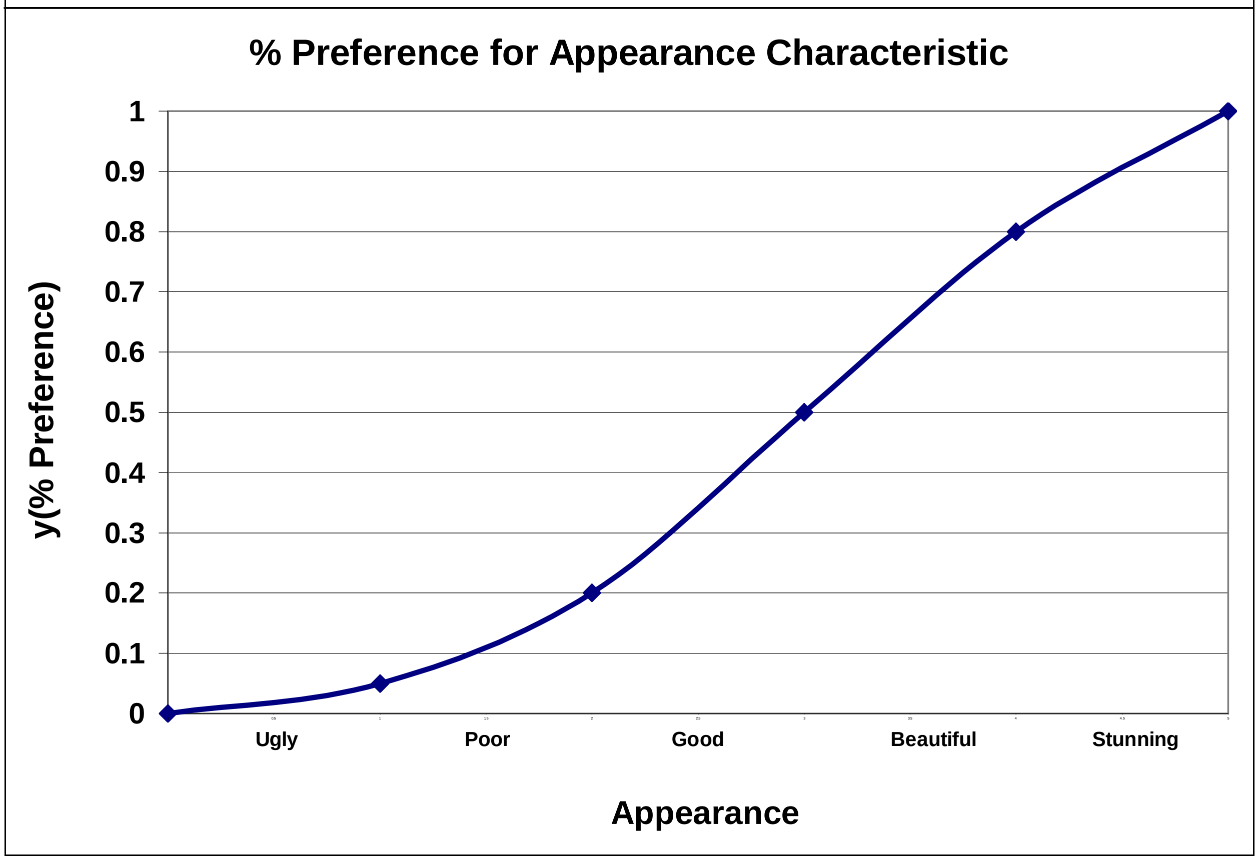

Figure 22. Consumer perference as a function appearance

*The function is generated by fitting a trend line to the plot. This curve is generated based on estimated importance to a hospital. No actual hospital surveys were taken. This is an example.

From Figure 22, it can be expected that most consumers are going to prefer a material type that is stunning/beautiful is visually pleasing. Now that the preference of the consumer has been estimated with consumer descriptions of appearance, it is now necessary to develop a system to measure the physical qualities of appearance. In this case, appearance is defined by the number of color, texture, architectural options, and ability to blend/mesh with a hospital that a particular material may have. Particular materials may have more or less options than another.

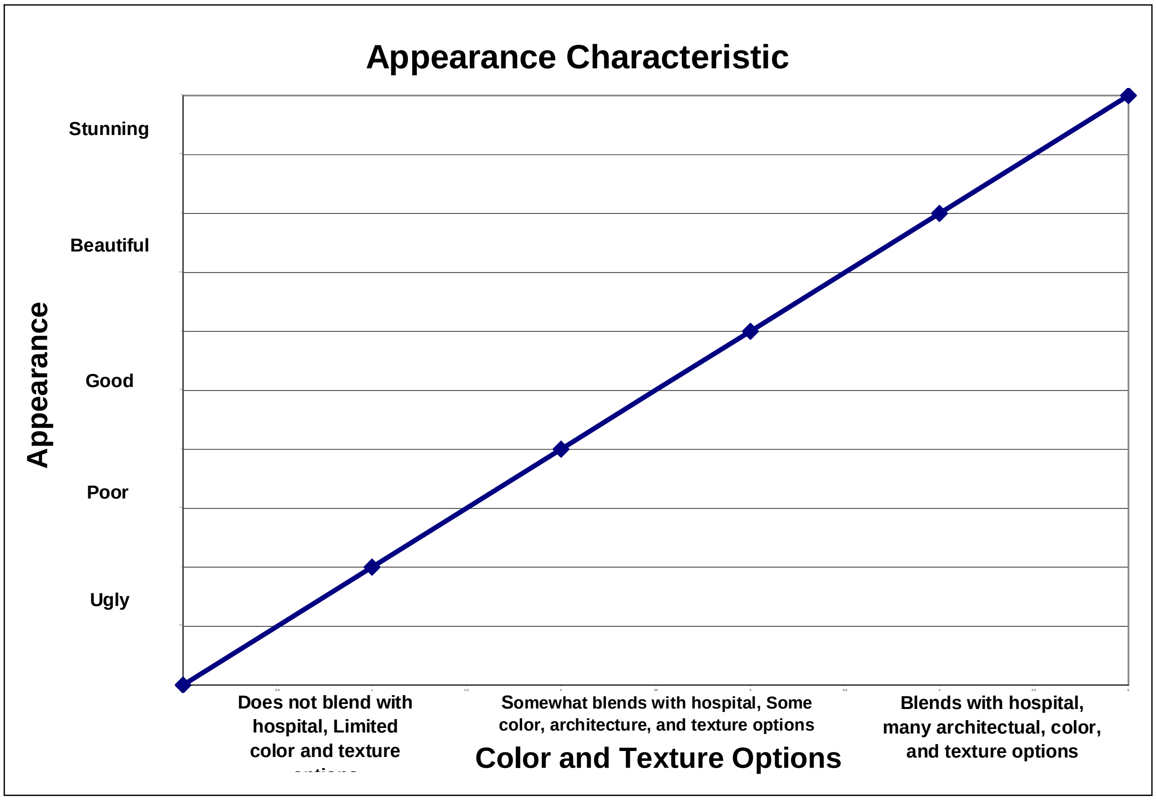

Figure 23. Appearance versus Color and Texture Options

*The above figure describes the correlation between appearances based on options that aid in blending with a hospital. The above figure is an estimate based on assumption.

The % preference versus appearance Figure 22 indicates that people prefer a structure that will blend with a hospital. It can be seen in Figure 23 that most people would prefer many architectural, colors, and texture options in their material of choice. By formulation of the correlation, it is now possible to relate the consumer preference % to the physical property of color and texture options. This is important, because it allows the evaluation of the product before reaching the consumer. The function allows quantification of % preference by simple input of the amount of color and texture options that a material has available. The producer can then change the product to adequately adjust to the estimated preference of the consumer. The % preference versus color and texture options is shown in Figure 24.

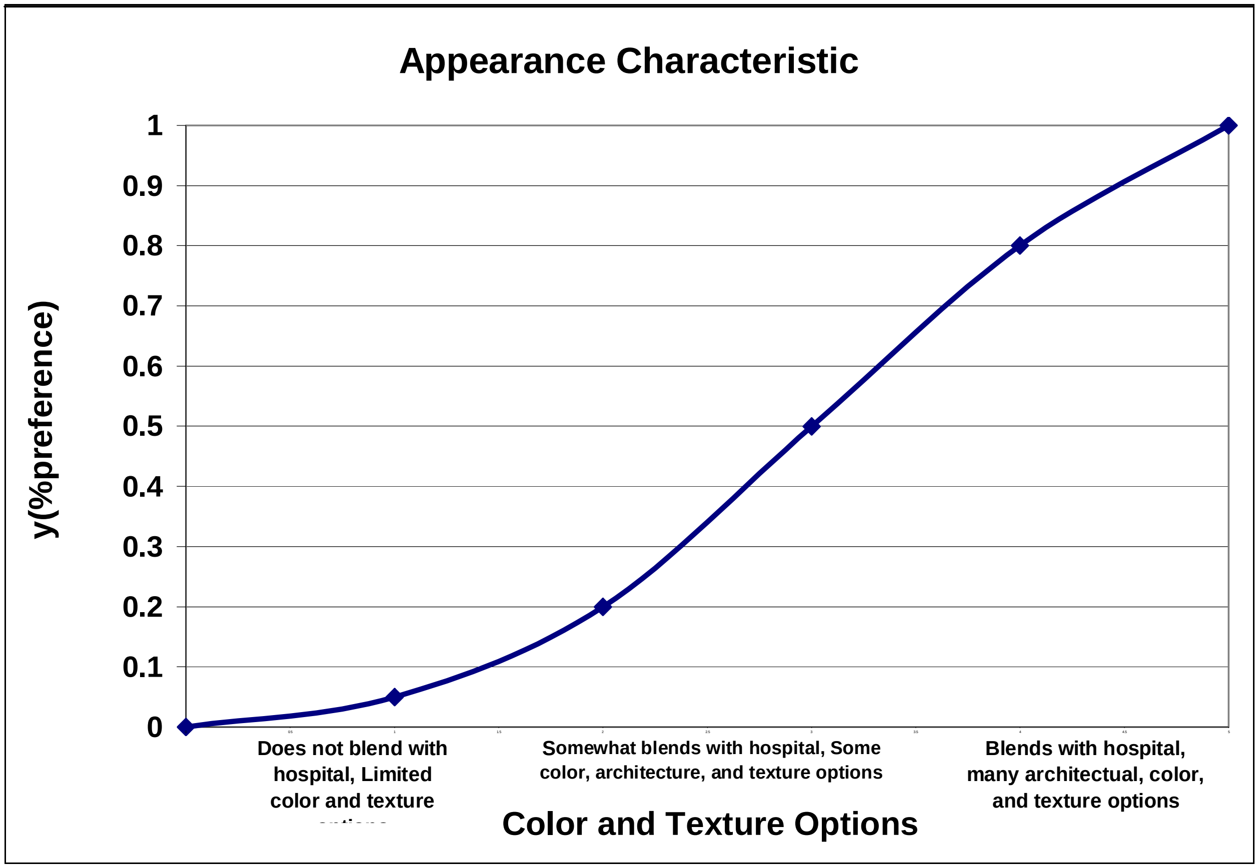

Figure 24. Consumer preference plot as a function of appearance

*The function is generated by fitting a trend line to the plot. The function yields a y_i score that signifies the % preference of the consumer. This number is multiplied by the calculated weight in order to give the preference of the characteristic. This curve is generated based on estimated importance to a hospital. No actual hospital surveys were taken. This is an example.

The utility function found from Figure 24 is shown in the following formula.

Y(% preference Appearance)=$-0.0134x^3 + 0.1248x^2 - 0.0888x + 0.0063$

Where: x is the amount of color, texture, and architecture options that a material has to blend in with a hospital

Manipulation of Hospital Oxygen Concentrator for Appearance Characteristic

Now that the consumer preferences toward appearance have been estimated, the producer can now determine the material that will draw in the most consumers toward the oxygen concentration design for a hospital. Figure 24 strongly indicates that consumer will largely prefer the most options possible to have choices for their concentrators.

The hospital oxygen concentration system will be housed in a casing not only for appearance but also for protection of the unit. The unit will be manufactured at a warehouse and taken to a hospital to install. Adding a casing before shipping would add bulk to the concentrator. Thus, it is important to have materials for this casing that are easily transportable, lightweight, durable, and assembled onsite at a particular hospital.

The expected area for the concentrator to take up is approximately 120 ft^2 with a height of 13 feet. In order to house the hospital oxygen concentrator and allow room for maintenance, viewing, and monitoring, the casing is assumed to have dimensions of width X 20ft in length X 15ft in height or 1,100 ft^2.

The most readily available light weight, durable, maintenance free, strong materials that offer a wide range of colors and can be used to house the oxygen concentrator are in Table 15 with associated costs for building the unit.

Material	Quoted Price	Total Cost
Vinyl Siding	$1.6/ sq ft [30]	$1,760
Aluminum Siding	$1.7/ sq ft [30]	$1,870
Veneer Stone Siding	$3.5/ sq ft [31]	$3,850

Table 15. Types of materials with associated costs for oxygen concentration system

Vinyl siding is "cost effective and virtually maintenance-free"[32]. It is produced and sold in a vast array of colors, textures, and shapes [32]. It is also light weight and easy to assemble which would be ideal for the hospital concentrator. The hospital could pre-order the materials to their liking to the company that is producing the materials. By doing so, the colors and textures could match the respective hospital and offer a appealing and professional look. The only disadvantage is that vinyl siding is sensitive to intense heat and can melt. It would be important for the compressors to be as far away from the siding as possible.

Figure 25. Example of vinyl siding[33][34]

Aluminum is another popular option on the market. It is also inexpensive, durable, and requires very little maintenance [32]. It can be painted to the consumers preferences for their hospital and can be textured [32]. It does not come in as many colors and texture options as vinyl, but it is light weight for shipping and is a stronger material. However, aluminum siding can scratch and dent which would be visible [32]. Unlike vinyl the color on aluminum does not go all the way through the material [32]. Aluminum also can be subject to oxidation caused by the weather [32]. The only remedy is to repaint the siding.

Figure 26. Example of aluminum siding[35][36]

Lastly, veneer is another great option for a hospital to consider when wanting a professional and attractive oxygen hospital design. It adds a rich, natural stone look to any project [31].

Veneer is easy to assemble, lighter than stones, and less expensive. The color ranges are limited with only black, grey, and white [31]. Its textures are also limited to that of type of stone texture is used for a particular project. Overall, veneer is a good product but would not blend in well with most hospitals today due to its limited color and texture range.

Figure 27. Examples of veneer with artificial stone[31]

The best materials have been found that will be specifically good for this project in terms of easy assembly and transport. Overall, vinyl siding will offer the highest consumer preference with the most color options and textures available. It is also the least expensive material and would not add a significant cost to the oxygen concentrator total cost. By using aluminum or vinyl siding, more consumers will be likely to be drawn to the hospital concentrator.

Noise

Noise is an important characteristic for a hospital when evaluating an oxygen delivery system. Noise from the hospital oxygen system could cause hearing loss, effect patient sleep, and hurt verbal communication in areas closest to the apparatus. Compressors in the hospital oxygen concentrator design could put out up to a maximum 120 dB [37] within 10 feet of the system which may have negative effects on the hospital atmosphere and community. It is necessary to house the hospital concentrator unit within walls layered by noise absorbent foam for noise reduction.

The following figure (Figure 28) is a plot of the estimated % consumer preference towards different noise amounts that a consumer would use to describe a product (noisy, very noisy, etc). Two types of people, tolerant and non tolerant toward noise were modeled in this example to compare different preferences of people. It is important to note that this is an estimate of how people react. No scientific surveys were taken in order to produce the curves in Figure 28.

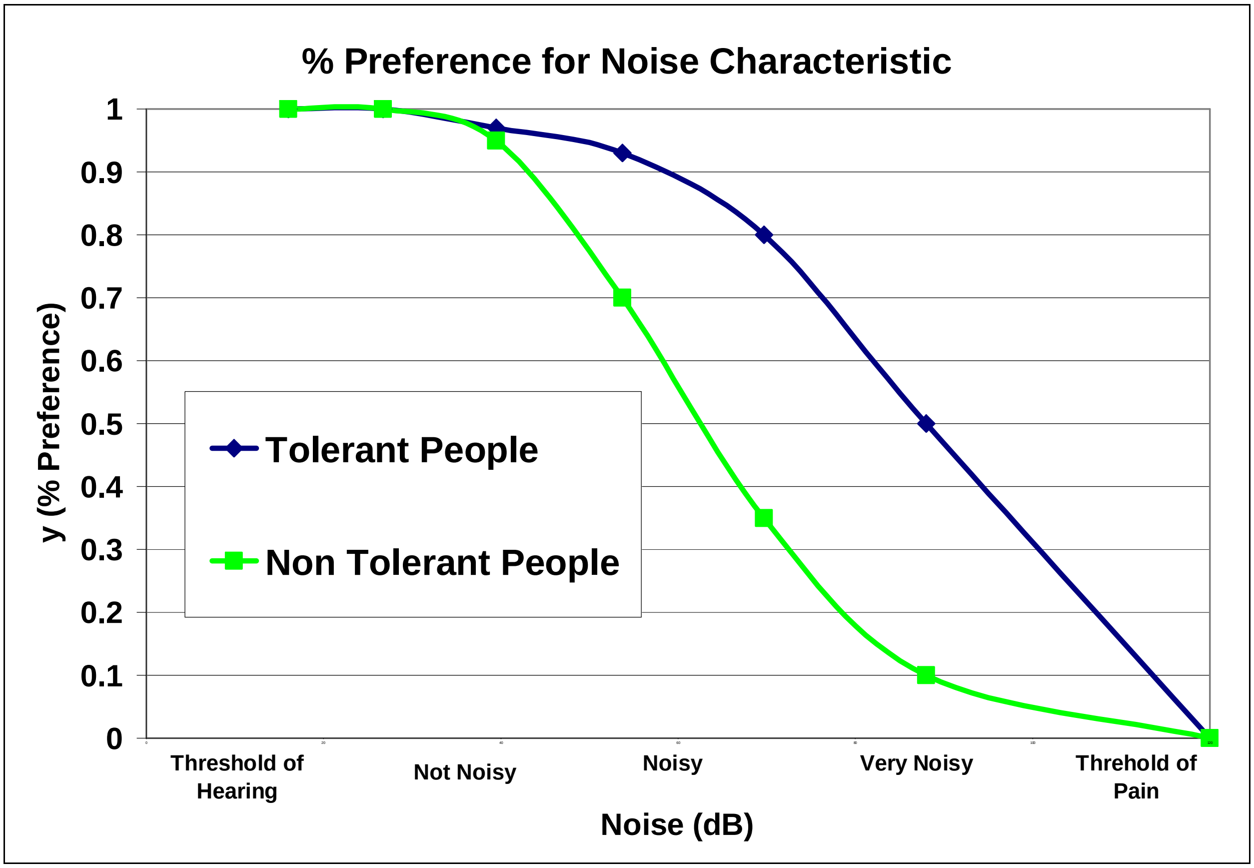

Figure 28. Plot of %preference versus noise

*No actual surveys were taken. This is an estimated example.

The important information that can be found in Figure 28 is the relative estimated difference between the two types of people. The two types of people were estimated to vary a lot in their noise preferences when there is a considerable amount of noise in the noisy, very noisy, and threshold of pain area. It was also estimated that when the sound level got to the “not noisy” level or approximately 20-40 decibels, the interest of both types of people would begin to be similar. In order to please both types of people and all in between, the hospital oxygen concentration system needs to operate within the “not noisy” region.

The basis for the noise characteristics are in Table 16 with associated familiar sounds that can be heard everyday. The approximate loudness with regard to ordinary conversation is also included in Table 16 for an easy comparison to determine relative loudness. The physical relationship between the noise characteristic and common everyday noises was found and is plotted in Figure 29.

Noise Characteristic	Sound Environment	Sound (dB)	Loudness relative to conversation
Threhold of Hearing	Threshold of hearing	0	Don't hear anything
Threhold of Hearing	Rustling leaves	10	1/32nd as loud as conversation
Not Noisy	Quiet house interior or rural nighttime	20	1/16th as loud
Not Noisy	Quiet office interior or watch ticking	30	1/8th as loud
Not Noisy	Quiet rural area or small theater	40	1/4th as loud
Noisy	Quiet suburban area	50	1/2 as loud
Noisy	Office interior or ordinary conversation	60	Ordinary Conversation
Very Noisy	Vacuum cleaner at 10 ft.	70	Twice as loud
Very Noisy	Passing car at 10 ft./garbage disposal at 3 ft	80	4 times as loud
Very Noisy	Passing truck at 10 ft./food blender at 3 ft.	90	8 times as loud
Threhold of Pain	Passing subway train at 10 ft./lawn mower 3 ft	100	16 times as loud
Threhold of Pain	Night club with band playing	110	32 times as loud
Threhold of Pain	Threshold of pain	120	64 times as loud as conversation

Table 16. Noise characteristics in relation to sound environment, level, and relativity to conversation[38]

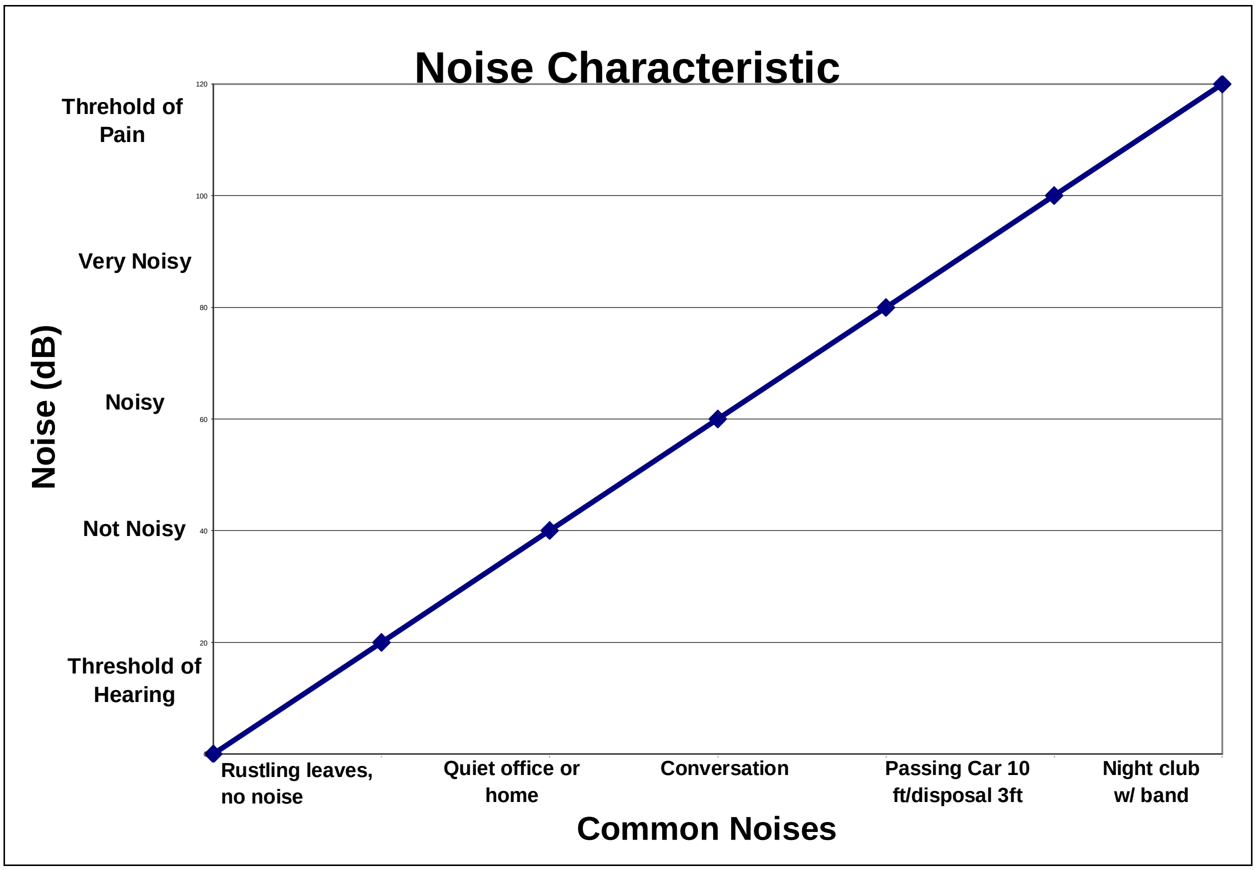

Figure 29. Physical representation of the noise characteristic versus everyday noises

Now that the noise characteristic has been plotted versus everyday common noises a consumer would be subjected to on a regular basis. The function in Figure 29 allows for further quantification of % preference by simple input of the relative noise of a sound in relation to the physical attributes of common noises. Figure 30 is a plot of % preference versus the common noises.

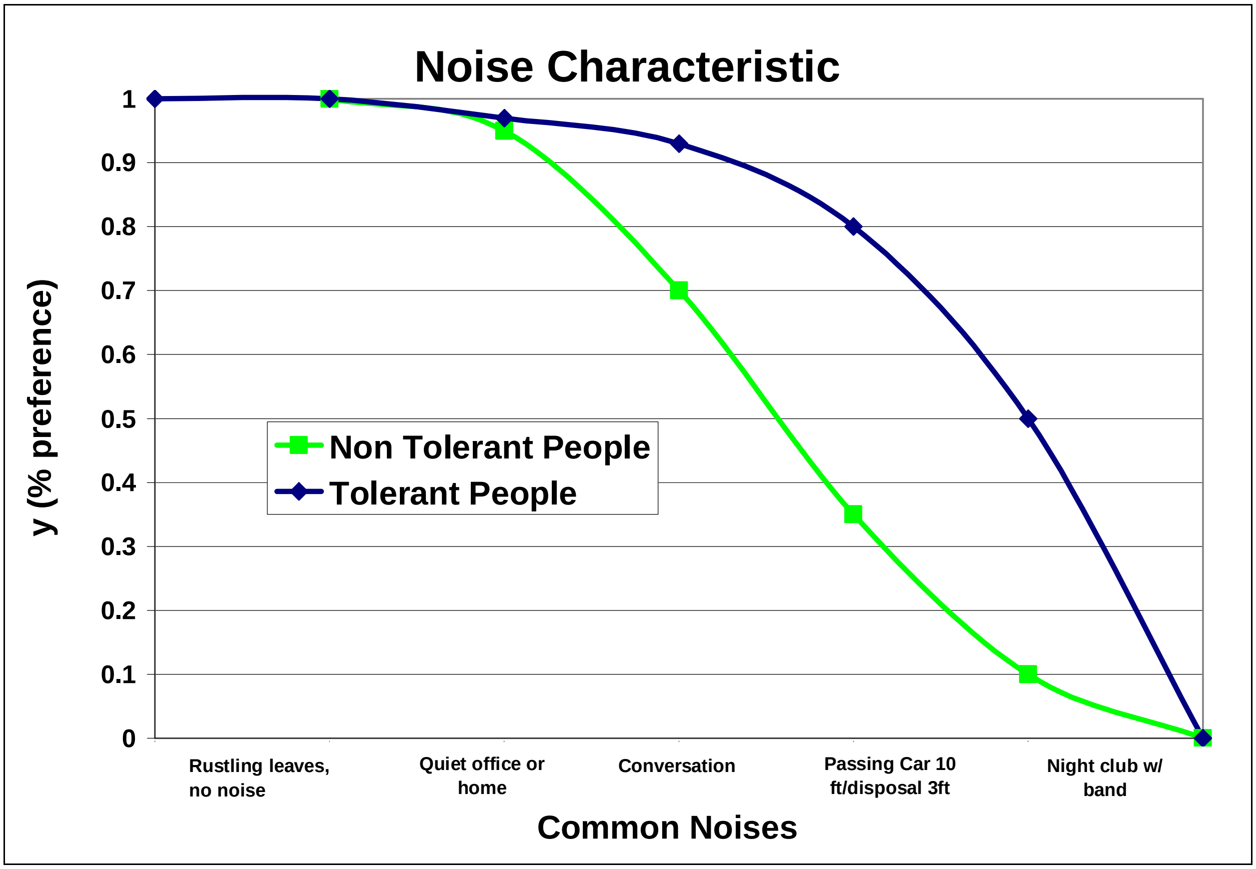

Figure 30. Plot of %preference versus noise

*The function yields a y_i score that signifies the % preference of the consumer. This number is multiplied by the calculated weight in order to give the preference of the characteristic. No actual surveys were taken. This is an estimated example.

The resulting equations from Figure 30 are shown below for both tolerant and non tolerant type of people. Depending on the consumer tolerance, one equation or the other will be used in determining % preference toward the hospital oxygen concentrator that radiates a specific amount of noise.

Non-tolerant y(%preference) = $4E\text{-}06*x^3 - 0.0007*x^2 + 0.0278x + 0.724$

Where: x is the common noise associated with a noise characteristic.

Tolerant y(%preference) = $5E\text{-}07x^3 - 0.0002x^2 + 0.0103x + 0.8713$

Where: x is the common noise associated with a noise characteristic.

To develop the unit that will appeal to the most consumers, the non tolerant utility equation will be used. It is assumed that if the design is pleasing to the non tolerant people then the tolerant people and all in-between will be pleased as well.

Manipulation of Hospital Oxygen Concentrator for Noise Characteristic

The % preference versus noise Figure 28 indicates that both tolerant and non tolerant people would prefer a system that is "not noisy." After relating noise to physical attributes, Figure 30 shows that most people would prefer a quiet office or home environment amount of noise. By formulation of the correlation, it is now possible to relate the consumer preference % to the physical property of common noises. This is important, because it allows the evaluation of the product before reaching consumer. The function allows quantification of % preference by simple input of the common noise has comes from the oxygen concentrator. The producer can then change the product to adequately adjust to the estimated preference of the consumer.

The dimensions of the proposed unit are 10ft in width X 20ft in length X 15ft in height with a surface area of 1,100 ft^2 that needs to be covered by the noise proofing foam. There are several types of noise reducing materials with varying prices available to the public. The more noise a particular product reduces, the more expensive the material costs. A comparison of materials with noise reducing capabilities, price per roll, and relative cost to cover the hospital unit housing is shown in Table 17.

	Reduction %	Dimensions/sheet	$/sheet	# Sheets Needed	Total Cost ($)
Ultra Barrier	95	1.25in X 4ft X 8 ft	295	34	10141
Quiet Barrier	90	1/4in X 4.5 ft X 20ft	361	12	4412
Econo Barrier	80	1/8in X 4.5 ft X 30ft	260	8	2119
Sound Proof Foam	70	1.125in X 4ft X 8ft	70	34	2406

Table 17. Noise barriers characteristics[39]

Figure 31. Quit Barrier Foam [39]

Figure 32. Ultra Barrier Foam[39]

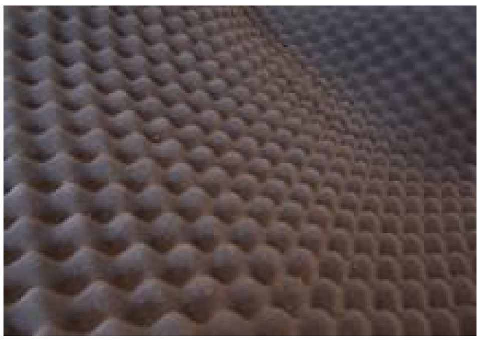

Figure 33. Soundproof Foam [39]

Figure 34. Econo Barrier Foam [39]

Before choosing the type of sound absorbing barrier that will be included with the hospital oxygen concentrator, the consumer preference towards noise was first estimated. By estimating the consumer preference toward sound, the material for the unit could be chosen that would draw the most consumers toward the product.

After the decision to have a type of foam that will not be noisy and relating it to physical everyday noises, a function was created with the noise characteristic plotted against the type of sound absorbing material. The graph of the utility function is shown in Figure 35.

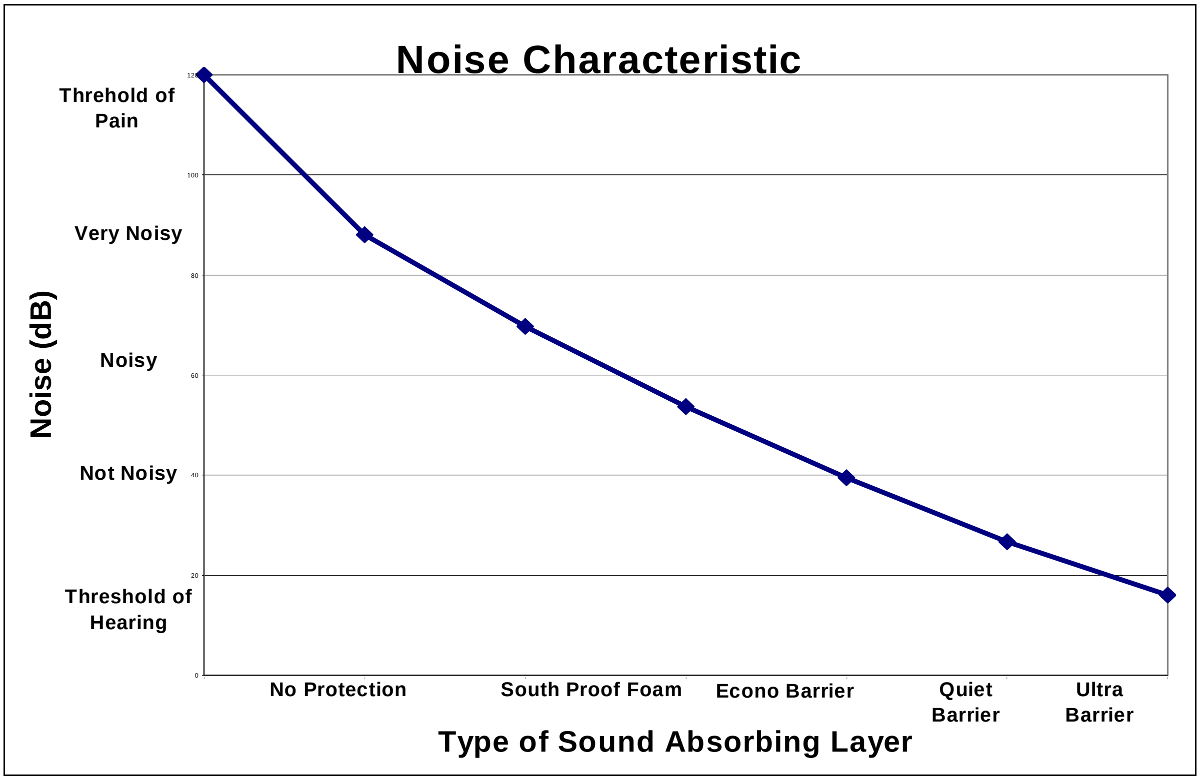

Figure 35. Noise characteristic versus type of sound adsorbing layer

*The noise absorbing capabilities can be found in Table 18.

The sound proofing materials that are in the not noisy region and below in figure ### are the Econo Barrier, Quiet Barrier, and Ultra Barrier products. These products are the best materials to draw in more consumers to the product. Using the noise reduction percentage found in Table 17, Table 18 shows the noise level change and associated costs if each of the materials were used to absorb 120dB of noise from a compressor.

Material	Reduction %	Compressor Sound (dB)	New Sound Level (dB)	Total Cost ($)
Ultra Barrier	95	120	6	6490
Quiet Barrier	90	120	12	2888
Econo Barrier	80	120	24	1300
Sound Proof Foam	65	120	42	1540

Table 18. Sound adsorbing materials with associated noise level change and costs[39]

Overall, both the Quiet Barrier absorbent foam and Ultra Barrier offer the highest consumer preferences with 90% and 95% reduction in noise. Using Ultra Barrier foam does not have a significant gain in consumer preference, approximately 1%, but is more expensive than Quiet Barrier. Thus, by using Quiet Barrier foam, maximum preference toward the noise characteristic can be achieved for the hospital oxygen concentrator and bring the most consumers toward the product.

Ease of Use

Ease of use is an essential issue for any hospital when evaluating their oxygen delivery system and method. Hospitals have been continually hampered by heavy liquid oxygen bottles when filling their oxygen storage systems and transporting patients. The proposed oxygen concentration system eliminates the problems of having to use a large supply of liquid oxygen. However, it is still vital that in a moment of crisis, oxygen delivery not only needs to be fast but also at an exact flow rate.

A % preference (y_i) versus ease of use is plotted in Figure 36 to estimate the preference of the consumer toward the ease of use characteristic. Ease of use is defined by how much training is needed in order to operate the device and to get oxygen to patients throughout the hospital. This is an estimate based on how consumers would react to using an oxygen concentrator system from operating the unit itself to delivering oxygen to patients.

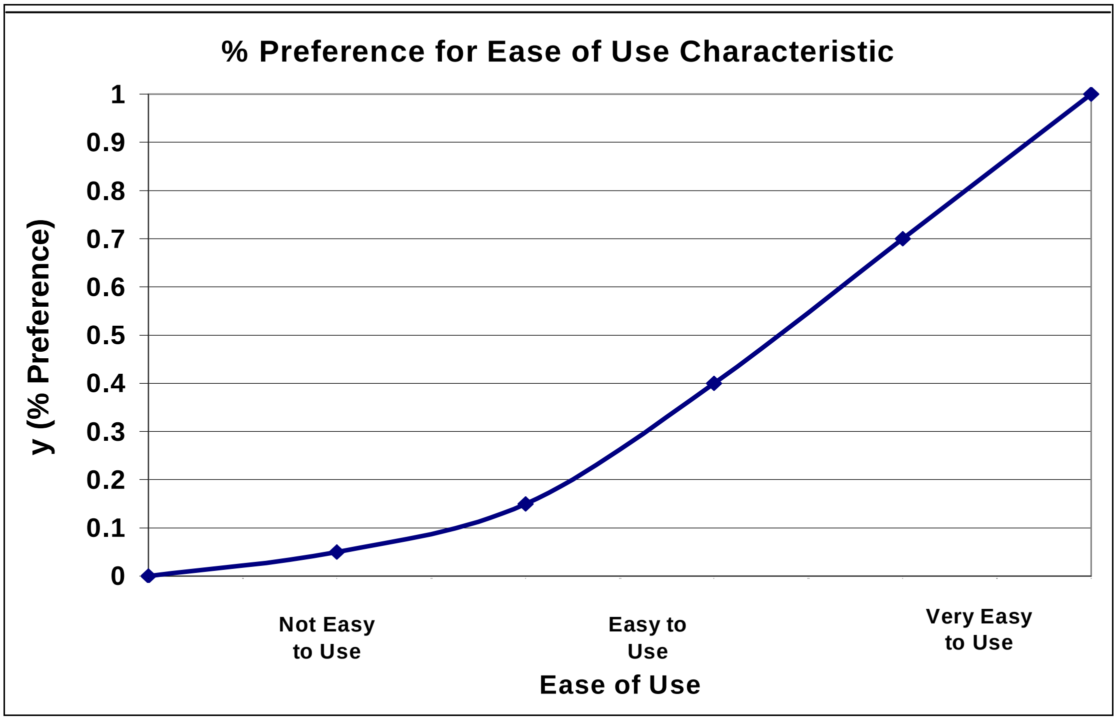

Figure 36. Consumer preference as a function of ease of use

*No actual hospital surveys were taken. This is an example.

The % preference plot indicates that most hospitals would prefer an oxygen system that is very easy to use. It was estimated that hospital management would not want to take any chances with having a difficult system and would be largely in favor of a system that is extremely easy to operate. A system of measure based on consumer description of ease of use to the amount of training necessary for employees to have in order to operate the oxygen system adequately.

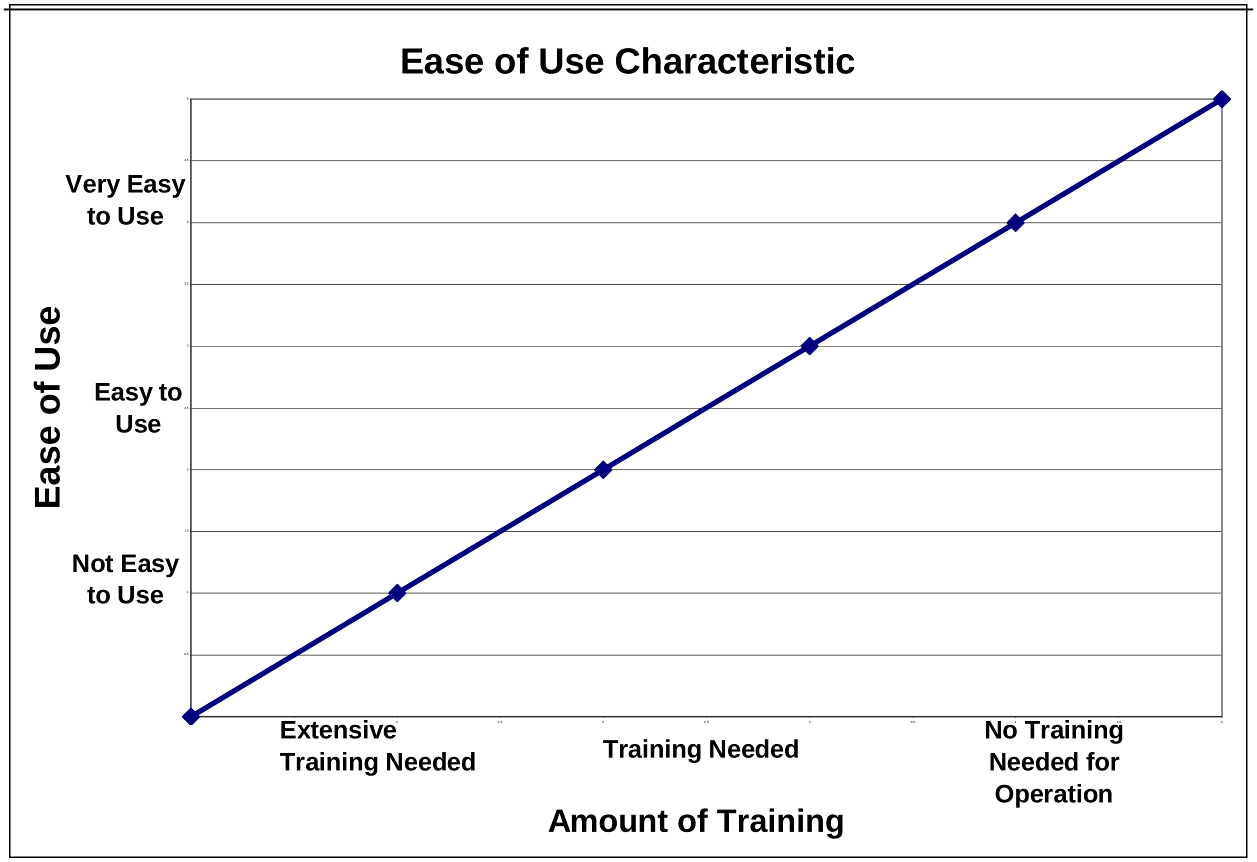

Figure 37. Ease of use versus amount of training

*This figure describes the correlation between ease of use and training for hospital use of the oxygen concentrator design. This is an example.

The correlation in Figure 37 was linked to the % preference in order to produce the consumer preference toward the amount of training in Figure 38.

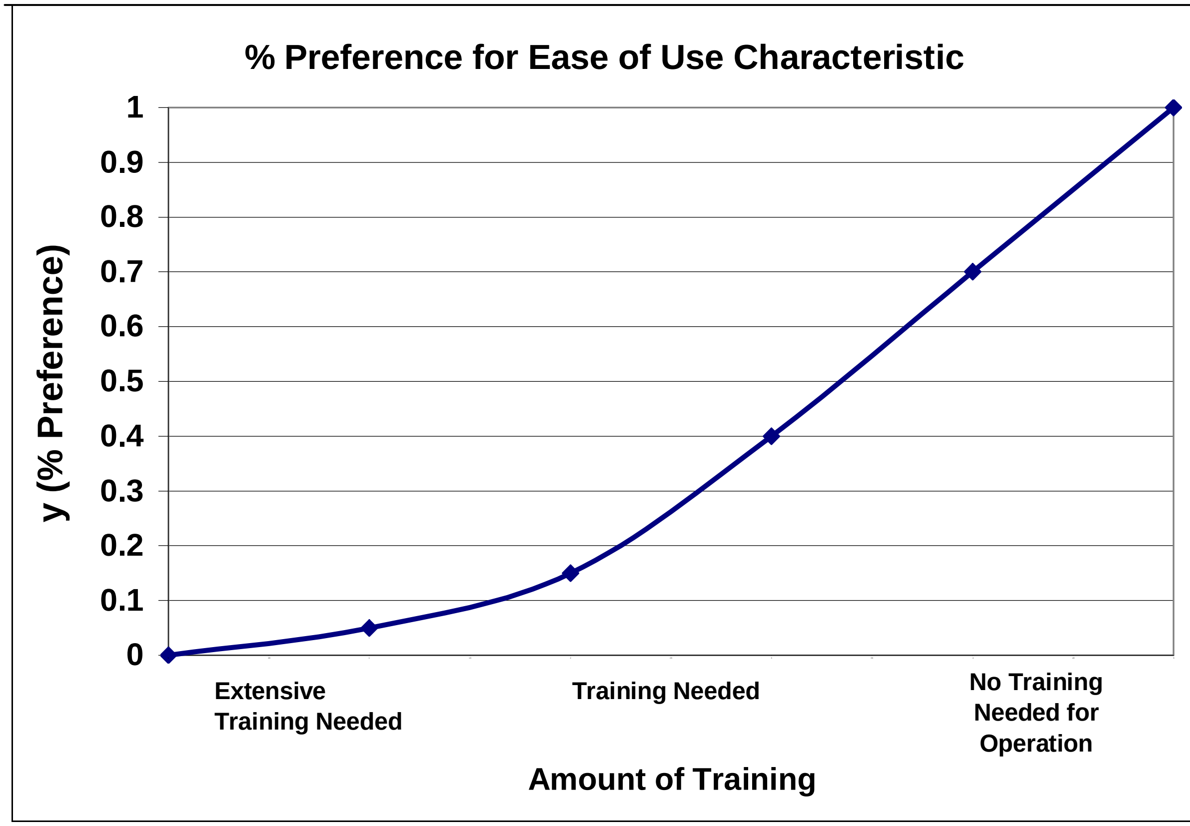

Figure 38. Consumer %preference toward the amount of training

*The function yields a y_i score that signifies the % preference of the consumer. This number is multiplied by the calculated weight in order to give the preference of the characteristic. No actual surveys were taken. This is an estimated example.

The resulting % preference equation to be used in calculation of the total preference when multiplied by the characteristic weight is shown in the following formula.

Y(%preference) = 0.0366x2 + 0.0227x - 0.0089

Where: x is the amount of training

Manipulation of Hospital Oxygen Concentrator for Ease of Use Characteristic

It is important to note that training will not have an associated cost. Making the oxygen concentration system more easy to use does not have a large associated cost with it. It is designed to be able to run independently without hospital personnel to monitor it constantly. It would be beneficial if the new system could utilize the liquid oxygen delivery system already in place in most hospitals. By using the installed lines and valves and tapping directly into the high pressure storage tank introduced in the design, hospital employees would need no training on equipment they know how to use. Ease of use is primarily used in determination of a β value, since it is still a very important characteristic.

Reliability

Reliability is perhaps one of the most important characteristics for a hospital when determining whether to purchase the oxygen concentrator. If the hospital pressure swing system is not reliable, it could break down and cost people their lives. Hospital operations that would be effected are the following but not limited to surgeries, emergency rooms, life support systems, intensive and other care units. The reliability characteristic is not only important but absolutely essential.

In order to develop an accurate picture of how consumers would react to reliability, preference values toward the reliability characteristic were estimated. It was expected that as the reliability for a system increases, the consumer % preference toward that product would also increase. Figure 39 shows the graph that relates the consumer preference % to the reliability characteristic with the words used by consumers to describe it.

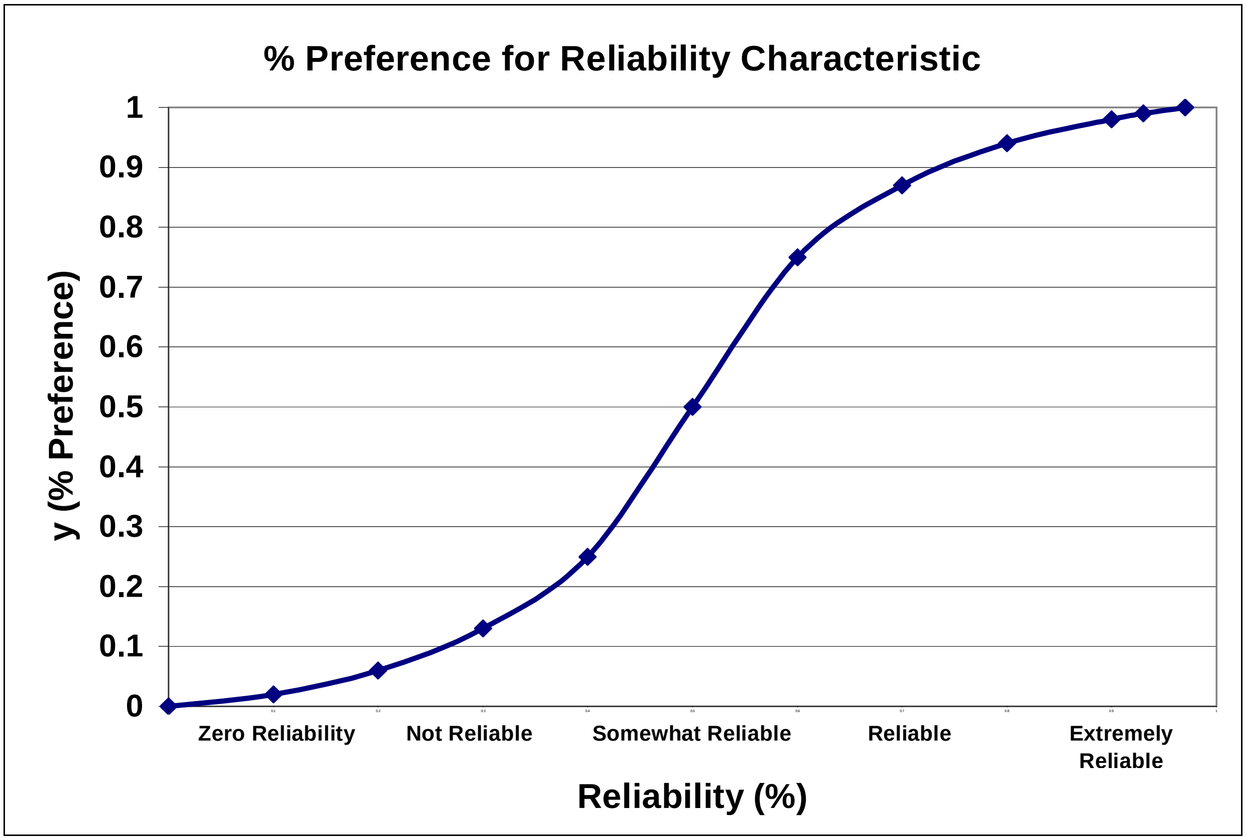

Figure 39. Percent preference versus reliability

The reliability of a product depends on the combined reliability of all of the parts that can fail within the unit. Reliability is most commonly related to the mean time between failures (MTBF)[40]. If the mean time between failures is high, lasting several years than the corresponding reliability would be 100%.

The reliability of a part was calculated with the following formula[40]:

$$R = e^{-\left(\frac{h}{MTBF}\right)}$$

Equation 14

Where: h = number of hours of operation. (ex 1 year = 8760 hours)
Mean Time Between Failures (MTBF) = 1/λ
λ = fails/million hours

Manipulating Equation 13 gives the following equation that relates reliability % and MTBF with variable time.

$$\frac{-h}{\ln(R)} = MTBF$$

Equation 15

Using the reliability percentages and time of 1 year, the MTBF values were calculated and plotted in Figure 40.

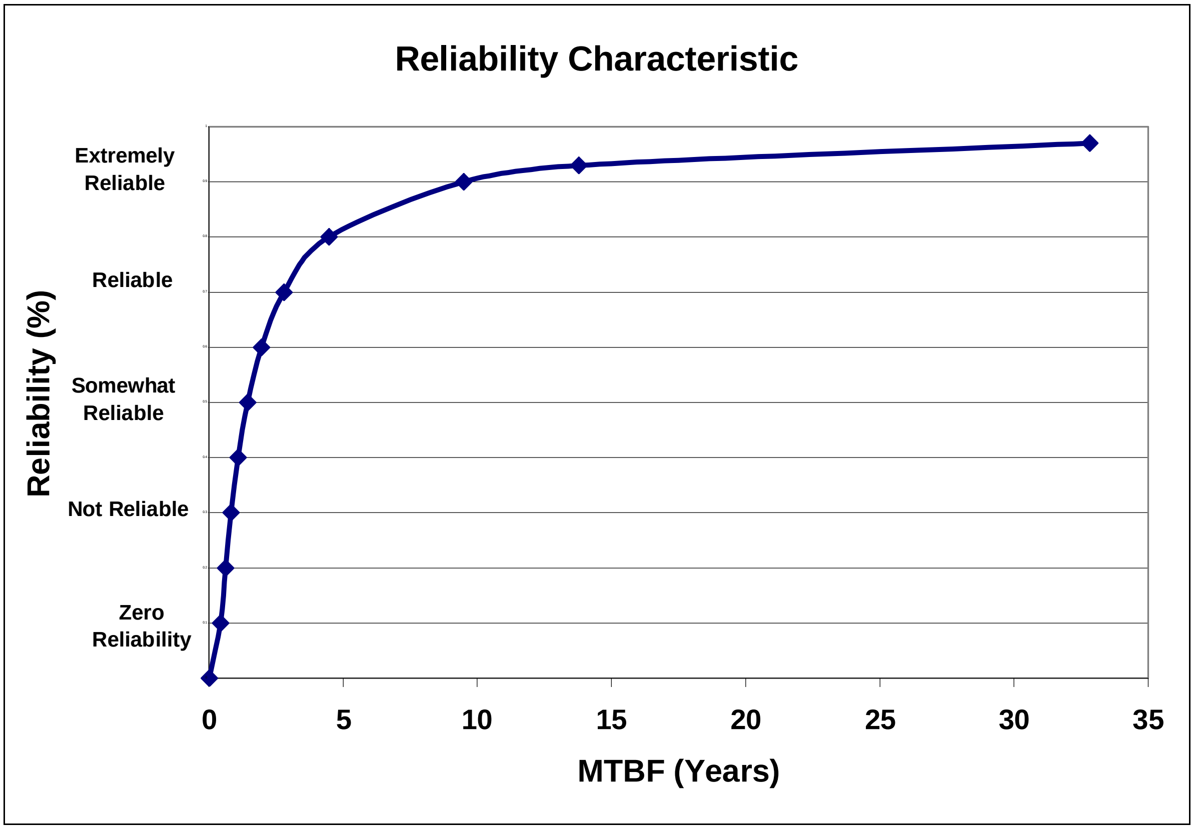

Figure 40. Reliability verse MTBF

*MTBF in 1 year as a basis. This is an example.

The correlation in Figure 40 was linked to the % preference in order to produce the consumer preference toward the MTBF physical attribute in Figure 41.

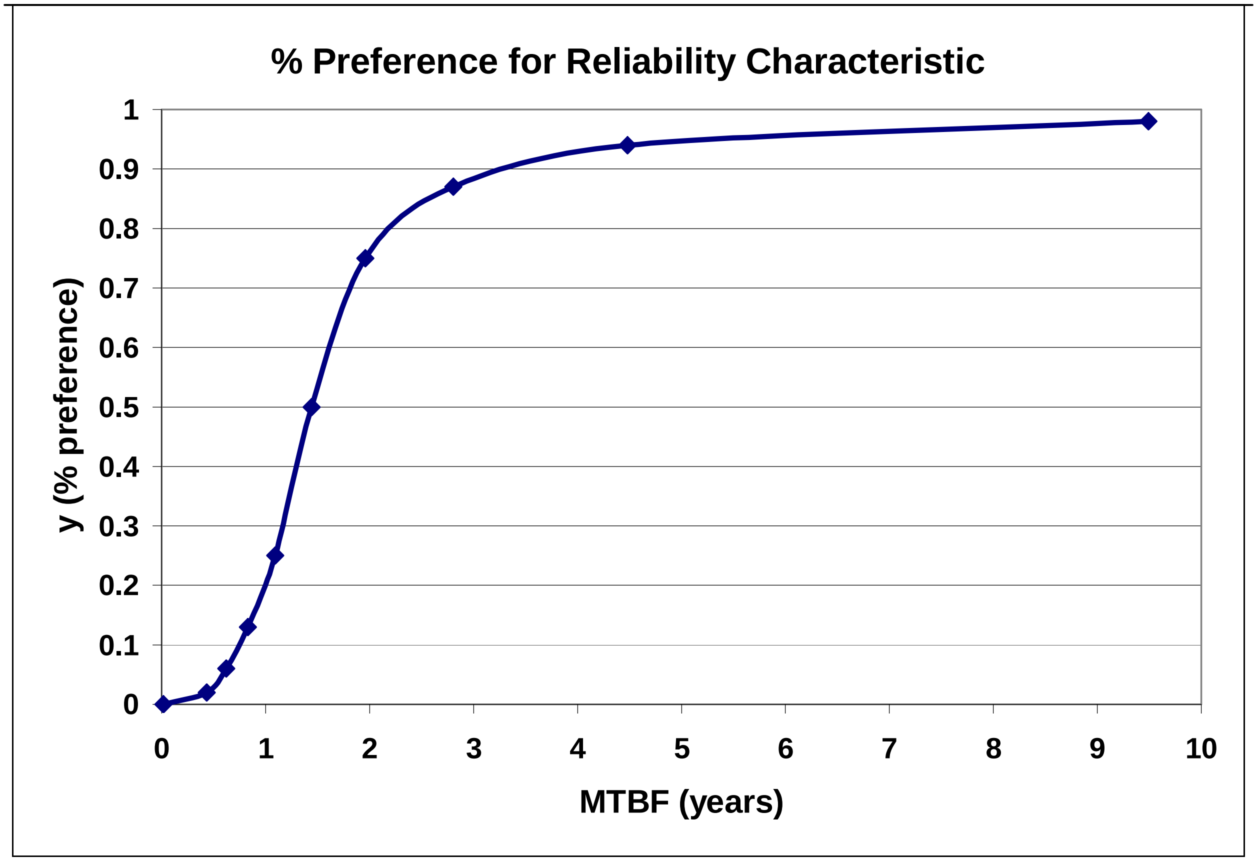

Figure 41. Percent preference versus MTBF

*The function is an estimation of the preference of a consumer versus reliability taken from surveys. The function yields a y_i score that signifies the % preference of the consumer. This number is multiplied by the calculated weight in order to give the preference of the characteristic.

The resulting % preference equation to be used in calculation of the total preference when multiplied by the characteristic weight is shown in the following formula.

Y(% preference for Reliability)=$0.0037x^3 - 0.0796x^2 + 0.5394x - 0.159$

Where: x is the MTBF in years.

Manipulation of Hospital Oxygen Concentrator for Reliability Characteristic

If the mean time between failures is high, lasting several years than the corresponding consumer preference would be 100%. It is necessary to determine the reliability of a typical PSA system so that correct actions can be taken to manipulate the system and increase % preference. The following units are subject to failure and were taken into account when evaluating the reliability of the hospital oxygen concentrator: *Compressor, Valves, Tank, and Columns.*

The reliability of a part was calculated with the following formula as introduced before in Equation 13. Once all of the reliabilities have been calculated for each part for one year, they are multiplied together to give the overall reliability for a system in the following formula.

$R_{total} = R_{compressor} * R_{valves} * R_{columns} * R_{tank}$

The following Table 19 gives the λ, MTBF, reliability for each part, and overall reliability for year one of a pressure swing adsorption system as an example[41].

Example of Realibility Calculation for Year 1			
Unit	**# Fails/(million hrs) (λ)**	**MTBF (1/λ)**	**Reliability exp(8760/MTBF)**
Compressor	10/5.0587	505870	0.983
Valves	9/5.805	645000	0.987
Tank	1/.125	125000	0.932
Columns	1/.125	125000	0.932
	Total Reliability Year 1 (R1*R2*R3*R4)		**0.843**

Table 19. Example of reliability calculation for year 1

*The #fails/million hours data was taken from NPRD in order to estimate the hospital unit reliability.

The same process was repeated for 10 years of operation to develop an accurate picture of how the oxygen concentrator would behave over a decade of lifespan with a given set of compressor, tank, valve, and column failure rates. The final reliabilities are in Table 20.

Reliability Over 10 Years	
Year	**Reliability**
1	0.843
2	0.710
3	0.599
4	0.504
5	0.425
6	0.358
7	0.302
8	0.254
9	0.214
10	0.181

Table 20. Estimated reliabilities for each year over 10 years for hospital unit

The previous table is represented graphically in Figure 42.

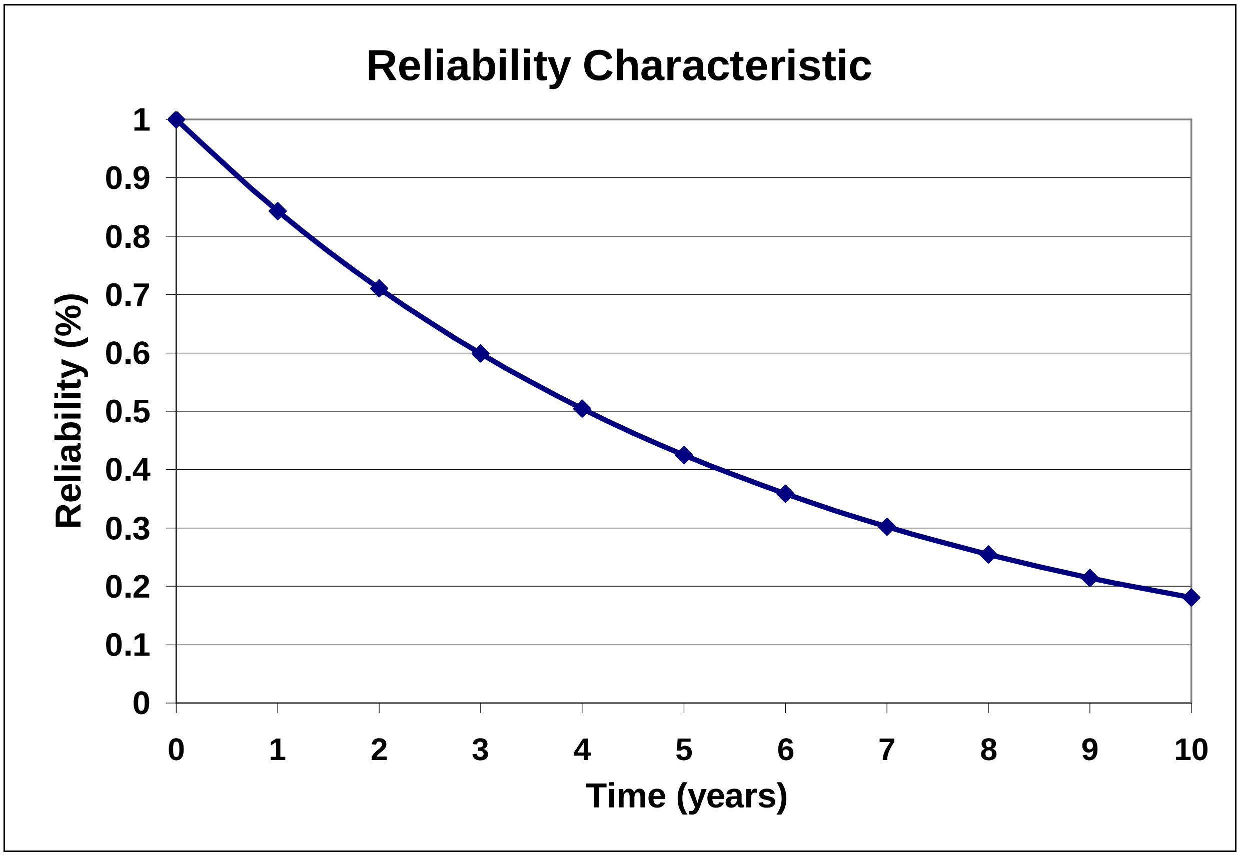

Figure 42. Estimate of reliability versus time for a typical PSA system

Figure 42 shows that a typical pressure swing adsorption system falls below 50% reliable between the 4th and 5th year.

There are two options that will dramatically increase the % preference of hospital management when looking at the oxygen concentrator design.

- Finding materials with larger MTBF
- Adding a second pressure swing adsorption system to complete the overall unit

Companies typically do not readily supply their calculated MTBF for their equipment. However, it is safe to assume that there will be a several hundred dollar to thousand dollar increase for parts that have a higher MTBF. There will be a considerable increase in cost of materials if the MTBF failure increases.

When evaluating the reliability of a system, especially for a hospital, there has to be hardly any room for failure. As stated before, the failure could risk patient's lives and completely halt surgeries and treatments within a hospital. It was shown that the reliability of one unit at the 5 year mark will be under 50%. One unit also has the risk of failing during the years reliability is high.

If only one pressure swing adsorption system was used, hospital would have to keep extra liquid oxygen on hand in case of failure. It is predicted that hospital management would take this fact into account when evaluating the hospital oxygen concentrator. They may wonder why they should purchase the oxygen concentrator when they would have to keep a large amount of liquid oxygen on hand in case of system failure.

In order to combat this problem, two PSA systems could be sold together as one unit similar to Figure 43. If the primary PSA system were to fail, a control computer would immediately switch on the second back up system. The secondary system until a maintenance person could rapidly come out on call to fix the primary unit. At that time the primary unit would be turned back on as the secondary unit was turned off again.

Figure 43. Two PSA systems[42]

Certain parts could be integrated together like the high pressure storage tank and silica gel to cut down on equipment costs. The equipment costs and raw materials would approximately double for the producer, but the added reliability and safety of two units would drive the % preference high. The equipment costs and raw materials will be introduced in the Business Model section. The percent preference would increase demand in the long run and hopefully reduce the added equipment costs. For purposes of safety, reliability, and to avoid lawsuits, a two PSA system unit would be best.

Durability

Durability is another important characteristic when evaluating an oxygen supply. Durability is sometimes confused with reliability. In comparison, durability means to resist wear decay, and to be enduring. Reliability is defined as something that is dependable and no apt to fail. They are both related in that if something is not durable or resistant to wear, it will likely be more apt to fail.

A consumer is predicted to both want something that is reliable and durable for an oxygen supply system. Figure 44 relates the estimated % preference of the consumer against durability and the words used to describe it.

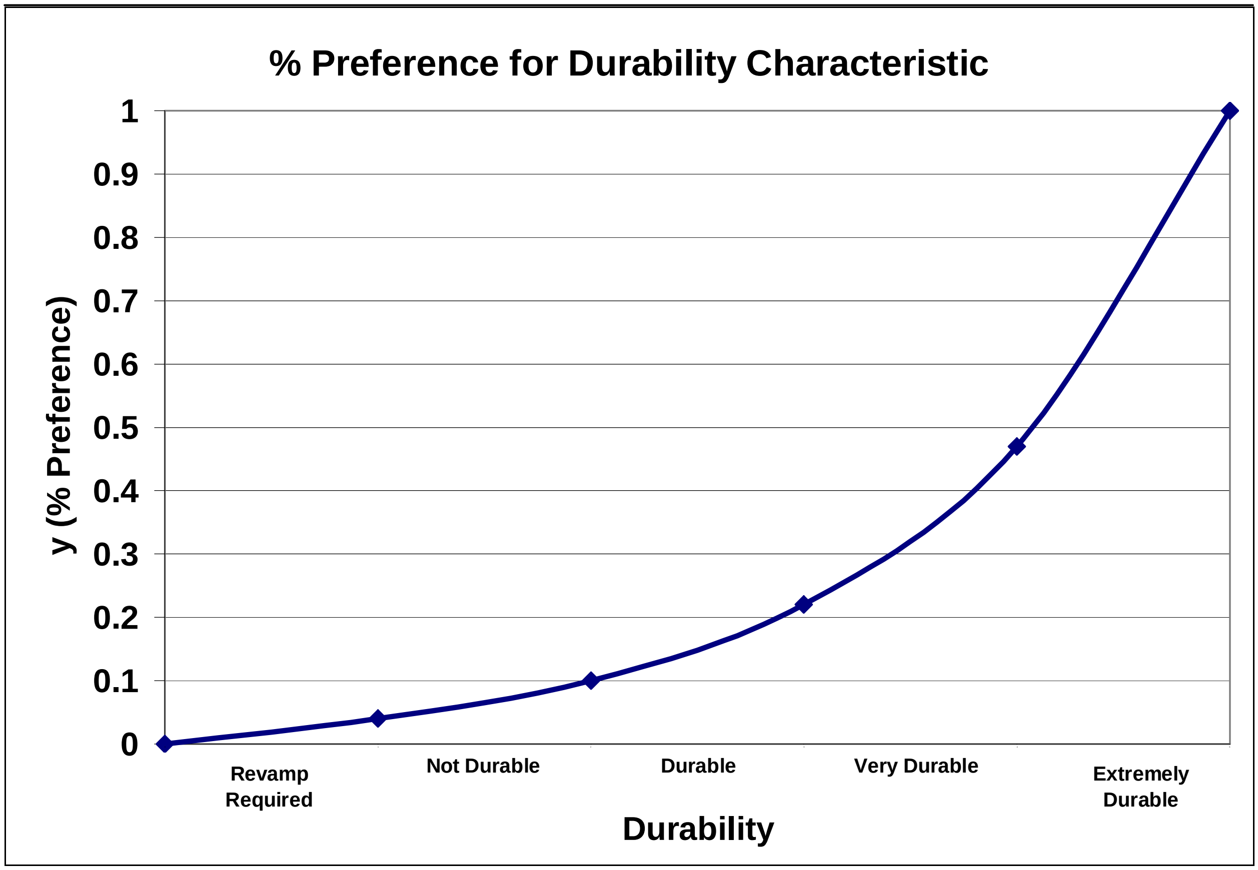

Figure 44. Consumer preference as a function of durability

*No actual hospital surveys were taken. This is an example.

Figure 44 predicts that as durability increases, the consumer preference toward a product will increase exponentially. At a maximum of 100% preference, a process would be described as "Extremely Durable." The physical attribute for durability is the time to complete revamp of a pressure swing adsorption system. No data for the specific time to revamp for pressure swing adsorption systems or liquid oxygen supply systems in hospitals was found to be available. The time for revamp for the specific parts could be estimated from the reliability and warranty provided from specific companies. The information found from companies about specific parts are in Table 21.

	Service Life Description	Assumption for Time to Revamp
3 way ball control valves	Very Long [43]	>5 years
Compressors	5 year warranty [22]	5 years
Tanks/Columns	Long [41]	>5 years

Table 21. Service life expectancies of parts

The 3 way control ball valves for the oxygen concentrator were very vague on the information regarding service life other than a "very long" description. Tanks for both oxygen supply systems and columns were estimated to have a long service life due to no moving parts. The compressors have the most service parts and were found to have a warranty up to 5 years. From the above information, it is assumed that at the 5 year mark when the compressor is no longer guaranteed and the control valves have run through several thousand cycles, it will be time to revamp the unit. Liquid oxygen supply also contains valves that will require revamp. The five year mark for revamp time is also evident from the reliability of less than 50% after 5 years. The wear of the valves is likely to be causing some of the failures and would need to be replaced.

Since the revamp time has been estimated from provided data of each of the parts, the durability characteristic can now be related to the physical property of time to revamp. The relation between the two properties is shown in Figure 45. The figure estimates that if the apparatus makes it the full 5 years before needing a revamp, it could be considered extremely durable.

The correlation in Figure 46 was linked to the % preference in order to produce the consumer preference toward the time to revamp physical attribute in Figure 45.

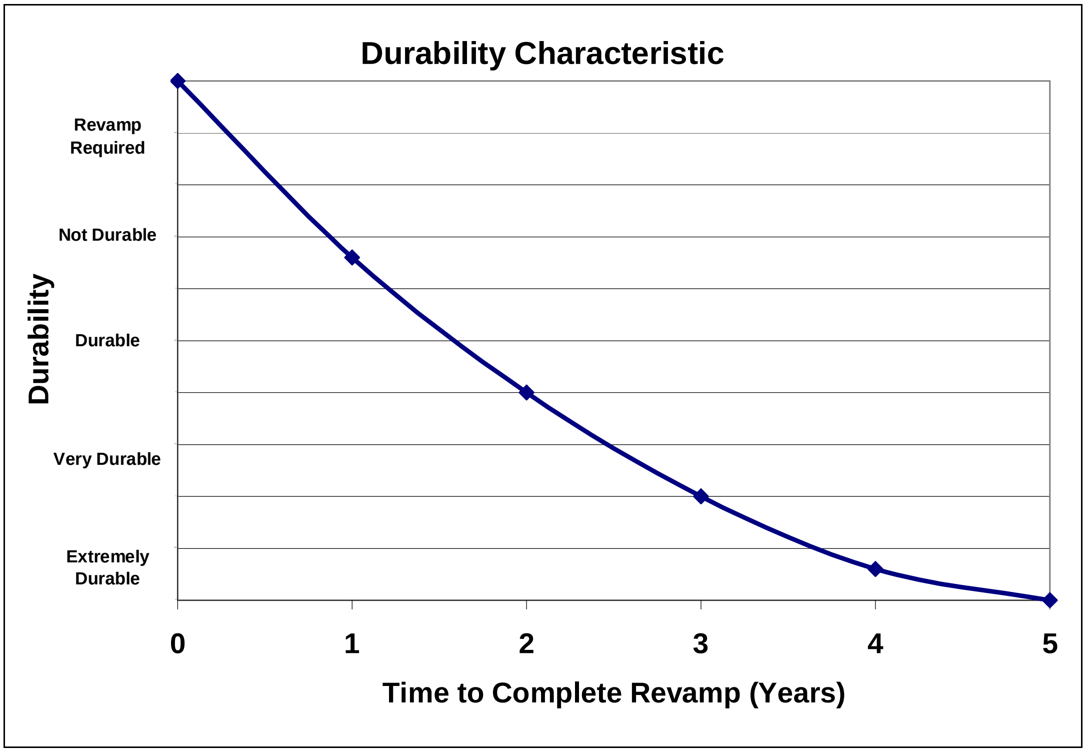

Figure 45. Durability versus Time to Complete Revamp

*This is an example.

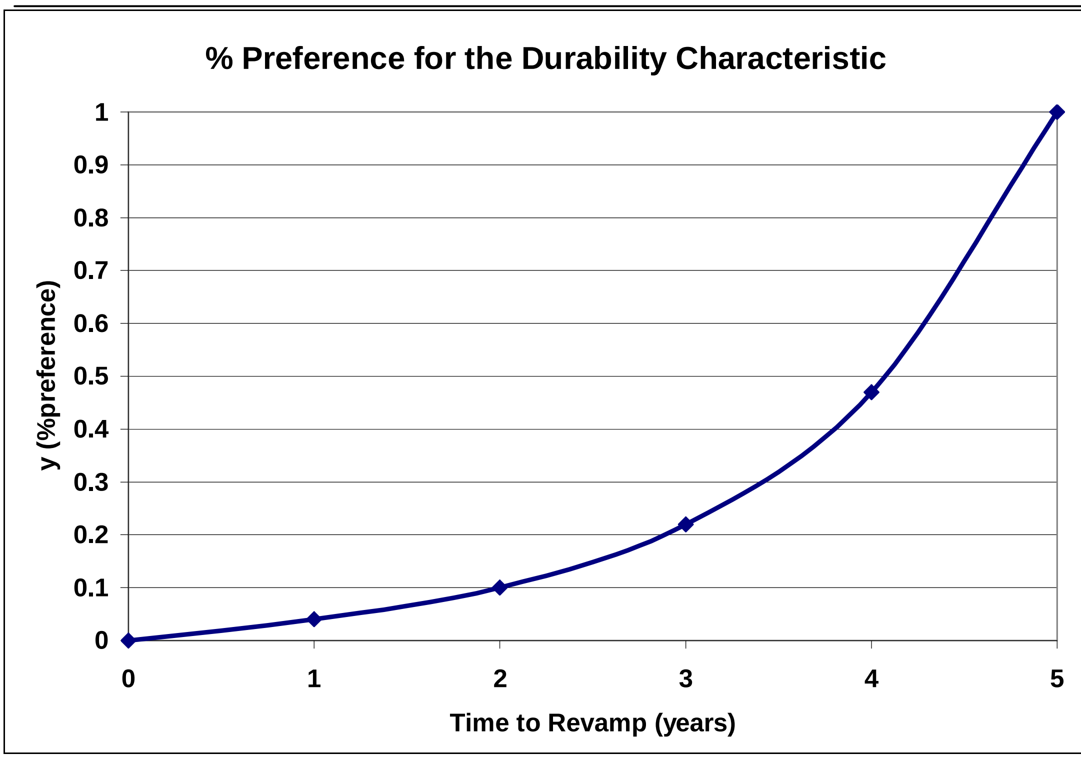

Figure 46. Consumer Preference versus Time to Revamp

*The function is an estimation of the preference of a consumer versus durability taken from surveys. The function yields a y_i score that signifies the % preference of the consumer. This number is multiplied by the calculated weight in order to give the preference of the characteristic.

$$Y(\%\text{ preference of Durability})=0.014x^3 - 0.0475x^2 + 0.0881x - 0.0037$$

Where: x is the revamp time in years.

Manipulation of Hospital Oxygen Concentrator for Durability Characteristic

It has been shown that to gain % preference of the consumer of the hospital oxygen concentrators, it is desirable to increase the durability by any means possible without increasing cost significantly. However, most valves are very durable and can withstand millions of cycle times. Ball valves are especially known to be good for gaseous applications [44]. The only items that would increase durability preference is to find a compressor that has a longer warranty and find parts with longer MTBF values. The longer MTBF values may indicate less resistance to wear and increased durability. Most compressors and valves are designed for maximum durability in order to gain consumers. Thus, the parts to be bought may be at the maximum durability and may not differ significantly from one company's parts to the next. There may be no significant cost for parts with added durability, but it is still essential when calculating the % preference for the optimal β values.

Frequency of Maintenance

The last important characteristic that will be used in determination of overall preference H_i is frequency of maintenance. Maintenance is important, because if an item needs to constantly be repaired then it creates inconvenience and increases overall cost to the consumer if the warranty is expired. Maintenance is directly related to the reliability characteristic as well. The less MTBF for the oxygen supply system, than the more times it will have to be serviced. Figure 47 relates the estimated % preference of the consumer to that of frequency of maintenance and the words used by the consumer to describe it.

Just like for the noise characteristic, it was estimated that frequency of maintenance would have two different types of people, those that are tolerant towards the frequency of maintenance and those who are not. Figure 48 relates frequency of maintenance to the physical attribute of number of maintenance visits per year.

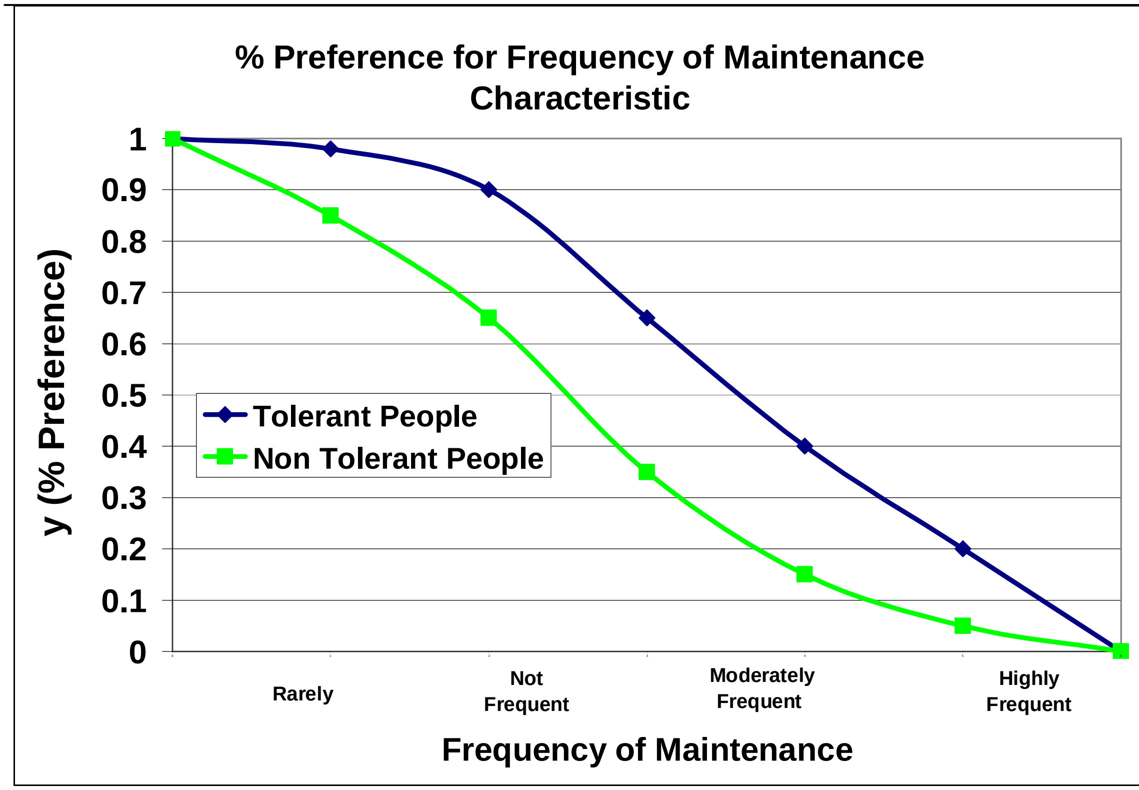

Figure 47. Percent Perference versus Frequency of Maintenance

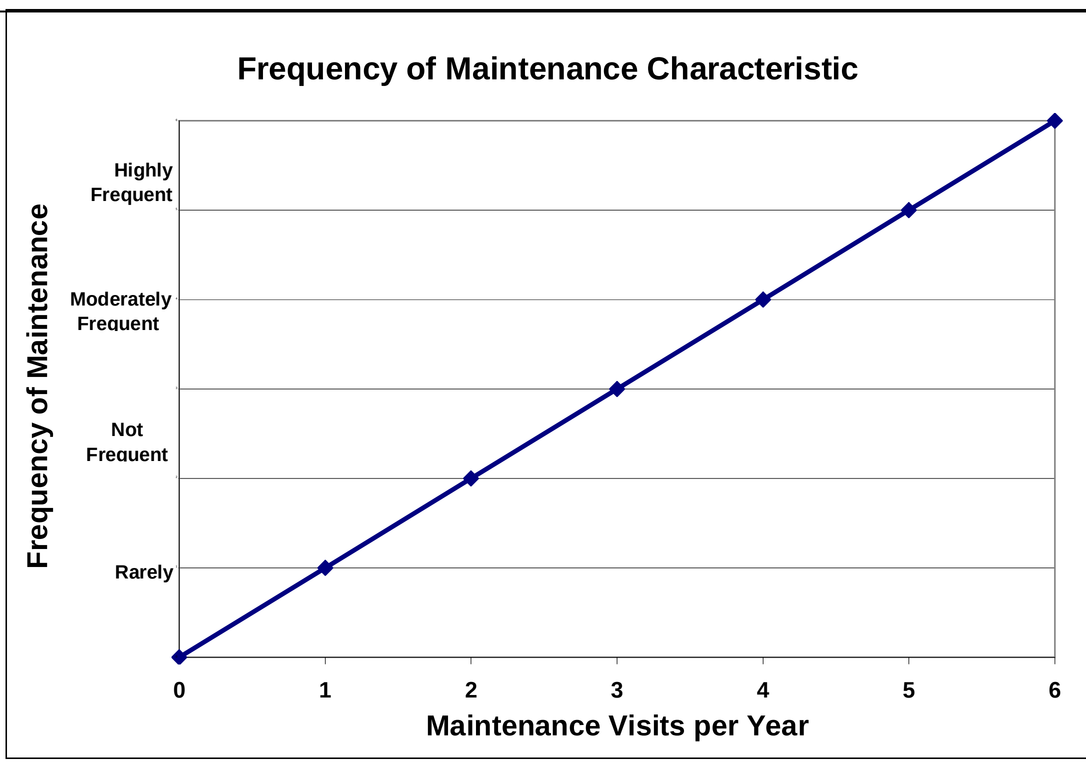

Figure 48. Frequency of Maintenance versus Maintenance Visits per Year

*This is an example.

The correlation in Figure 48 was linked to the % preference in order to produce the consumer preference utility function toward the maintenance visits per year in Figure 49.

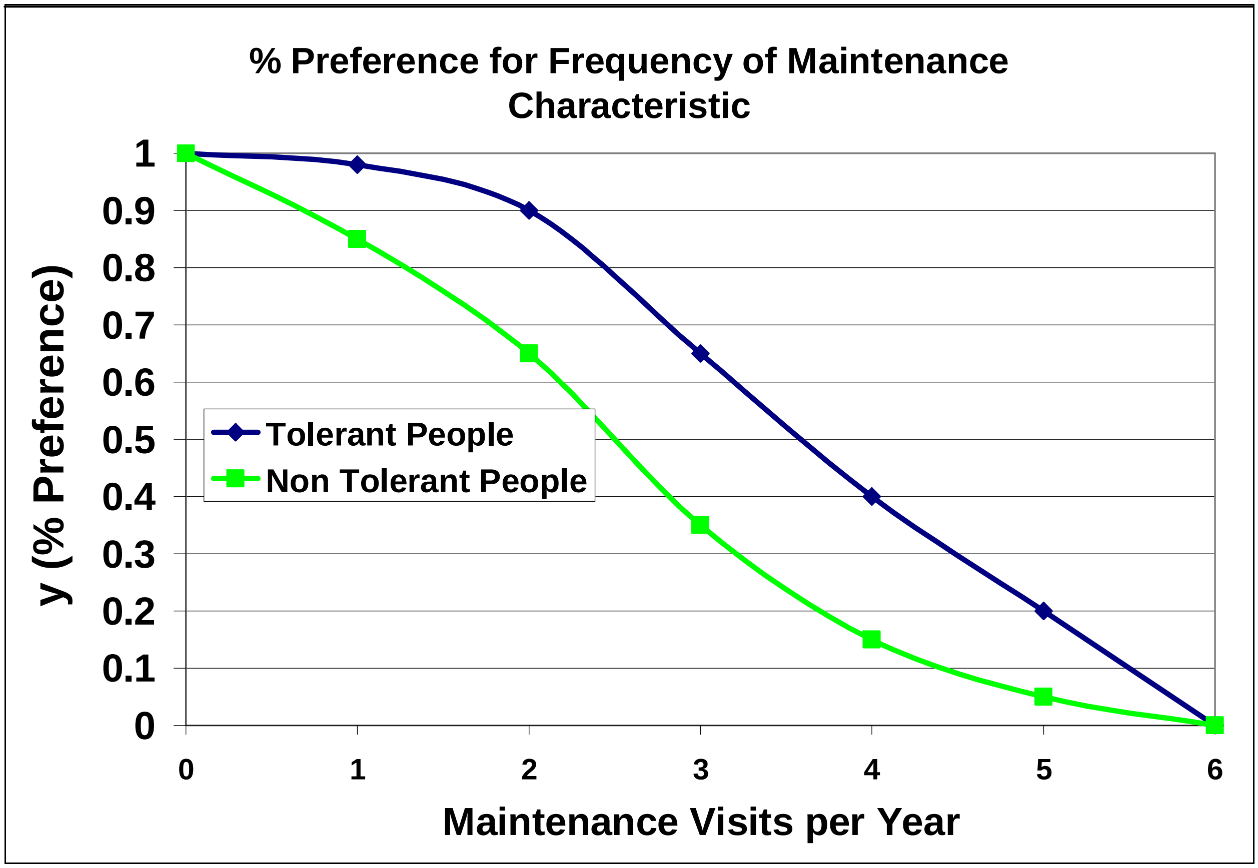

Figure 49. Consumer Preference versus Maintenance per Year

*The function is an estimation of the preference of a consumer versus maintenance taken from surveys. The function yields a y_i score that signifies the % preference of the consumer. This number is multiplied by the calculated weight in order to give the preference of the characteristic.

The following correlations for the consumer preference were developed from Figure 49.

Non-tolerant Y(% preference)=$-0.0083x^3 - 0.0607x^2 - 0.1012x + 1.0036724$

Where: x is the maintenance visits per year.

Tolerant Y(%preference) = $y = 0.0078x^3 - 0.0879x^2 + 0.082x + 0.9962$

Where: x is the maintenance visits per year.

Just like with the noise characteristic, the non tolerant utility equation will be used to determine the overall preference values H_i. The assumption again is that if the non tolerant people are pleased then the tolerant people and all in-between will be pleased as well.

Manipulation of Hospital Oxygen Concentrator for Frequency of Maintenance Characteristic

Just as with reliability and durability, in order to increase the % preference of the consumer toward the hospital oxygen concentration unit is to find items with the largest mean time between failures. This will increase equipment costs for the producer, but by obtaining parts with larger MTBF values will cause three characteristics to have more consumer preference thereby overcoming the increase in cost of the parts because demand will increase.

Conclusion of Consumer Utility and Preference Section

All utility and % preference functions have been plotted and their associated equations were determined. As stated before, all of the % preference functions (y_i) are related to physical characteristics that can be manipulated in order to determine the hospital oxygen concentrator design appeal to consumers. The following is a summary of all the % preference equations found from all of the % preference versus physical attribute graph for each characteristic:

Y(% preference Appearance)=-0.0134x^3 + 0.1248x^2 - 0.0888x + 0.0063

Where: x is the amount of color, texture, and architecture options that a material has to blend in with a hospital

Non-tolerant y(%preference of noise) = 4E-06*x^3 - 0.0007*x^2 + 0.0278x + 0.724

Where: x is the common noise associated with a noise characteristic.

Y(%preference of ease of use) = 0.0366x2 + 0.0227x - 0.0089

Where: x is the amount of training

Y(% preference for Reliability)=0.0037x^3 - 0.0796x^2 + 0.5394x - 0.159

Where: x is the MTBF in years.

Y(% preference of Durability)=0.014x^3 - 0.0475x^2 + 0.0881x - 0.0037

Where: x is the revamp time in years.

Non-tolerant Y(% preference of maintenance)=-0.0083x^3 - 0.0607x^2 - 0.1012x + 1.0036724

Where: x is the maintenance visits per year.

Depending on the different values associated with each of the important characteristics will yield a different % preference value (y_i). These values are use in equation 9 that was presented earlier but can be found below.

$$H_i = \sum w_i y_i$$

Equation 16

The % preferences are multiplied by their respective weights in order to find the preference (H_i) for each characteristic. The summation of all of the preference values will yield the overall consumer preference toward the hospital design. Once this value has been determined the superiority function β can be determined by dividing the competitor preference by the hospital design preference. This value will be used in the consumer utility maximization relation (Equation 10) in order to find demand as a function of price in the business model which is introduced in the following section.

Business Model

This section contains the explanation of the techniques used to maximize the net present value (NPV) for the hospital oxygen concentrator design. All businesses want to maximize NPV of their product. The equation used for NPV for this project is presented below[45].

NPV = Revenues –Total Product Costs-Fixed Capital Investment-Total Equipment Costs

Where: ***Total Product Costs = Total Raw Materials Used+Variable Production Costs+Administrative Costs+Advertising Costs+Distribution Costs+Fixed Charges***

The raw materials, equipment costs, and distribution costs in the NPV equation are based off of the demand for the product. A more in-depth discussion on NPV values will be presented later in this section.

To obtain maximum NPV, the revenues must increase while the costs decrease. Every attempt was made to decrease the associated costs of the hospital unit when designing the product while increasing consumer preference. By doing so, not only will the price of the unit be better for the consumer, but also will increase demand. If the price of the unit increases, the demand will decrease.

In order to find the optimal demand and price for the hospital design, a consumer utility maximization equation must be chosen. There are several different equations in which to choose for this project. The chosen microeconomics equation (Equation 10) was already presented in the consumer utility and preference section.

$$\phi(d_1) = p_1 d_1 - \left(\frac{\alpha}{\beta}\right)^{\rho} p_2 \left[\frac{Y - p_1 d_1}{p_2}\right]^{1-\rho} d_1^{\ \rho} = 0$$

Equation 17

The above equation predicts $d_1=d_2$ when the prices are equal and when $\alpha/\beta=1$, monotone decreasing value of d_1 and p_1, and monotone decreasing value of d_1 with β (the larger β is the worse product 1 compares)[29].

The budget (Y) for the estimated 350 large hospitals in the United States is assumed to be equivalent to the large hospital "Van Buren Hospital" in San Antonio which has an estimated budget of around $200,000 per year for oxygen[1]. The average cost and competitor price (p_2) used for oxygen expenses by this hospital is $170,000 per year. The price includes all associated costs with liquid oxygen such as maintenance, delivery, oxygen etc. By using a yearly amount for a price of oxygen for a large hospital, the direct comparison of the hospital project to the main competitor could easily be made.

To maximize profit, one has the option of increasing α by increasing advertisement. However, if advertisement costs are high, it is possible to lose profit. It is important to determine the α value and its effect on NPV over a period of time. The method described will be presented at the end of this section.

The other value that can be manipulated to increase the NPV is β which is the preference of the consumer toward the competitor's product in comparison with the oxygen concentrator design. The β equation is presented again below:

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

Equation 18

Where: H_2 is the consumer preference of the competitor (liquid oxygen) and H_1 is the consumer preference of the hospital design.

For β to be at maximum preference or when H_1 is closest to 1, all of the important characteristics for consumer evaluation of oxygen supply systems must be maximized. However, as shown in the consumer utility and preference section, each characteristic has an associated cost with it. As consumer preference increases, so does the cost and the demand will decrease. Thus, the "best" product for the consumer is not necessarily going to be the best for the company. Therefore by changing values of the characteristics will allow for the maximized NPV and demand to be found for the hospital design.

Integration of Consumer Satisfaction Model

The first step in the consumer satisfaction model is to determine the optimal β value that will be used in the consumer utility maximization equation to find the price and demand that when multiplied together (revenue) minus the costs will yield the maximum NPV. The important characteristics for the evaluation of oxygen supply systems were already determined and explained in the consumer utilities and preference section. To calculate the β value, the liquid oxygen competition satisfaction value H_2 must be determined through surveys based upon the important evaluation characteristics. After issuing surveys to a limited number people in the class, the following Table 22 provides the results of the consumer satisfaction toward liquid oxygen as a means of providing oxygen in a hospital. The % preference values y_i were found from the utility equations.

Survey Results for Competition	% Preference (yi)	Weights of Characteristics (wi)	Preference/Characteristic (Hi)
Noise	0.930	0.175	0.163
Ease of Use	0.950	0.147	0.140
Appearance	0.580	0.112	0.065
Frequency of Maintenance	0.360	0.184	0.066
Reliability	0.900	0.205	0.185
Durability	0.760	0.177	0.135
		Total Preference H2=	0.753

Table 22. Total Preference of Liquid Oxygen Product

*Calculated from informal surveys. This is just an estimate and further surveys of actual hospital management is necessary to have more accurate results.

Next, the important characteristics for the hospital oxygen concentrator were manipulated in order to produce several different preference values (H_i). The following are examples of the different physical characteristics of the design with produced β values. The first example is that of maximum preference or when β is the lowest value possible, and the hospital design preference H_1 is maximized.

Best Hospital Oxygen Concentrator Design				
Characteristics	Description	% Preference (yi)	Weights (wi)	Preferences (Hi)
Noise	Quiet room (not noisy)	0.970	0.175	0.170
Ease of Use	No training (Very Easy)	1.000	0.147	0.147
Appearance	Lots of Color/Texture (Blends)	0.900	0.112	0.101
Frequency of Maintenance	once per six months/(not frequent)	0.900	0.184	0.166
Reliability	MTBF (Reliable)	0.950	0.205	0.195
Durability	Revamp Time (5 years) (Durable)	0.600	0.177	0.106
			Total Preference H1=	0.884
			β = H2/H1=	0.852

Table 23. Best hospital design with associated characteristics, % preferences, preference value H_1 and associated beta value.

As one can see from the table above, maximum preference for the oxygen concentrator product yields a preference value of .884. The corresponding β value from H_2/H_1 = .75/.85= .852. An example of a design that does not have maximum preference of H_1 is shown in Table 24.

Alternative Hospital Oxygen Concentrator Design				
Characteristics	**Description**	**% Preference (yi)**	**Weights (wi)**	**Preferences (Hi)**
Noise	Loud as bus at 10 ft (Very Noisy)	0.300	0.175	0.052
Ease of Use	Some Training (Easy)	0.700	0.147	0.103
Appearance	Limited Color/Texture (somewhat blends)	0.750	0.112	0.084
Frequency of Maintenance	three time per six months (frequent)	0.300	0.184	0.055
Reliability	MTBF small, 2 PSA systems, (reliable)	0.850	0.205	0.174
Durability	Revamp Time (3 years) (Durable)	0.500	0.177	0.089
			Total Preference H1=	**0.557**
			β = H2/H1=	**1.351**

Table 24. Concentrator design with associated characteristics, % preferences, preference value H_1 and associated beta value.

Several alternative designs were created in order for use in the consumer utility maximization function (Equation 10) and are presented in the summary Table 25 below.

Example Designs	
	Beta Values
Design1	0.882
Design2	0.92
Design3	0.95
Design4	0.97
Design5	1.05
Design6	1.12

Table 25. Examples designs with associated beta values.

Now that different beta values had been calculated, the consumer utility maximization formula was used under the assumption of perfect consumer knowledge (α=1) of the oxygen concentrator. The assumption of perfect knowledge is used solely to determine the prices, demands, and maximum NPV at different β values. Once these values are found, α will be varied with time to produce revenues, demands, NPV, and ROI over time.

After setting a price, the demand could be found by solving the consumer utility maximization equation for d_1. Thus, the specific revenues could be found for the different prices, demand sets, and beta values. An example of prices and demands are below in Table 26 for a β of .85.

Beta = .85	
Price	**Demand**
150000	291
175000	202
200000	140
225000	98
250000	69
275000	50
300000	36
325000	27
350000	20

Table 26. Prices and demands from consumer utility maximization equation when Beta=0.85 and alpha=1

Before the NPV for the oxygen concentration unit could be calculated all associated costs had to be determined.

Fixed Capital Investment

The fixed capital investment (FCI) can be described as the amount of money needed to supply the necessary plant and manufacturing facilities for business operations. The hospital design is a special case in that a plant is not necessary to build the units. The units are assumed to be built on site. The only necessary fixed capital investment will be that of office furniture and related equipment. The fixed capital investment estimation and total capital investment (TCI) is presented below in Table 27.

Capital Investment for Hospital Oxygen Concentrator Design			
		Assumptions	**Costs**
Office Furniture and Related Equipment		**Quantity**	
Desks	$250/desk (office depot) [46]	4	$1,000
Chairs	$115/chair (office depot) [46]	6	$2,760
Phones	$60/phone (multi line) [46]	6	$360
Computers	$800/computer (Dell Precision) [47]	4	$3,200
Office Supplies (stapler, rulers, paper)	$300 for all supplies [46]	N/A	$150
Printer/Copier/Fax Machine	$300 (Intellifax-400e) [46]	1	$300
House keeping supplies (Vaccum, Mop)	$200 (Dirt Devil - Bagless Upright) [48]	1	$300
Tools including nuts and bolts	$3000/tool set (northern tools) [49]	3	$9,000
Bobcat Forklift	$3000 used price [estimate]	1	$3,000
Total estimated fixed capital investment			**$20,070**
Working Capital		**15% of TCI**	**$3,542**
Total Capital Investment			**$23,612**

Table 27. FCI estimation for hospital oxygen concentrator.

*Numbers are estimated only and consider the bulk capital investment costs.

Total Equipment Costs

The cost of the equipment was determined from the design variable such as volume, flow rate, and traditional pressure swing adsorption technology. All estimates for the equipment were obtained from venders or estimates from the internet. As stated in the proposed use of technology section, two pressure swing columns, 4 three way control valves, two Palatek Compressors, control computer, and a high pressure storage tank were included in on pressure swing adsorption system. In order to increase reliability, two PSA systems will be used in the package sold to hospitals. The combined PSA systems will share the high pressure tank and silica gel column only.

Estimation of Equipment Cost of 1 Unit			
	Basis for Estimate	**Quantity**	**Equipment Costs**
Nitrogen Removal Column	Quote	4	$32,000
Drying Column	Quote	1	$200
Palatek Compressor 200UD	Quote: $9800	2	$19,600
Palatek Compresser H30D7	Quote: $5000/unit	2	$10,000
High Pressure Storage Tank	Fig.12.53 in P&T	1	$12,000
3 Way Control Valve	Quote: $700/unit	8	$5,600
Control Computer	Quote	1	$600
Total Equipment Costs			**$80,000**

Table 28. Estimation of Equipment Cost for Hospital Unit

Total Product Costs

Total product cost for the hospital oxygen concentrator can be broken down into several different categories that were individually calculated before the total product cost value could be determined. The following categories relate directly to the total product cost for the oxygen concentrator as stated before in the NPV equation.

- Total Raw Materials Cost
- Total Variable Production Costs (operating supplies, utilities, and maintenance)
- Fixed Charges (rent, royalties)
- Total Administrative Costs
- Total Distribution and Marketing Expenses (Advertising and Shipping Expenses)

Total Raw Materials Cost

Raw materials are any materials that are consumed or used in the production of the final product and are not equipment. The raw materials in the oxygen concentrator are the LiAgX zeolites, AgA zeolites, silica gel, siding material, and noise absorbing foam. The raw materials are based on demand and units sold. As the number of units that are manufactured increases, so will the cost of the raw materials. For purposes of estimation, it was initially assumed that 20 oxygen concentrators will be sold in year one of the project. The raw materials are presented in Table 29.

Raw Materials Cost			
	Basis for Estimate	**Rate or Quantity**	**$**
Silica Gel	$.22/100g quote 20 units sold in first year*	920 g	$20
LiAgX Zeolite	$.4/100g quote 20 units sold in first year*	4130 kg	$165,200
Silver Zeolite A	$.4/100g quote 20 units sold in first year*	1230 kg	$49,200
Quiet Barrier Noise Proof Foam	Quote: $361/sheet [39]	16 sheets to cover casing of unit	$115,520
Vinyl Sidiing	Quote: $1.6/sq ft [39]	1400 sq ft to cover	$44,800
		Total Raw Materials Cost	**$214,420**

Table 29. Estimated Raw Materials Cost

*all quotes from Sigma Aldrich

Table 29 shows that the zeolties are the largest expense for the hospital project. In order to cut costs, research was done to determine if the zeolites could be produced instead of purchased. To mass produce zeolites as described in, a complex system of mixing, drying, and storage in a non-moisture environment is needed [50]. The production would require a plant and would not be economical for the company producing the oxygen concentrators. New employees would have to be hired and expensive equipment purchased making this option not feasible.

Total Variable Production Costs

Any expenses that are subject to change while the business is in operation are considered to be variable production costs. In the case of the oxygen concentrator, these costs are utilities, operating supplies, and maintenance for the building. All of these will be variable depending on a given situation and use. Some months operating supplies will be needed more often than others as an example. The variable costs were estimated to be an average over the course of a year and are presented in Table 30.

Variable Production Costs			
Utilities	**Basis for Estimate**	**Rate or Quantity**	
Electricity	150 bulbs, 23W, full year operation	$.13/kWh [45]	$3,884
	Office heating/cooling/electronics 900W/hr		$1,157
Water	Assume 100 gal/day	$1.98/1000 gal (Georgia cost)	$723
Operating Supplies (variable costs)			
Pencils	12 BIC Mechanical Pencils $5.50 [46]	Use 288 per year	$132
Staples	Swingline $1.50 per box [46]	Use 3 boxes per year	$5
Ink for Printer	$60 per black/color ink combo package [46]	Use 6 per year	$360
Pens	12 Bic Pens $5.50 [46]	Use 96 per year	$44
Paper	$33 per case of multipurpose paper [46]	Use 2 per year	$66
Maintenance and repairs on building		Estimate of .05 of FCI	$1,150
		Total variable production costs	**$7,520**

Table 30. Estimated Variable Production Costs for Hospital Unit

It should be noted that royalties were not included in the variable production costs. Pressure swing adsorption with two columns was patented in 1958 by Skarstrom that purged at low pressure [51]. This is the type of PSA that is used in the hospital unit. Before 1995, patents typically lasted for 10 years after introduction. Thus, the patent for this technology has expired and no royalties will be paid. Also, the zeolites are being purchased, so no royalties would be required.

Fixed Charges

The only assumed fixed charges the rent for an operation warehouse. The warehouse was chosen to be in Atlanta, Georgia. It is 3,200 square feet with 20% office and 80% warehouse space[52]. The reason the warehouse was chosen was because it is small and has office space, security, and a great location. The warehouse is located within fast and easy access to I-285 and I-75 easy shipping truck access and supplies to be brought to the warehouse [52]. It is also located within a few miles of Atlanta Hartsfield International Airport. If any supplies were shipped by air, they could possibly be delivered more quickly. The quoted rent is $6.9/sq ft/year which leaves a total rent per year of $22,080 [52].

Figure 50. Warehouse Facility[52]

Total Administrative Costs

The administrative costs for this project include the salaries of the employees that are needed for the business to be operational. The following Table 31 contains all employees for the hospital oxygen concentration business along with estimated yearly salaries in order to calculate the total administrative costs.

Administrative Costs			
Employees	**# employees**		
Engineers	1	Assume $60,000 salary/year	$60,000
Accountant	1	Assume $30000 salary/year	$30,000
Skilled Labor	2	Assume $30000 salary/year	$60,000
Traveling Salesman	1	Assume $35000 salary/year	$35,000
Secretary	1	Assume $25000 salary/year	$25,000
Traveling Maintenance	1	Assume $35000 salary/year	$35,000
		Total Administrative Costs	**$245,000**

Table 31. Administrative Costs

The head manager role for the company is expected to be an engineer. The engineer is expected not only to oversee all operations but to help in building the units with the skilled labor employees. The skilled labor employees will travel to each hospital site to install the unit completely. An accountant is necessary to keep track of all incoming/outgoing cash flow, keep a budget, and do the company taxes. The secretary will serve to answer phones, keep track of all shipments, and all scheduling.

The last two employees will spend most of their time traveling. The salesman will constantly be on the road and talking to hospital management in order to further the consumer knowledge and sell the oxygen concentrator product. The maintenance person will be dispatched as maintenance is needed on any sold equipment. He is also expected to help with assembling units while not on call.

Distribution and Marketing Expenses

In order for all of the large hospitals to have adequate knowledge of the product that has been created is to advertise. By increasing the knowledge α, is it assumed that more units will be sold. There is a limited consumer base that will need information on the oxygen concentrator in order to make the choice of whether or not to purchase the product. The first line of advertising will be in the form of brochures and DVDs intended to inform hospital management of how the system works as well as the benefits of a purchase. The associated costs will be for producing the brochures and DVDs and shipping them to the various hospitals.

To reach even more consumers on a personal level, the traveling salesman will make trips to different hospitals around the nation. The costs associated with the traveling salesman are airfare, hotel, food, gas, and car rentals. It was estimated that the salesman will visit 70% of large hospitals within the first year at an average of 3 days per trip with 35 trips per year. It is also assumed that in major metropolitan areas the salesman will be able to visit more than one hospital in those areas. The associated costs for the advertising just described are found in Table 32 and are based on a rate of high advertising.

As units are sold, it will be necessary to ship them to their destination. It is assumed that each unit will be assembled at the warehouse other than the casing and sent to the consumer. The shipping costs per year are associated with the demand for the amount of units and will vary year to year. The assumption that 20 units will be sold is used again in estimating the cost for the first year of operation. The total cost for the first year due to shipping is found in Table 32.

Distribution and marketing expenses			
Distribution and marketing expenses			
	Basis for Estimate	**Rate or Quantity**	
Sales personnel expenses	Assume visits 70% large hospitals = 175, only 3 day/ trip estimate, 35 trips/year		
	Airfare	$400/trip	$14,000
	Hotel	$100/trip per day	$10,500
	Food	$50/trip per day	$5,250
	Rental Car / Gas	$80 per day for rent and gas	$8,400
	Total Sales Expenses per Year		**$38,150**
Advertising	Assume high advertising from calculations	Estimated $100,000	
	Brochures	$1/brochure, send 50 to each hospital/year	$12,500
	DVD	$8/DVD, send 10 to each hospital/year	$20,000
	Mailing expenses	Assume 10lb per box at $20/box	$10,000
	Total Adversing Expenses (high advertisement rate)		**$42,500**
Shipping	20 units shipped in first year from demand es	$.3/kg, unit weight ˜ 16000kg	$192,000
Total Distribution and marketing expenses			**$272,650**

Table 32. Total Estimated Distribution and Marketing Expenses for Year 1

Now that all costs associated with the total product cost have been calculated, they can be combined to form the total cost. The value for the estimated total cost for the first year of operation is shown in Table 33.

Total Product Cost for First-Year Product: Pressure Swing Adsorption for Large Hospitals			
Operating time day/year	250		
Estimated units fabricated/year	20		
	Basis for Estimate	**Rate or Quantity**	$
Silica Gel	$.22/100g quote 20 units sold in first year	1840 g	$81
LiAgX Zeolite	$.4/100g quote 20 units sold in first year	8260 kg	$660,800
Silver Zeolite A	$.4/100g quote 20 units sold in first year	2460 kg	$196,800
Quiet Barrier Noise Proof Foam	Quote: $361/sheet	16 sheets to cover casing of unit	$115,520
Vinyl Sidiing	Quote: $1.6/sq ft	1400 sq ft to cover	$44,800
		Total Raw Materials Cost	$1,018,001
Variable Production Costs			
Utilities			
Electricity	150 bulbs, 23W, full year operation	$.13/kWh	$3,884
	Office heating/cooling/electronics 900W/hr		$1,157
Water	Assume 100 gal/day	$1.98/1000 gal (Georgia cost)	$723
Operating Supplies (variable costs)			
Pencils	12 BIC Mechanical Pencils $5.50	Use 288 per year	$132
Staples	Swingline $1.50 per box	Use 3 boxes per year	$5
Ink for Printer	$60 per black/color ink combo package	Use 6 per year	$360
Pens	12 Bic Pens $5.50	Use 96 per year	$44
Paper	$33 per case of multipurpose paper	Use 2 per year	$66
Maintenance	$5000 per maintenance visit	Estimate 1/10 break down in year 1	$10,000
		Total variable production costs	**$10,607**
Fixed Charges			
Warehouse	**$6.9/sq ft/year quote**	**3200 sq ft, Atlanta, Georgia (20% office)**	$22,080
		Total Fixed Charges	$22,080
Administrative Costs			
Employees	**# employees**		
Engineers	1	Assume $60,000 salary/year	$60,000
Accountant	1	Assume $30000 salary/year	$30,000
Skilled Labor	2	Assume $30000 salary/year	$60,000
Traveling Salesman	1	Assume $35000 salary/year	$35,000
Secretary	1	Assume $25000 salary/year	$25,000
Traveling Maintenance	1	Assume $35000 salary/year	$35,000
		Total Administrative Costs	**$245,000**
Distribution and marketing expenses			
Sales personnel expenses	Assume visits 70% large hospitals = 175, only 3 day/ trip estimate, 35 trips/year		
	Airfare	$400/trip	$14,000
	Hotel	$100/trip per day	$10,500
	Food	$50/trip per day	$5,250
	Rental Car / Gas	$80 per day for rent and gas	$8,400
		Total Sales Expenses per Year	$38,150
Advertising	Assume high advertising from calculations	Estimated $100,000	
	Brochures	$1/brochure, send 50 to each hospital/year	$12,500
	DVD	$8/DVD, send 10 to each hospital/year	$20,000
	Mailing expenses	Assume 10lb per box at $20/box	$10,000
		Total Adversing Expenses (high advertisement rate)	$42,500
Shipping	20 units shipped in first year from demand es	$.3/kg, unit weight ~ 16000kg	$192,000
		Total Distribution and marketing expenses	$272,650
	Total Product Cost		**$1,568,337**

Table 33. Estimated Total Product Costs for Year 1

Optimal Beta Value and NPV

All information necessary for calculation of the NPV has been determined in the previous section. As presented earlier, revenues used in conjunction with the costs associated with the project, the NPV for different preference values (β) can be calculated and plotted. By plotting this data, the optimal preference value can be determined for the project. The following figures (Figures 51, 52) are plots of NPV versus Unit Price with varying β values and associated Demand versus Unit Price with varying β values.

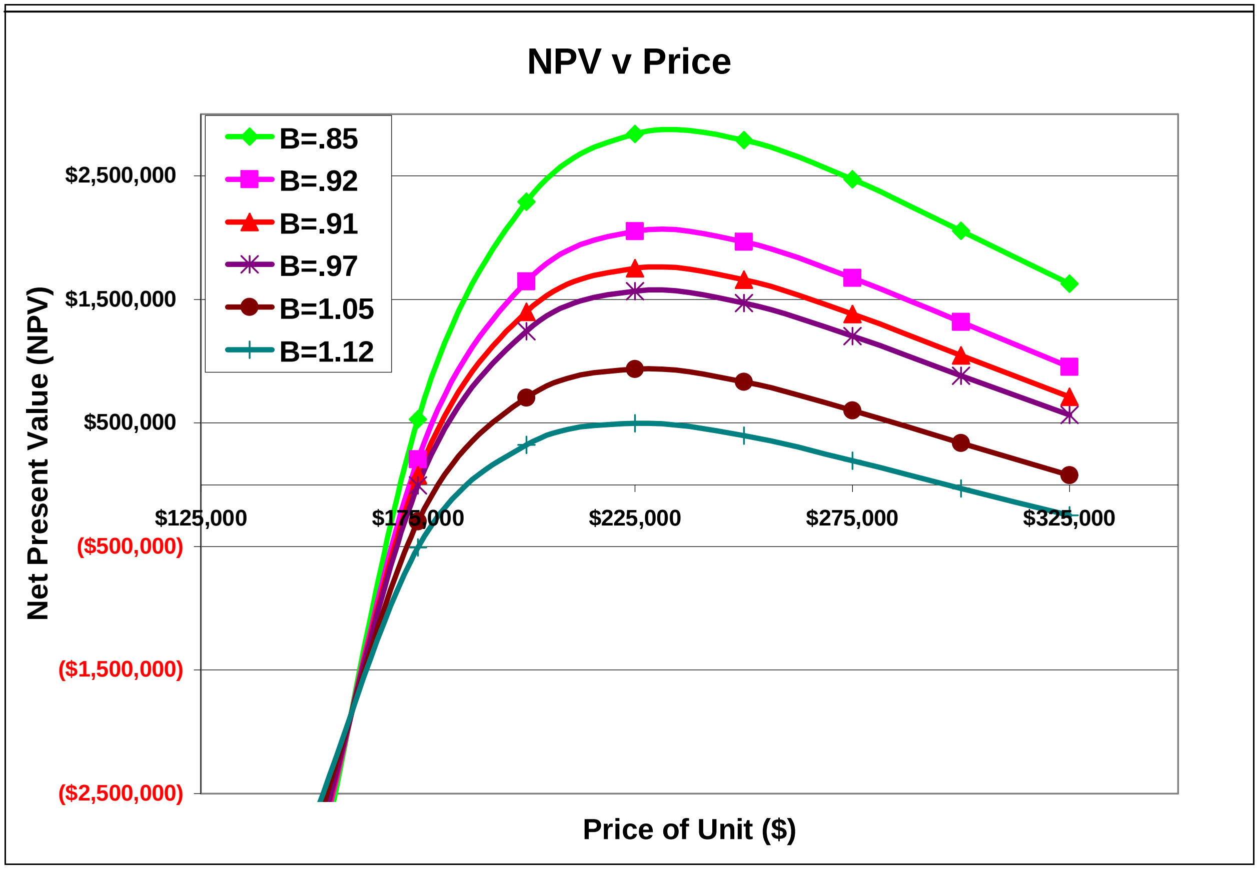

Figure 51. NPV versus Price with varying beta values

*The optimal beta value for maximum NPV for the hospital design can be determined from this graph. The optimal price for the unit can also be seen at the maximum of the curvature.

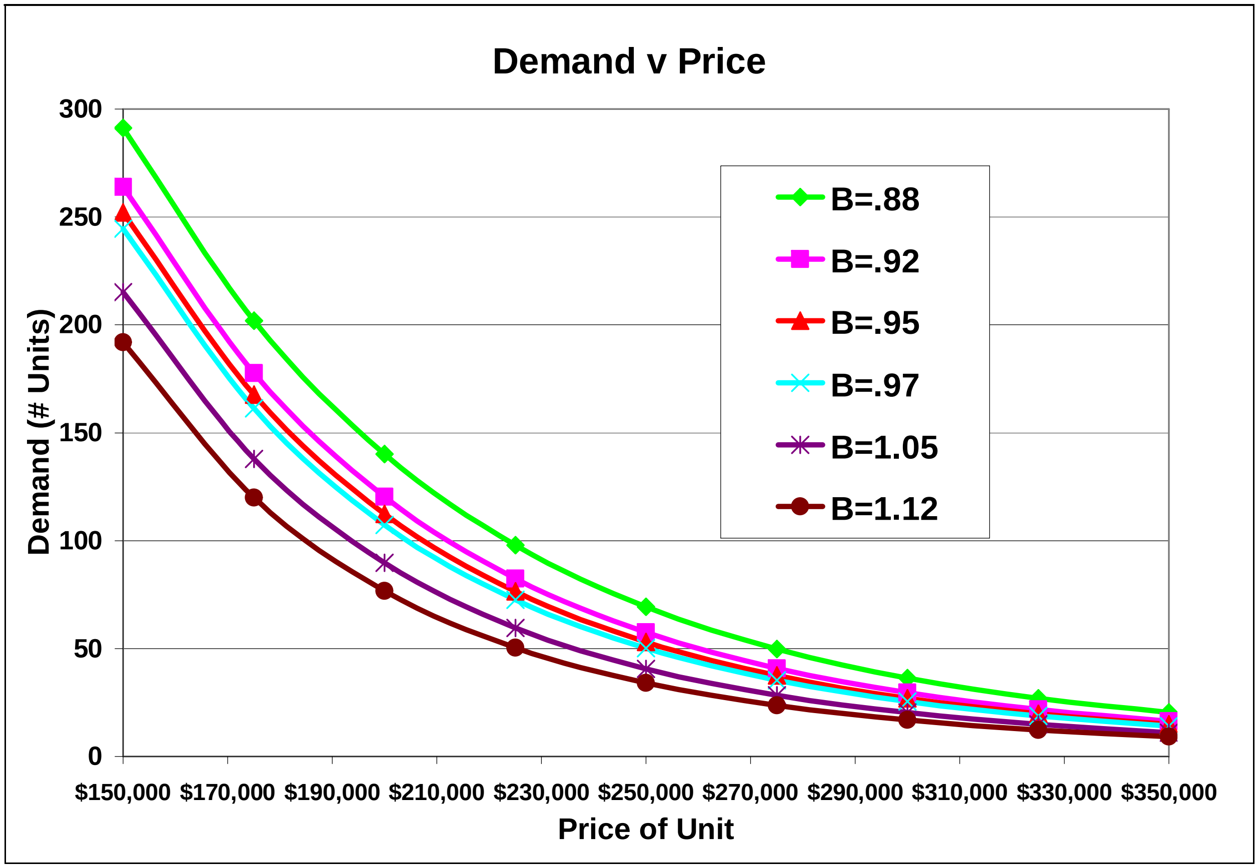

Figure 52. Demand versus Price with varying Beta values

The information to be taken from Figure 51 and Figure 52 is the max estimated NPV, unit price, demand, and optimal β value. The optimal preference value β is equal to .85 at the price of $250,000 per unit yielding a maximum NPV of approximately $2.8 million for 5 years of operation under the assumption that the consumer has perfect knowledge of the product. The demand for the unit at the price of $250,000 is approximately 70 units.

An important fact to note about the information just presented specifically deals with the β=.85. It can be seen that this is actually the "best" product for the consumer and the company. Even though the price of the total product went up due to sound absorbing foam, siding material, and two pressure swing adsorption systems, the overall consumer preference overcame the effect of the added cost and demand increased. Also, by having a system that needs less maintenance, the cost to the producer to maintain those units becomes less as well.

Larger values of β by definition will have less consumer preference. Figure 51 shows that the higher the β value will cause the overall NPV to decrease. As stated previously, the consumer budget is approximately $200,000 per year for 350 large hospitals in the United States.

The hospital unit will be priced only $50,000 over the 1 year budget of a hospital. A more likely scenario for a hospital is to have equal payments of $125,000 for two years. The payments are under the budget of large hospitals for oxygen per year and their budget for both years. After the point at which the unit is paid in full, the average large hospital should be able to save several thousand dollars that can be used elsewhere in the hospital.

Return on Investment

The return on investment (ROI) is valuable for any business. Even though there is a possibility of a positive NPV, if the ROI is not substantial then the project may not be worth pursuing. The return on investment equation is below (Equation 19).

$$ROI = \frac{\text{Pr}\,ofit}{Total\,Capital\,Investment}$$

Equation 19

Profit is the net earning for the year after income taxes have been paid. The total capital investment was calculated and shown in Table 31 and remains a fixed value at approximately $23,612. The returns on investment % values for year 1 of the hospital oxygen concentration product were calculated for each consumer preference β value at maximum consumer awareness and were plotted against price in Figure 53.

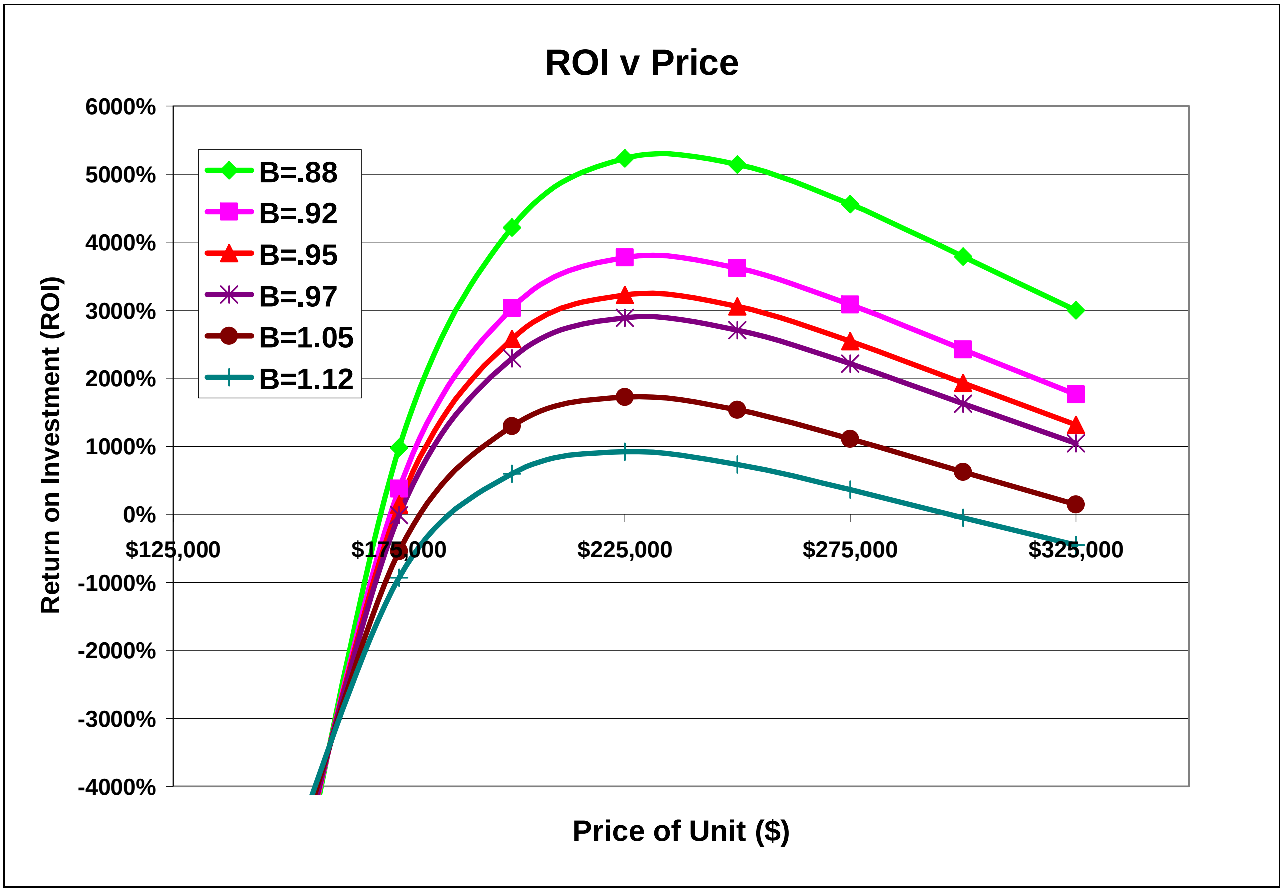

Figure 53. Return on Investment % versus Unit Price for varying consumer preference values.

As can be seen in the above figure, the β value yields the highest return on investment % at approximately 5200% at maximum perfect conditions for year 1 of production. The reason for this large number is the large calculated NPV at minimum β, full consumer knowledge, and the low TCI for the overall project.

Varying α with Time

The object of this section is to show the knowledge of the hospital product (α) over a period of time. It is also used to further estimate the demand versus time for the oxygen concentrator now that the best β and price were found from the previous section. When finding the optimal β value, it was assumed the consumer market was completely knowledgeable of the product. Now that the β value has been determined, α was varied to obtain the entire scenario of the consumer utility maximization equation. Since there is only an estimated 350 large hospitals capable of fully utilizing the product at hand, it is assumed that minimal advertising costs will be associated with the hospital unit. Table 34 shows the estimated costs associated with high, medium, and low advertising.

Advertising Costs/Year	
Low	$15,000
Medium	$30,000
High	$42,500

Table 34. Estimated advertising costs per year for the hospital design.

Depending on the level of advertising will determine how quickly the consumer base will learn about the hospital product. Due to the limited market, it is assumed that complete consumer knowledge will be achieved with high advertising within two years. Of course there is a higher associated cost with high advertising. The knowledge gain versus time is shown below in Figure 54.

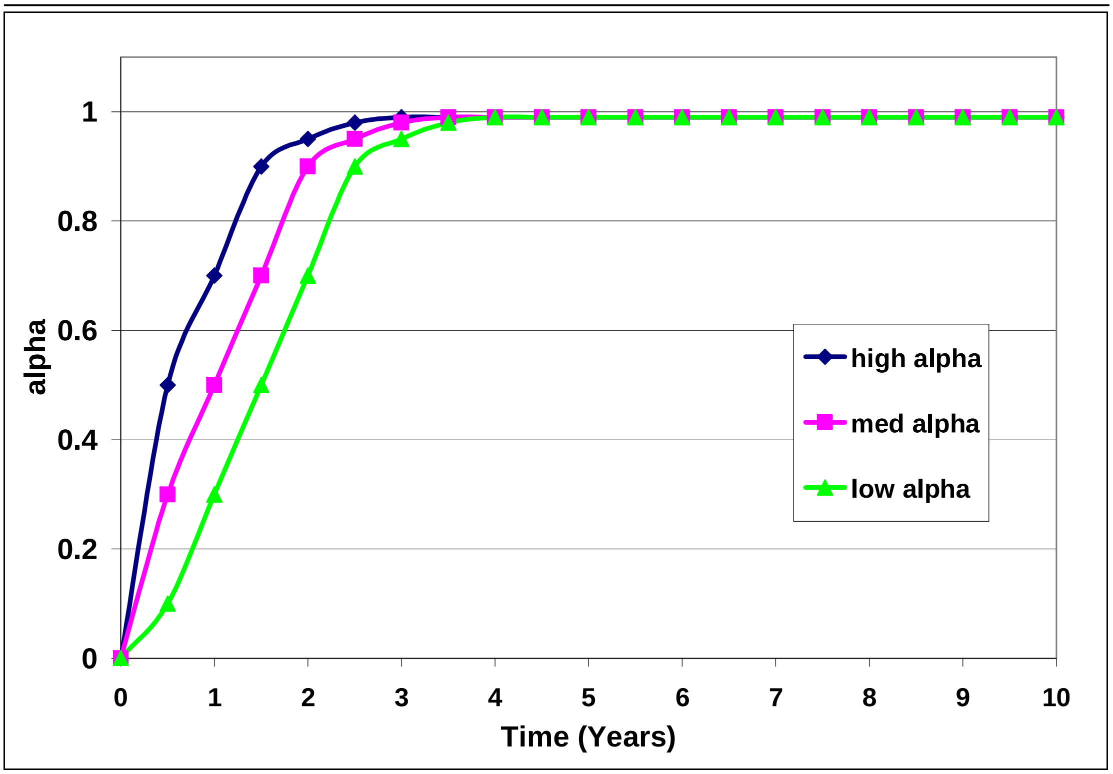

Figure 54. alpha versus time with different levels of advertising.

It was decided that high advertising would be best for the project in order for all the large hospitals to have adequate knowledge of the product as soon as possible. With high advertising, estimated market saturation is around 2 years while medium and low advertising take 3 to 4 years for market saturation, respectively. It is also a good idea for hospitals to have knowledge about the product in case the design is quickly duplicated by competition.

With the addition of variable α or consumer knowledge, the revenue for a period of time can be approximated. Revenue can be defined as amount of money received over a period of time without the inclusion of associated costs with the business operation. The following figure (Figure 55) is the revenue versus time for variable alpha over a period of 10 years.

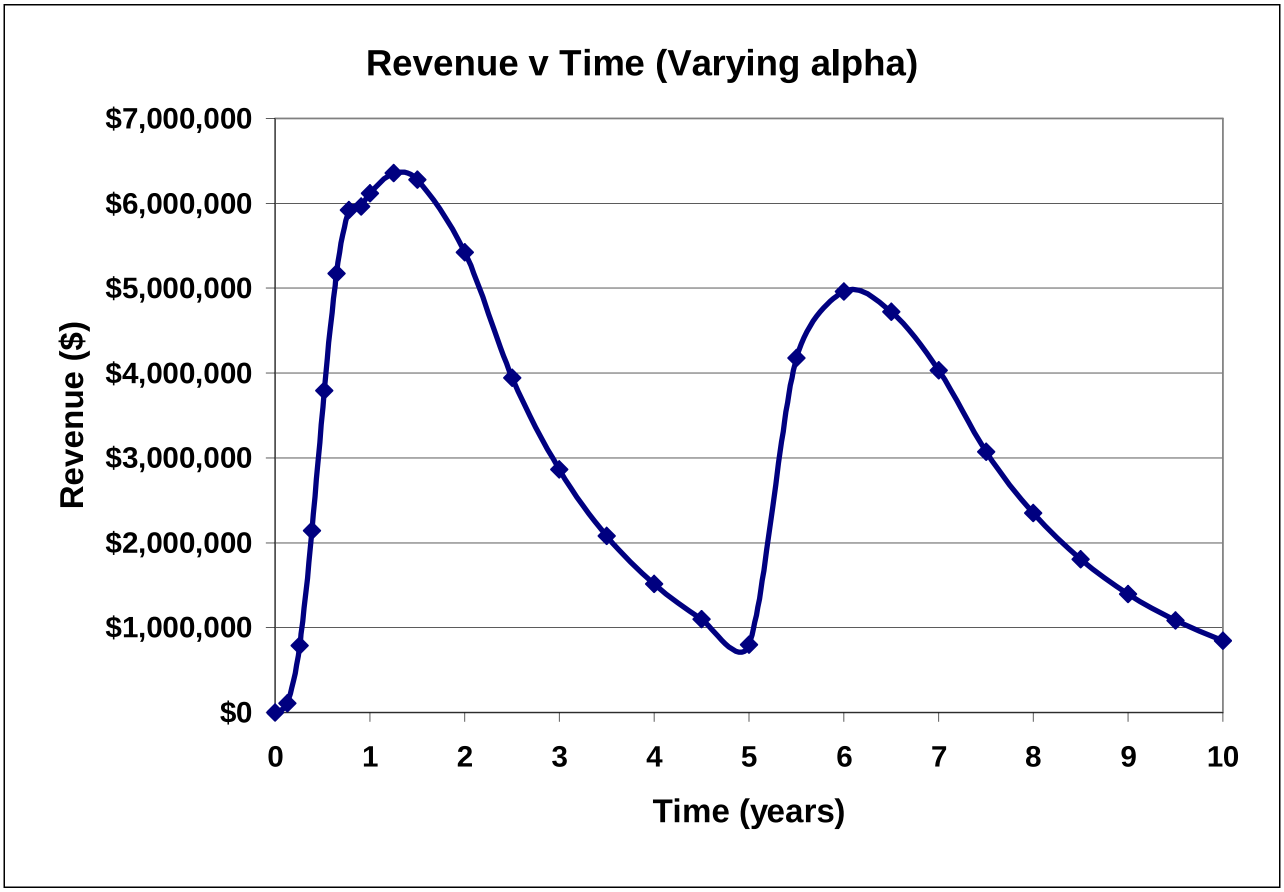

Figure 55. Revenue versus Time with high advertising and variable alpha.

As can be seen from Figure 55, after the hospitals gain perfect knowledge of the product, the revenue begins to decline. The reason for this trend is the available consumers of the hospital design. A maximum 350 hospitals could potentially purchase the item for their hospital. The available consumer base decreases as consumers purchase the oxygen concentrator. For example, if after 1 month of business three models were sold, the consumer base is now a maximum of 247. The decline in revenue comes from the decreased consumer base over time. However, from the consumer preference section it can be seen that an oxygen concentrator will need to be completely revamped after 5 years.

The assumption after 5 years is that the consumers will begin to purchase another concentrator to replace the primary PSA system in the two system set. Only the primary unit that has been constantly running over the 5 year period will be replaced. Thus, the reason for the jump in revenue at year 5 is associated with the previous consumers purchasing again.

The following figure (Figure 56) is demand versus time with varying alpha.

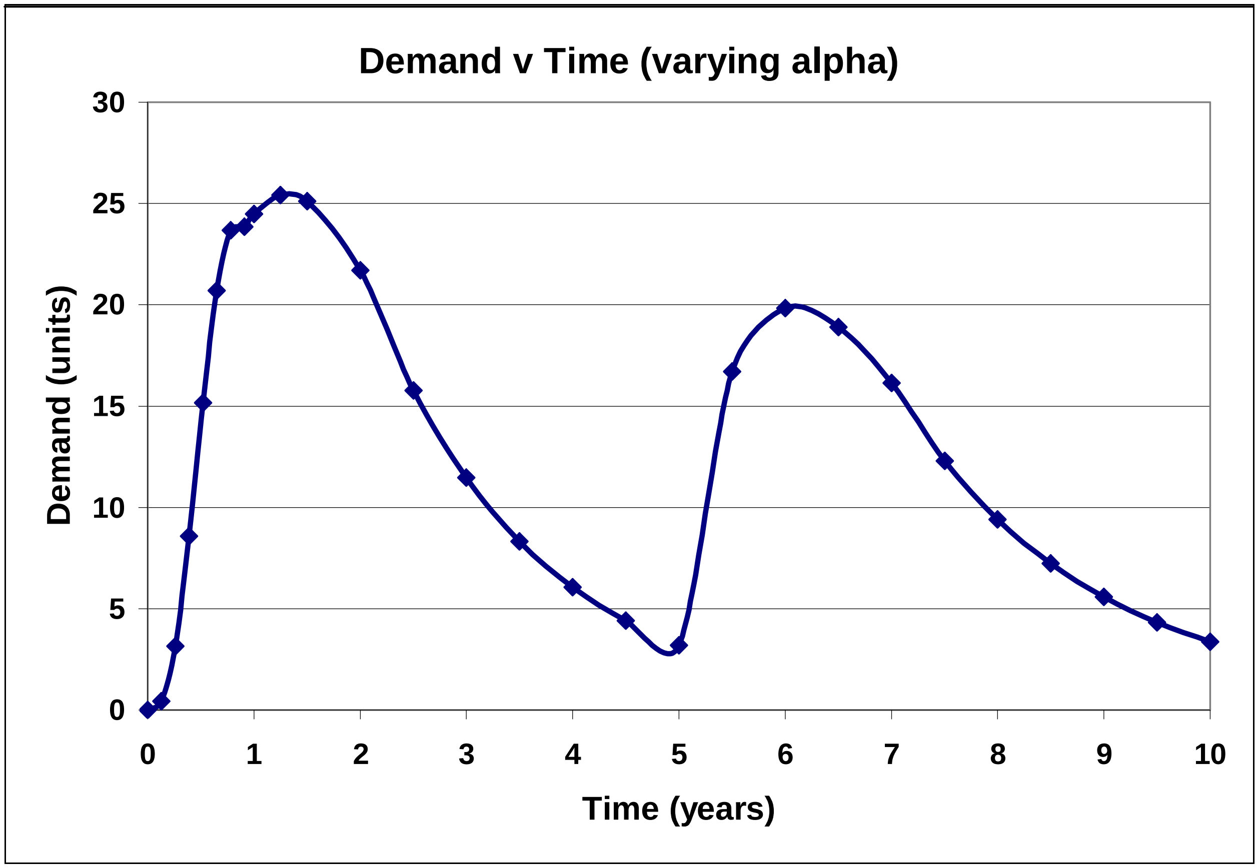

Figure 56. Demand versus Time with variable alpha.

As one can see from Figure 56, it follows the same general trend as Figure 55. The maximum demand for the product over a time is 26 units. As the 5 year limit is approached, it can be seen that the demand is only a few units per year but rises again from repurchases.

Previously in this section when finding the optimal β and price, the NPV was found to be \$2.8 million over the course of a 5 year period. However, at that time it was not possible to predict the NPV and ROI values over a span of time. The time chosen was two full buying periods or 10 years. A buying period is a period was chosen to be where most of the consumer base of 350 hospitals buys a unit. The cycle begins again when new units are bought at 5 years. After finding revenue over the 10 year period, NPV for each year could be found by subtracting all costs from the revenue obtained in that given year. The calculations were preformed and

Figure 57 contains the results. NPV is not traditionally shown in this manner, but is useful to understand the increase in overall value for each successive year.

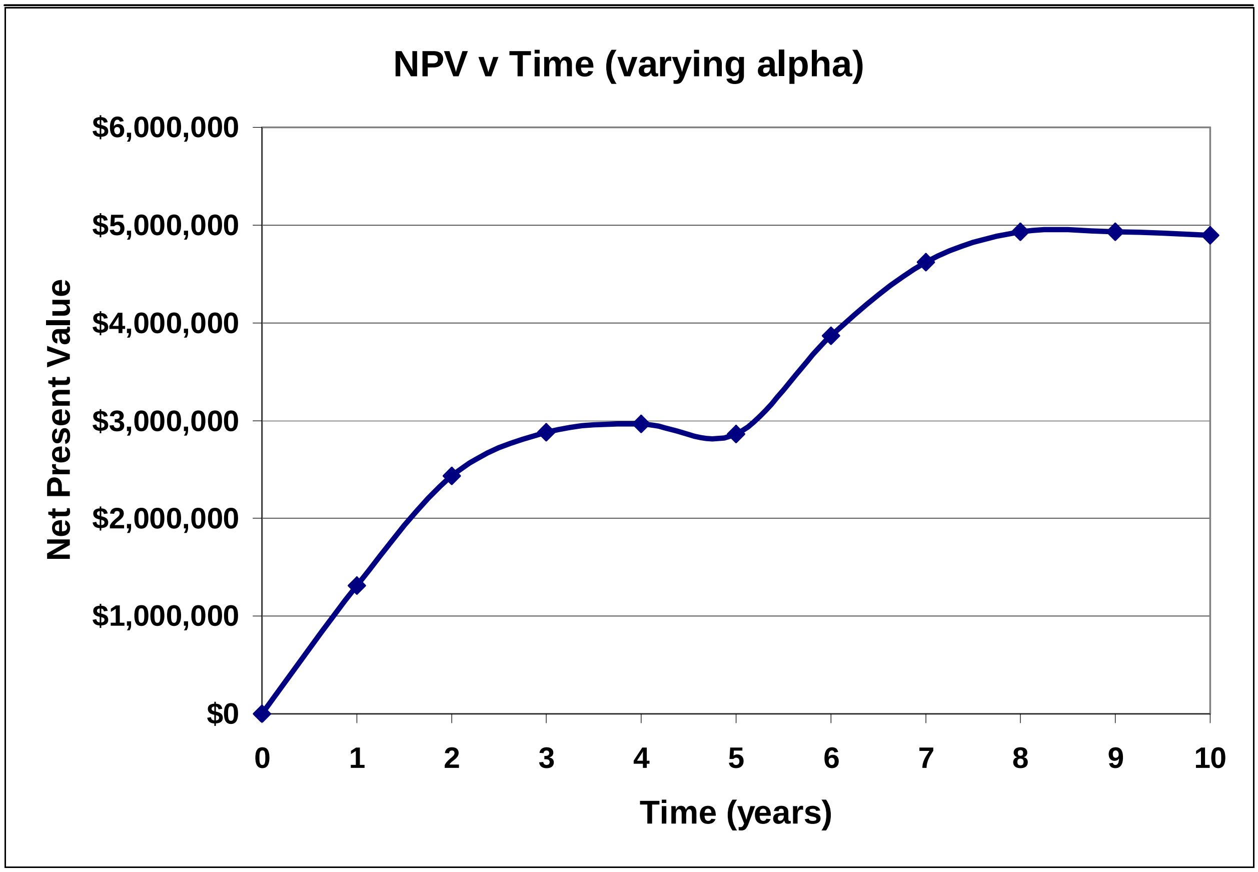

Figure 57. Estimated NPV versus Time in years over 10 years

The trend of the graph is as expected from previous Figures and calculations. The cumulative NPV continues to rise until the costs exceed the revenues around year 5. The slight decline from the consumer base being depleted is followed by the gain from the repurchasing period until the decline at year 10. The NPV is around $2.8 million at the 5 year mark as predicted from the optimal β and price calculations.

The ROI versus time plot in Figure 58 follows the same general trend and generally increases over the course of the 10 year period.

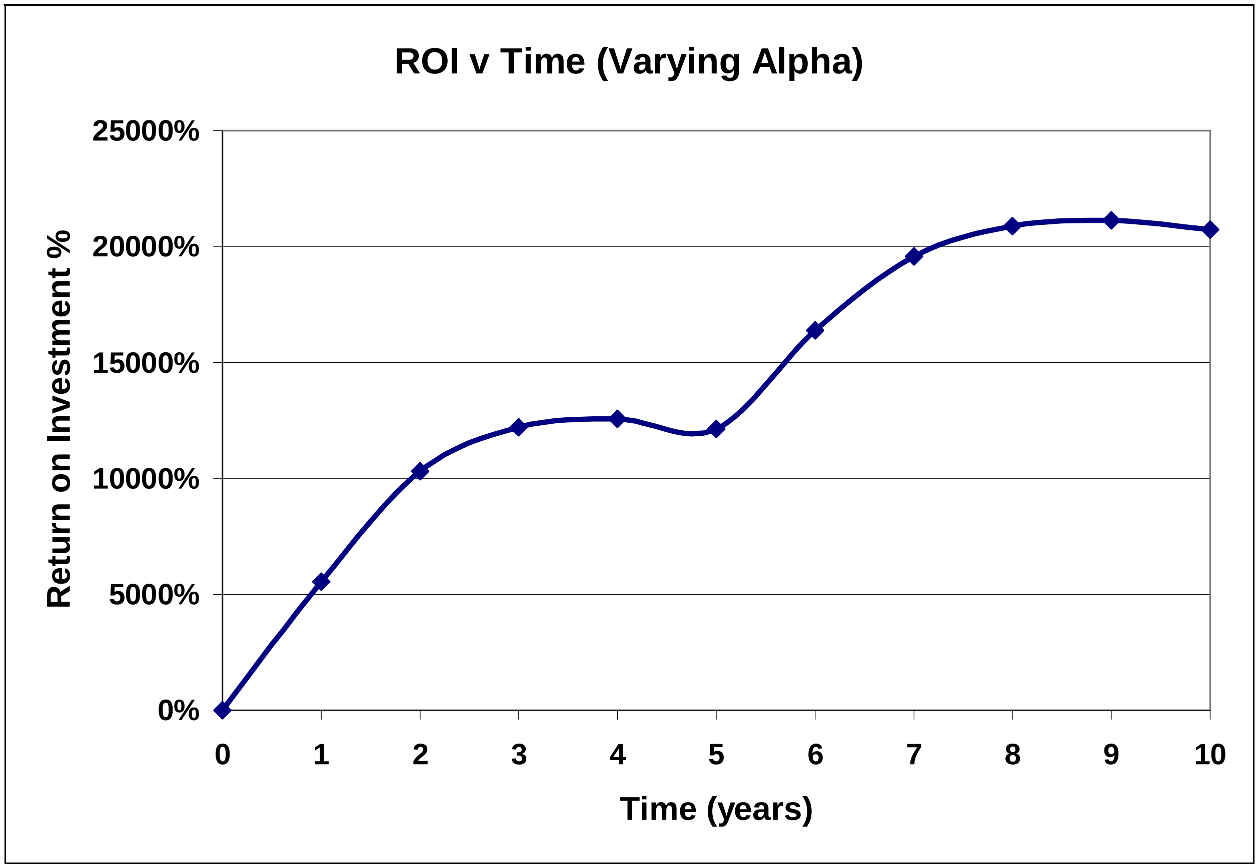

Figure 58. ROI versus time for hospital oxygen concentrator

The ROI at the end of the first year of operation for the hospital oxygen concentrator product is predicted to be around 5200%. Again the reason for the high ROI value is due to the large estimated profit, low capital costs, and initial perfect conditions with no competition for this product. The expected 5 year ROI mark is consistent with that found when calculating the optimal β and price as well.

In conclusion of this section, it has been estimated that the optimal $\beta = .85$ at a price of $250,000 per unit. The NPV has been calculated to be around $2.8 million over a 5 year span with a demand of 70 units. The first year NPV was found to be about $1.3 million with an ROI of 5200%. This product has been shown to be profitable when using the consumer utility maximization Equation 10, but there is still a possibility of losing money if the demand is less than estimated. The following risk section takes a brief look into different possibilities to determine at what point the product will not be profitable.

Preliminary Risk Estimates for the Hospital Oxygen Concentrator

The business model for the hospital oxygen concentration product has shown the product to be profitable with a high return on investment. It may be said that the high return on investment is "too good to be true" at 5200% for the first year and 12000% over the course of 5 years. There are several reasons for the high values for both the ROI and NPV.

The values presented in the business model section were calculated under perfect conditions. The perfect conditions are as follows:

- Consumer has no delay in purchasing, but purchases on the spot.
- Liquid oxygen competition does not lower prices to compete with the oxygen concentration
- No copy cats enter the market with a similar product
- Consumer utility maximization equation does not have error

It can be safely assumed that there is a probability of risk associated with the values presented under the perfect conditions. There is a great possibility that the values could be less than under the perfect conditions. To further evaluate the profitability of the hospital oxygen concentrator product, the following plots with different percentages of the demand associated with the perfect conditions are shown in Figures 59-62.

- Revenue versus Time
- Demand versus Time
- NPV versus Time
- ROI% versus Time

The following graphs show that as long as the demand for the hospital unit is above 25% of that of the perfect conditions than the product will continue to be profitable. There is still a chance that the actual demand will be lower than 25% but the greater probability lies in the range of 25% and above.

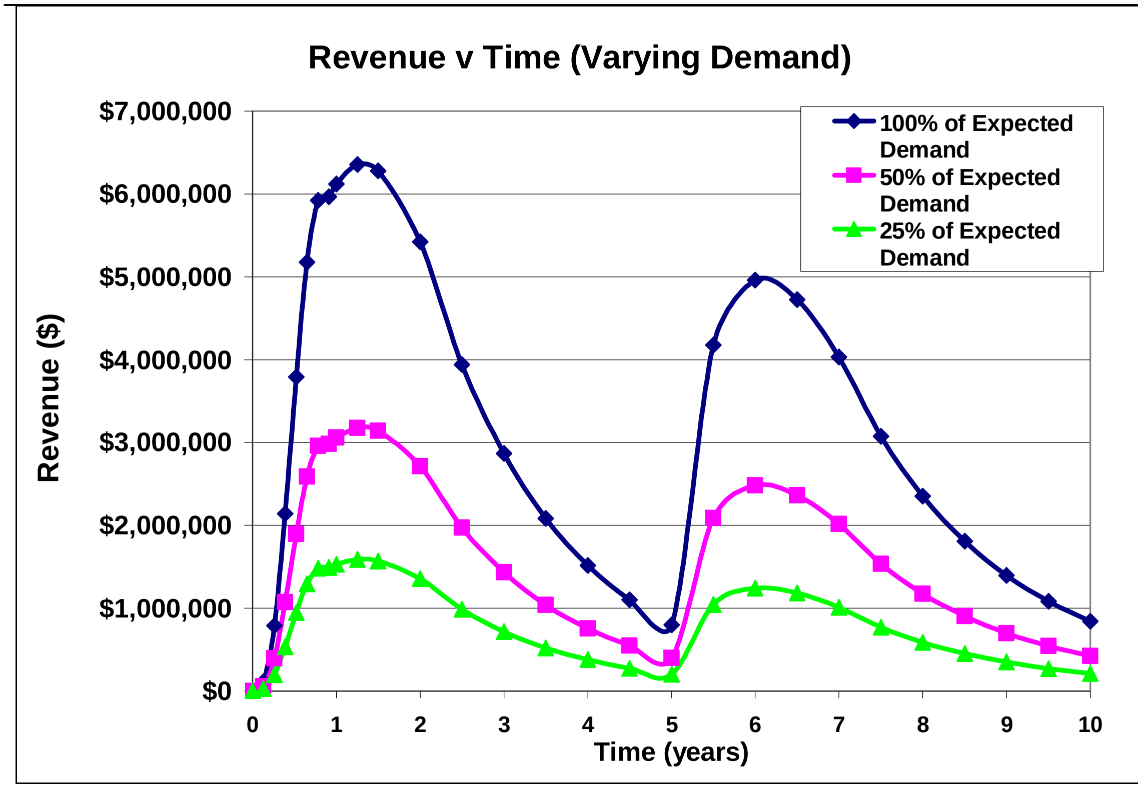

Figure 59. Revenue versus Time with varying percentages of demand of perfect conditions

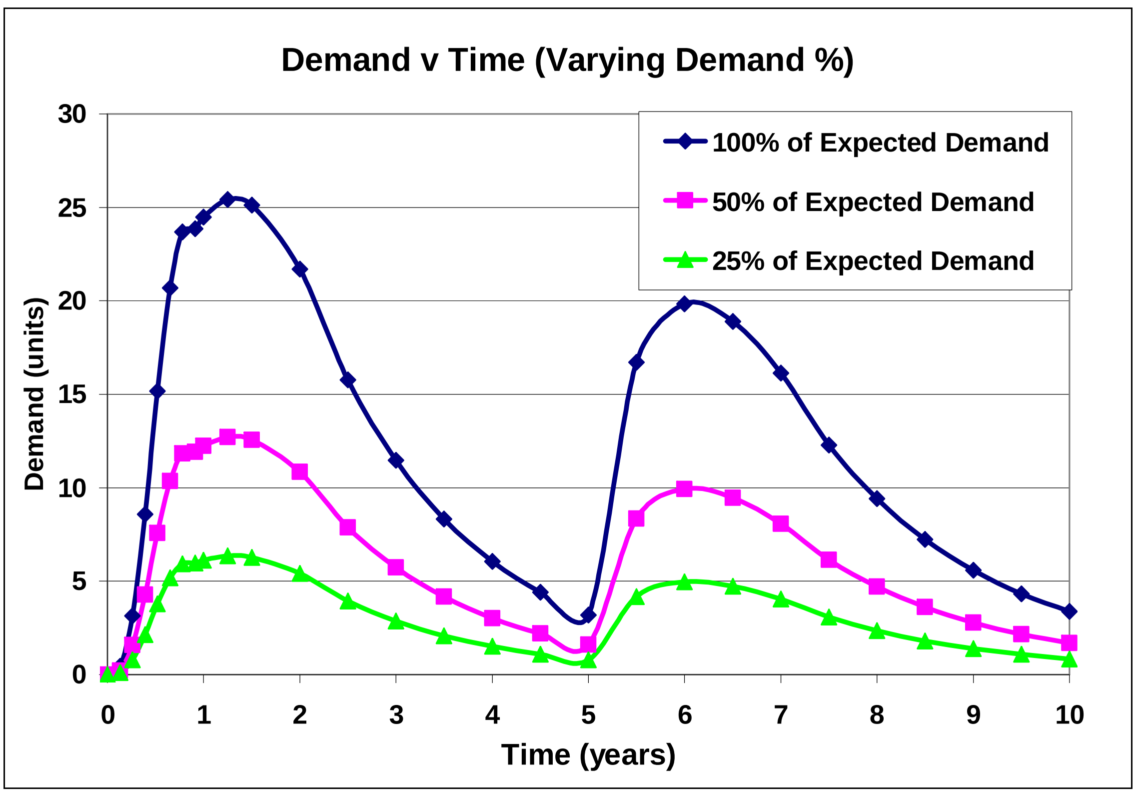

Figure 60. Demand versus Time with varying percentages of demand of perfect conditions

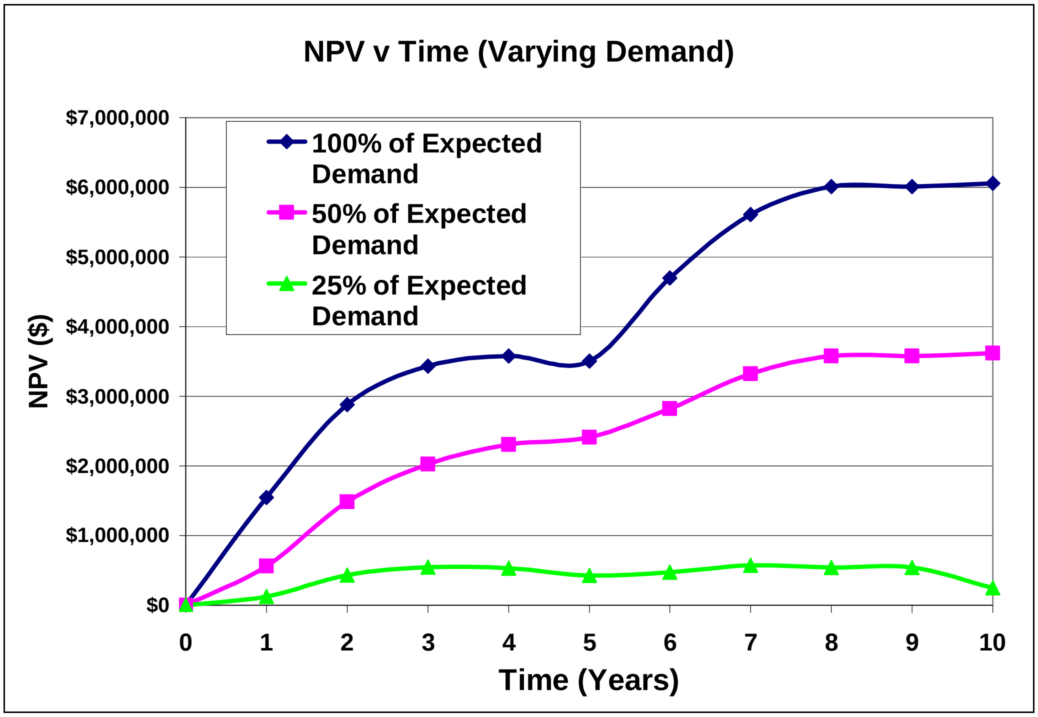

Figure 61. NPV versus Time with varying percentages of demand of perfect conditions

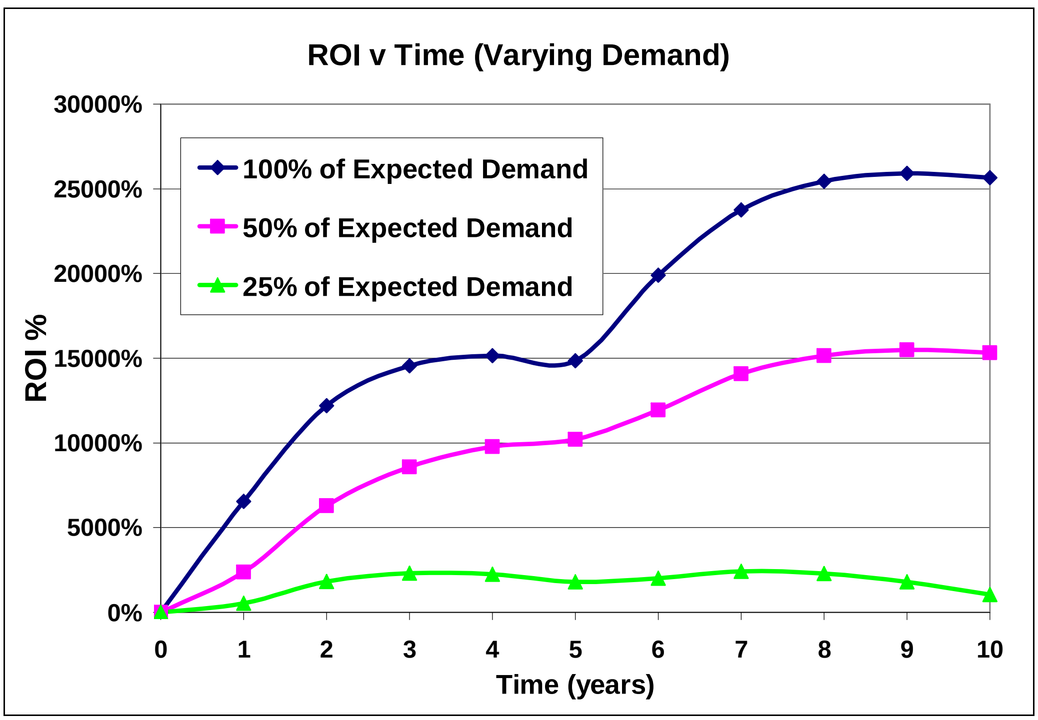

Figure 62. ROI % versus Time with varying percentages of demand of perfect conditions

Overall, it has been shown that there is risk associated with the production of the hospital oxygen concentration design. However, as long as it is 25% above that of the demand of the perfect conditions, it will be profitable. Figure 62 also shows that despite the reduction in demand the ROI% for the first year still remains relatively high. More in depth analysis of risk and consumer/competitor reaction estimations need to be done for the introduction of the oxygen concentrator to the market. A strategic plan for action to combat the competitors would also further develop the risk and profitability analysis.

Brief Financial Analysis for Hospitals Purchasing Concentrators

The hospital oxygen concentrator will not only give a company a large return on investment, but it will save hospitals money as well. This makes the product very beneficial to hospitals looking to expand or cut corners in their budget. Table 35 is a brief look at the saving for a hospital over the first 5 years after purchasing the oxygen concentrator.

Preliminary Financial Analysis		
	Concentrator	Liquid Oxygen
Total Cost per 5 Year	$500,000	$850,000
Total Savings for 5 Years	$350,000	
Average Savings per Year	$70,000	

Table 35. Preliminary Financial Analysis for hospitals purchasing concentrator

From Table 35, the total savings for a hospital over 5 years is $350,000 with an average savings of $70,000 per year. The savings will increase in the five years following, because hospitals will only be purchasing one pressure swing adsorption system to replace their primary system. After initial analysis, it can be assumed that this would be a plausible option for hospitals when looking for a new oxygen supply system.

Conclusions

It has been shown that a pressure swing adsorption system with silver zeolites will produce 99% oxygen. Using this new technology, a hospital and portable oxygen concentrator designs were developed. Currently no oxygen concentrator, portable or large, is able to produce 99% oxygen. The technology of pressure swing adsorption utilizing two types of silver zeolites presented here might possibly cause a revolution within the oxygen industry.

The consumer utilities for the important characteristics such as appearance, noise, ease of use, reliability, durability, and frequency of maintenance were all determined in order to manipulate the hospital oxygen concentrator to attract more consumers. The final design had two pressure swing adsorptions system for safety, noise absorbent foam, and vinyl siding. Using these utility functions and the consumer utility maximization equation, the optimal β, demand, and price for the unit was found to be .85, 21 units, and $250,000, respectively. The ROI for year 1 was determined to be 5200% with an NPV of $2,800,000 over 5 years of operation and non risky conditions. Using a brief risk analysis, the project is estimated to be profitable as long as it is above 25% of the predicted demand from the consumer utility maximization.

Overall, it is now possible to deliver 99% oxygen to patients in a hospital, and those who want to enjoy a life without the restriction of limited oxygen supply in bottles of oxygen. Both models would be highly competitive in each respective market and would save consumers from the large expensive and heavy equipment of liquid oxygen supply. This is technology that will truly change the lives of millions of patients and those needing oxygen around the world for years to come.

Future Work/Recommendations

A hospital oxygen concentrator using pressure swing adsorption and silver zeolites could potentially rid of liquid oxygen expenses for hospitals entirely. The presented design may appear to be complex, but it is rather simple in operation. However, at the pace of technology and the application of optimization for the product could cause the venture to rapidly change design but not business goal. It would be important to keep up to date on available air separation materials and devices so that the producer may stay ahead of the competition.

Further evaluation, concentration, and study should be put toward cost analysis and the business model as a whole. Finding less expensive but superior parts for the apparatus would allow for drastic changes in the equipment and manufacturing costs. By doing so, the product price could be reduced allowing it to be more favorable in the consumer eye in comparison with traditional liquid oxygen systems.

The venture here is only for large hospitals. The same technology could be scaled down for middle sized hospitals as well. Middle sized hospitals do use large amounts of oxygen and comprise of the majority of the hospitals in the United States. A study could be done on the profitability of such a project just the same as has been presented for large hospitals in the paper. This project presents a difficult task of estimating how consumers will react to change and innovation in a field that has long been untouched.

Lastly, the results for the portable oxygen concentrator unit are exciting. Extensive design estimates, consumer utility, and business analysis should be performed for the concentrator. In the end, the possibilities for both the portable and hospital oxygen concentrator not only present situations for great profitability for a company, but mark the beginning at which liquid oxygen systems may be an obsolete technology in the future.

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Supporting Materials:

The following files were used in the completion of this project and were submitted at the time of the submission of the final paper.

CompleteConsumerPreferenceSection.xls
CosumerUtility Maximization, Costs, variable alpha.xls
Hospital&PortableDesigns.xls
Risk.xls
Wave Front Calculations.xls

A complete list of PDF journals, websites, and scanned copies of all references were submitted to Dr. Bagajewicz on completion of this assignment.