Solid Oxide Membranes

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Overview

- Background Information
- Design
  - Components of the System
  - Microchannel heat exchanger
  - Unsteady-state heat transfer model
  - Power Requirements and Supply
  - Safety and Controls
  - Unit Sizing
- Business Plan
  - Happiness models
  - Price/demand determination
  - Risk Assessment

Users of Oxygen Therapy

- Chronic Obstructive Pulmonary Disease (COPD) sufferers
  - Including: emphysema and chronic bronchitis
  - Not including asthma sufferers
- ALA estimates sufferers at 30 million[1]
- COPD cannot be reversed[1]
- Over 800,000 Oxygen Therapy Patients

Types of Oxygen Therapy

- Compressed Oxygen
- Liquid Oxygen
  - Require Professional to Refill
  - Limited by Tank Size
- Oxygen Concentrators
  - Very Large; Not Portable
  - The Portable *LifeStyle* by AirSep
- Solid Oxide Membrane

The Oxygen Therapy Market

- According to a Valley Inspired Products, LLC survey of oxygen therapy patients:
- The average patient receives 7 bottles of oxygen per week
- This correlates to a cost of $300-$500 per month
- The average patient leaves their home over 5 times per week
- They are away for an average of 3.9 hours

Product Goals

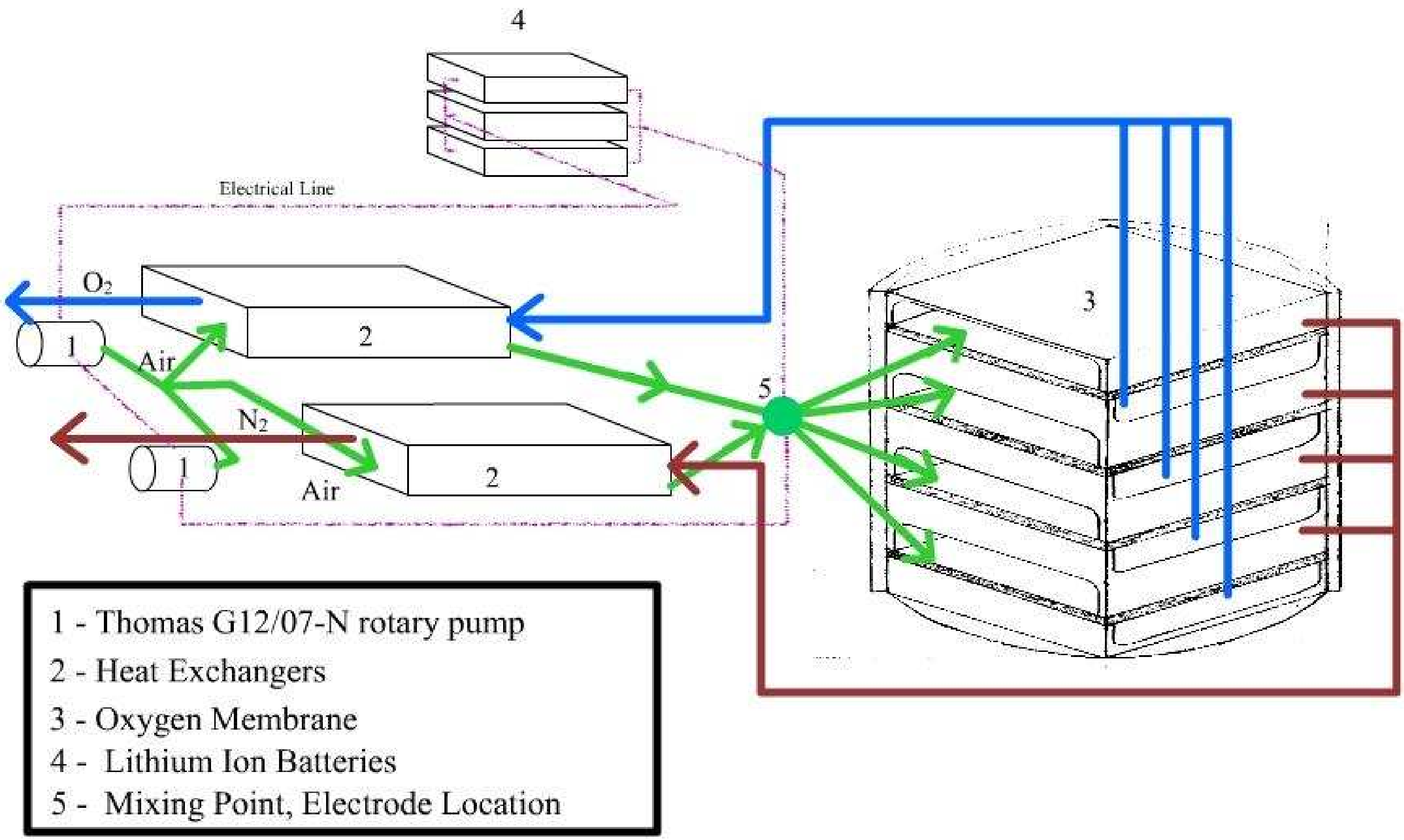
- Portable Oxygen Supply
- 4 Hour Battery Life
- Less than 10 lbs.
- Low Noise Output
- User-Friendly Operation
- Unit Cost of Less than $6000
- Consumer/Market Analysis

Executive Summary

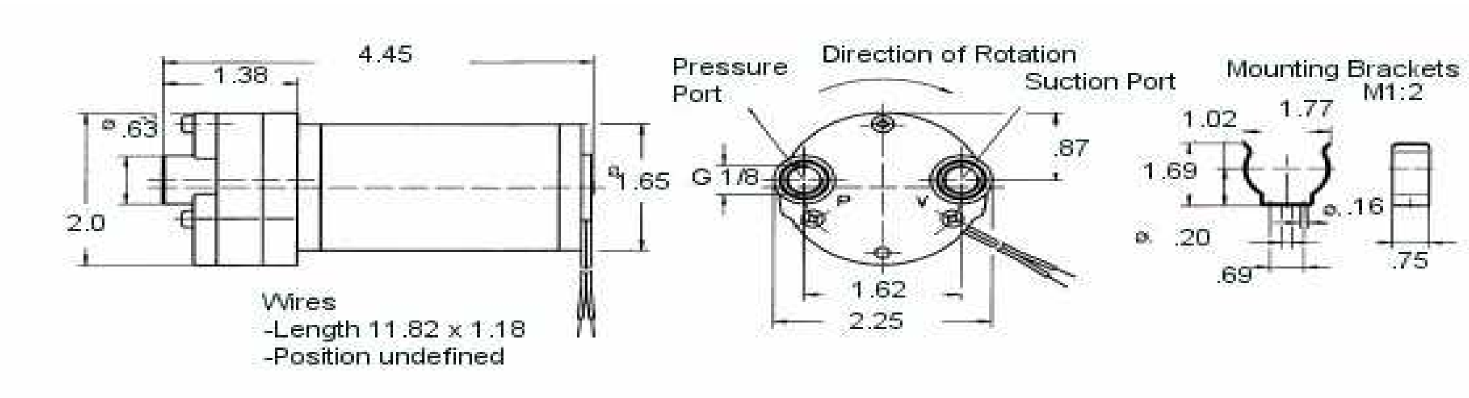
- *Objective*: Continue the design of a BICUVOX membrane system for mobile oxygen therapy
- *Focus*: Business Plan, Electrical System, Safety & Controls, System Design
- *Results*: Produces a minimum 5 L/min of 99.9% Oxygen from 15.2" x 9.5" x 12.2" unit weighing 10 lbs at a selling price of $5500

Unit Design

Overall System



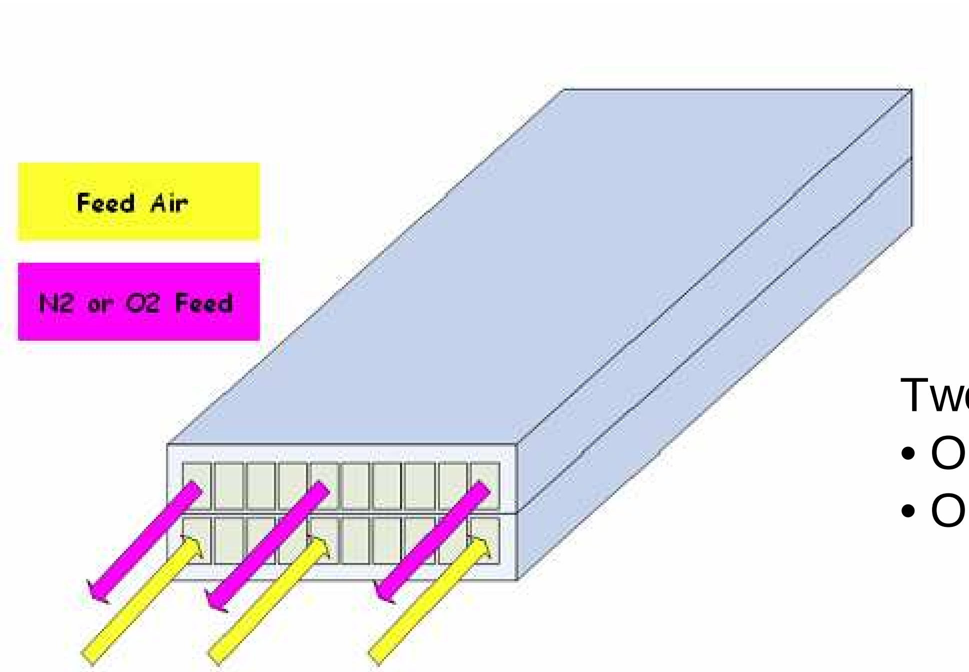
Thomas Rotary Air Compressor



- Power Requirement @ 5400 RPM = 2.3 W
- Voltage Requirement = 12 V
- Diameter = 2.25 in.
- Length = 4.45 in.
- Weight = 0.55 lbs.
- Flow rate = 29.76 L/min
- Pump Choice
  - Oil-less Operation
  - Maintenance Free
  - Pulsation Free, Low Vibrations

Source: Gardner Denver component Database

Microchannel Heat Exchangers



Two heat exchangers are used:
- One for Nitrogen and Air
- One for Oxygen and Air

Heat Exchanger Theory

- According to Adams et. al, the limiting hydraulic diameter for application of standard Nusselt Number Correlations such as the Gneielinski, is approximately 1.22mm

- The diameter of our microchannels are less than 1.22mm, so new correlations will need to be used

Heat Exchanger Theory

- A new Nusselt Number correlation was given by Choi et. al for flow of nitrogen in microchannels

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

Re < 2000

Or Wu & Little:

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

Re > 3000

Heat Exchanger Theory (cont.)

- The friction factor in microchannels is not well understood, but generally the friction factor is greater than standard correlations
- As a simplification, the traditional fanning friction factor is used to calculate the pressure drop with a correction factor of 1.75
- This correction factor is given by M.J. Kohl to be the highest deviation in the literature

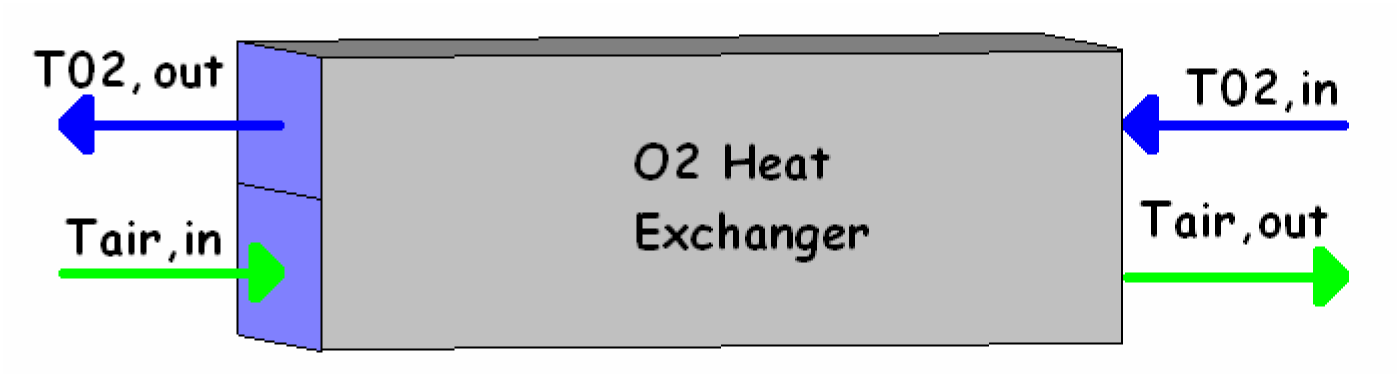
Heat Exchanger Theory (cont.)

- The pressure drop is used to size the heat exchangers
- The total pressure drop of one pass through a heat exchanger is kept below 1psi to account for other pressure drops in the system
- The area of foil used in the heat exchanger, the diameter of the tubes are minimized while the heat transfer is maximized

Heat Exchanger Theory (cont.)

- The exchangers are sized at steady state using an overall heat exchanger coefficient and bulk properties
- The width and length of the heat exchangers are kept constant at 7cm during sizing
- Air is diverted by a valve to each of heat exchanger to allow for maximum heat transfer between the streams

Microchannel Heat Exchangers



T02, in = 831.15K

T02, out = 298.15K

Tair, in = 294.35K

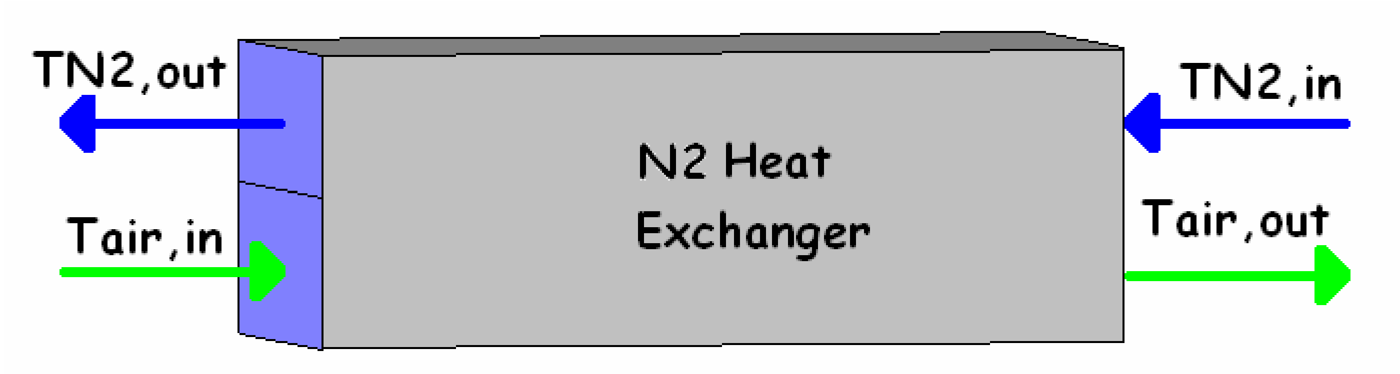
Tair, out = 831.14K

Number of channels = 315

Diameter of each channel = .07mm

Flow rate air = 5.36 L/min , Flow rate 02 = 5 L/min

Microchannel Heat Exchangers



TN2, in = 831.15K

TN2, out = 298.98K

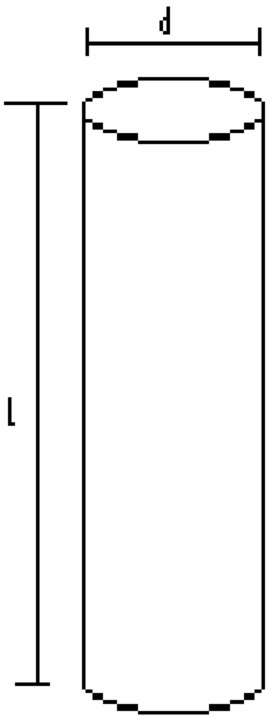
Tair, in = 294.35K

Tair, out = 831.14K

Number of channels = 127

Diameter of each channel = 0.5mm
Flow rate air = 18.54 L/min, Flow rate N2 = 18.8 L/min

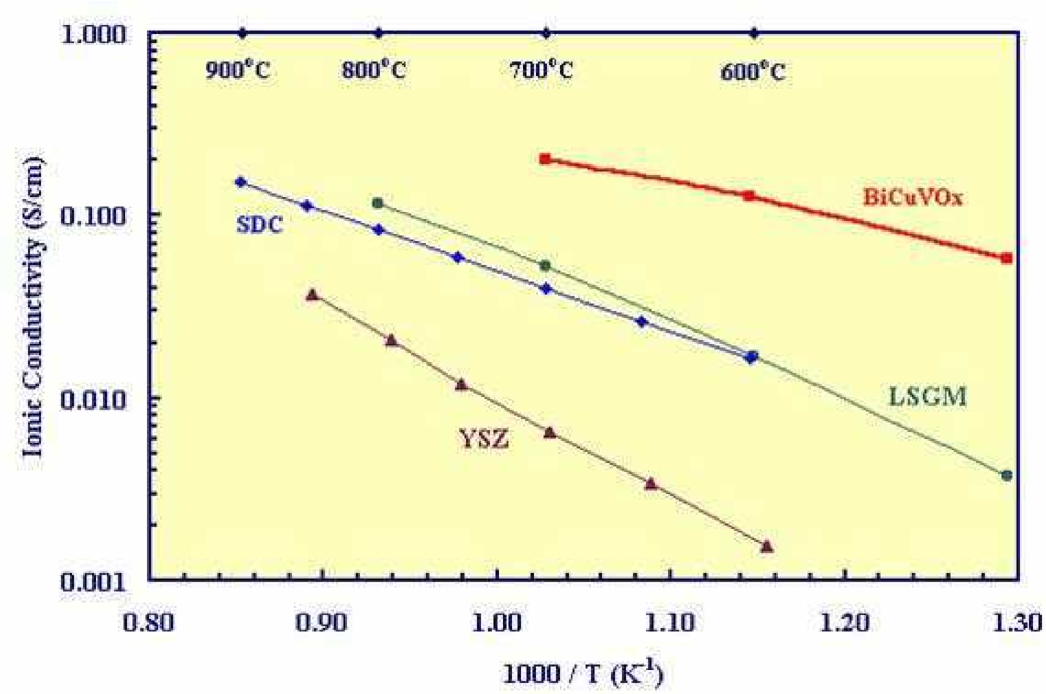
Nichrome Wire Electrodes



Nichrome Resistance Wire

- Diameter = 0.005105 m
- Length = 0.06096 m
- Resistance = 0.0029811 ohms
- Voltage Drop, at unsteady state = 2.15 V
- Voltage Drop at steady state = 0.042 V
- Time to heat up with air at 298K = 1.98 s
- Power Requirements at steady state = 0.61527 W
- Final Wire Temperature = 900K
- Temperature regulated by the control system

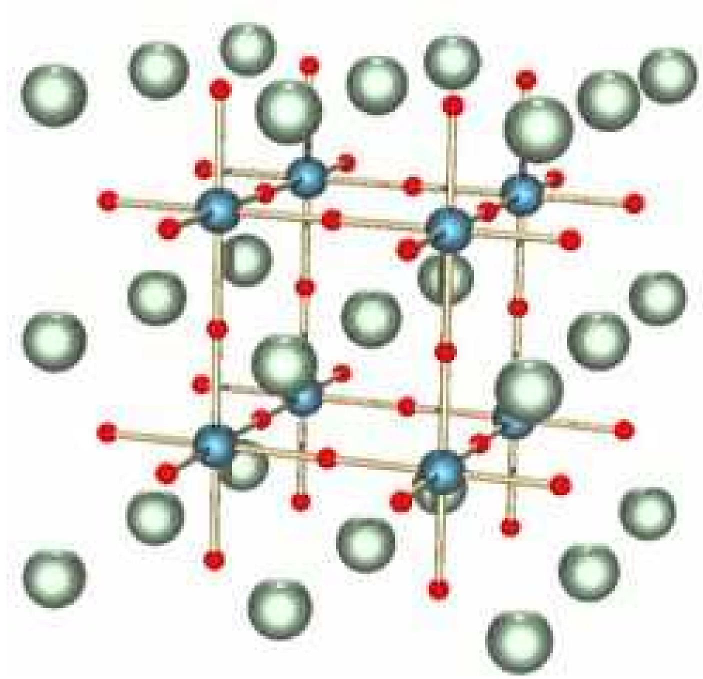
Membranes Considered



- Yttria-Stabilized Zirconia (YSZ)
- Samarium Doped Ceria (SDC)
- Strontium & Magnesium Doped Lanthanum (LSGM)
- Gadolinium Doped Ceria (GDC)

Membrane Choice

- Bicuvox.10
  - $Bi_2Cu_{0.1}V_{0.9}O_{5.35}$
- Crystal Structure
  - Tetragonal v. Orthorhombic
  - $Bi_2O_2^{2+}$ interleaved with anion-deficient perovskite-like sheets $V_{0.9}Cu_{0.1}O_{3.5}$
- Thermal Expansion
  - 10^{-5}/K



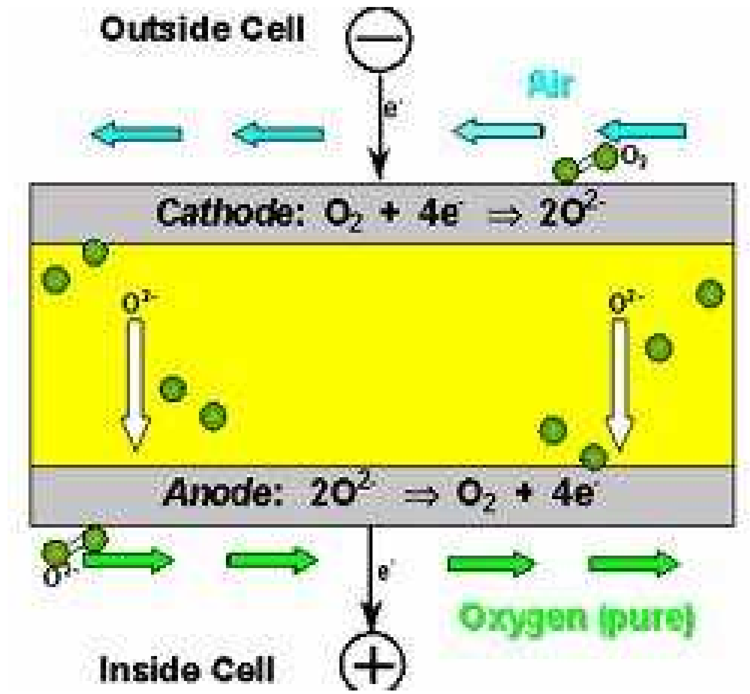
AXO_3 Structure

Kurek, P. et al. *Investigation of Order-Disorder Transition in BICUVOX Single Crystals*

Solid Oxide Membranes

- Relatively new technology
- Oxygen conducted through membrane by vacancies
- Oxygen is reduced at cathode to oxygen anion
- Combines at anode to form diatonic Oxygen
- Flux through the membrane

$$N_i = \frac{P_i}{l}(driving\ \ force)$$

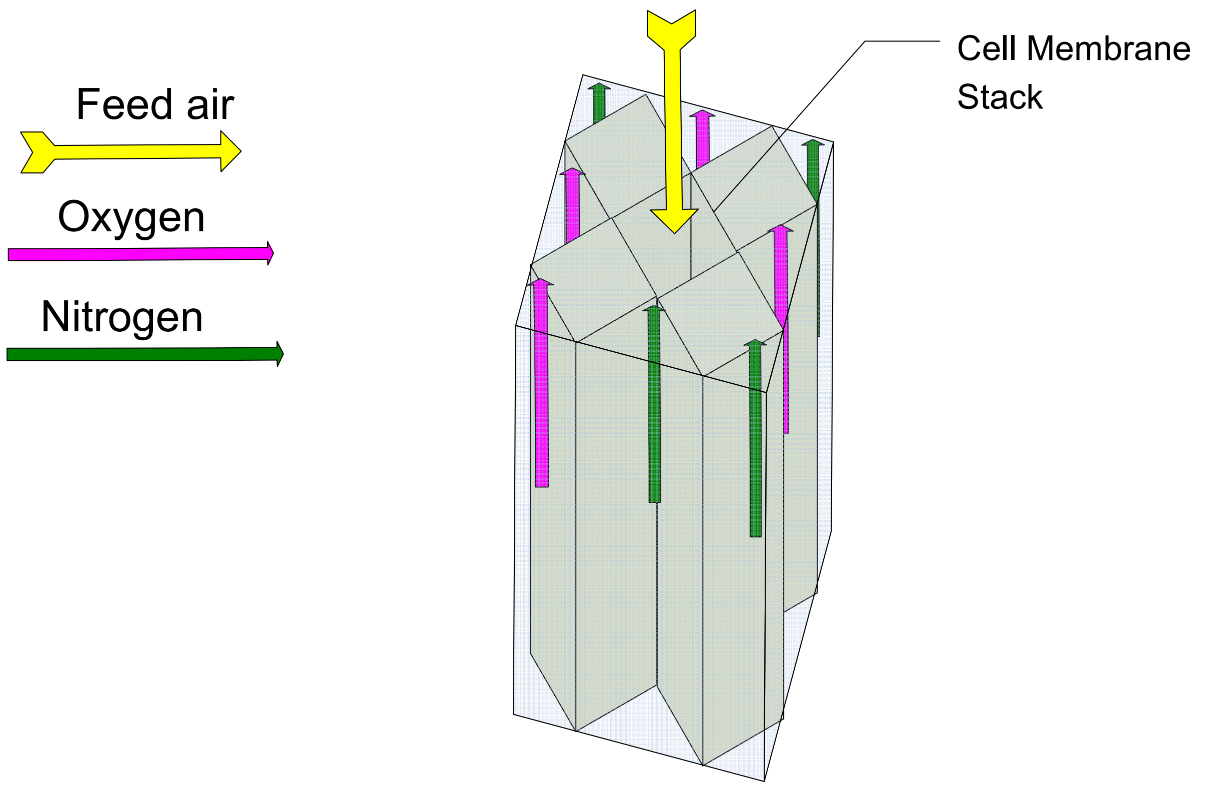


Membrane Specifications

number of plates	208	*source*	plates
Temperature	550	*source*	C
total volumetric flow rate of permeate	5	*spec*	L/min
molar gas volume (STP)	24.04	*calc*	L/mol
molar flow rate of permeate/plate	0.00002	*calc*	mol/s/plate
electron stoichiometry	4	*source*	mol electrons/mol O_2
Faraday constant	96485	*source*	C/mol electrons
current	6.431	*calc*	A
current density for BICUVOX.10	0.75	*source*	A/cm^2
total plate area required	12.87	*calc*	cm^2
side length of square plates	1.41	*calc*	in
thickness of plates	0.3	*source*	cm
air gap height	0.5	*source*	cm
electrode height	0.2	*source*	cm
total cell stack height	287.24	*calc*	cm
number of columns	4	*spec*	
height per column	6.65	*calc*	in
electrical potential for each cell	0.057	*calc*	V
total potential for stack	11.923	*calc*	V
power required	76.675	*calc*	W

Boivin et al. *Electrode-Electrolyte BIMEVOX System for Moderate Temperature Oxygen Separation*

Membrane Stack Arrangement



Patent # US 6,264,807 B1 (July 24, 2001)

Electrical System

- Power Sources
  - AC Power
  - 12 V Lithium Ion Battery Power
    - 4 hour battery
    - 2 hour recharge
- Voltage is diverted with a voltage regulator to the nichrome wire to allow for a faster heat up time
- The voltage direct towards the feed pumps is compromised, but a flow rate of 14.88 L/min for each pump is still achieved

Electrical System (cont.)

- Initially a switching mechanism allows no current to pass across the membranes
- At steady state most of the voltage is fed to the pumps and the membrane

Power Needed

Unit	Wattage	Hours	Watt-Hours
Membrane	76.7	4	306.8
Heating Element, Unsteady	29325.54	.00055	16.12905
Heating Element, Steady	0.61	0.166667	0.101667
2 Pumps	4.6	4	18.4
		Total Watt-Hours	*341.4307*

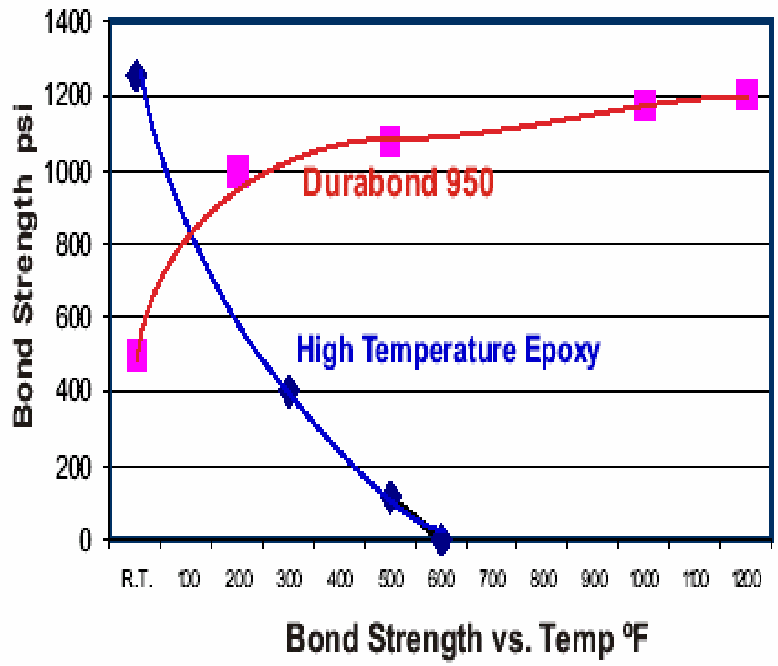
Lithium Ion Battery

- Specific Energy = 150 W-h/kg
- Energy Density = 400 W-h/L
- 341.43 W-h needed by the unit
- Results
  - 52.11 in^3 (or 2.75 x 2 x 9.5)
  - 5 lbs
- 4 Hour Battery Life
- 2 Hour Recharge

Liden, D., T.B. Reddy, *Handbook of Batteries*

Sealant

- Durabond 950
- High temperature application
  - Up to 1200°F (922K)
- Aluminum base
  - Safe for human use
  - Ni, Cr bases carcinogenic
- Bond strength increases with temperature
- Thermal expansion coefficient
  - 10^{-5}/K

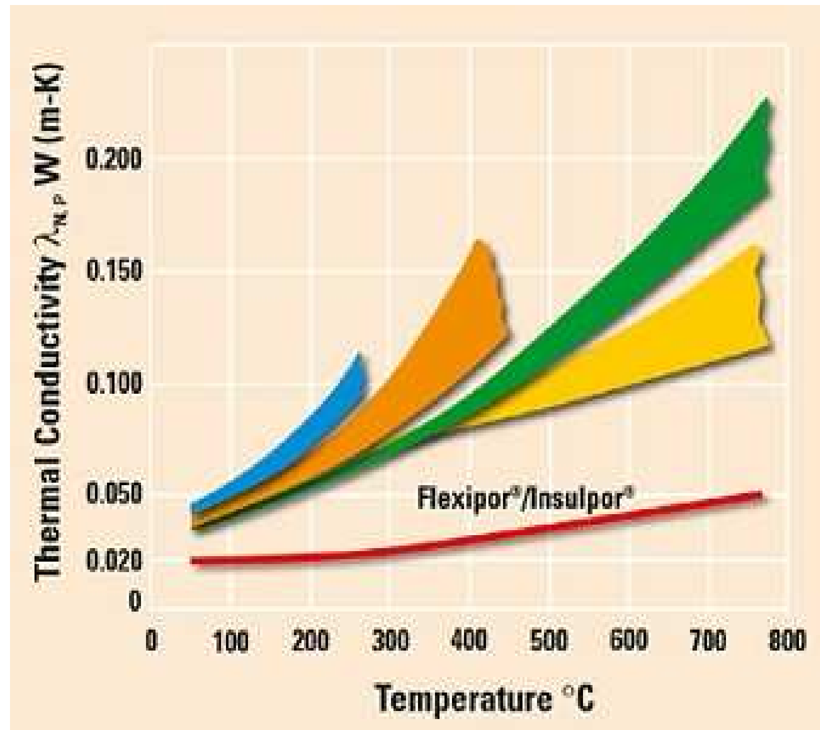


Inner Casing

- Magnesium oxide
- Used to support membrane stack and Insulpor©
- .5 cm thickness
- Safe for Humans
- Thermal expansion coefficient
  - 10.8^{-5}/K

Insulation

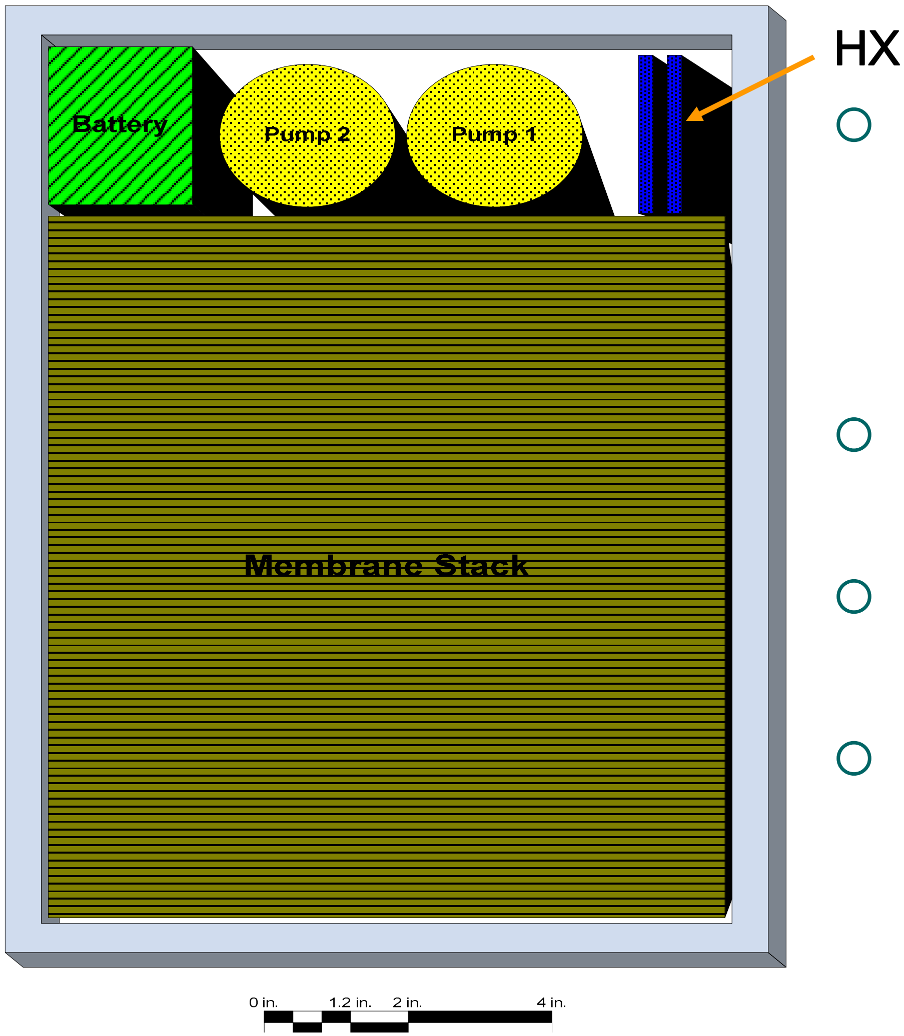
- Insulpor© vacuum insulation
- Use temperature up to 1050°C
- Thermal Conductivity
  - 0.0043 W/m^2K
- 2.5 in. thickness
  - Outside T=77°F
- Membrane Size
  - 12.1 x 9.4 x 12.1



Equipment Sizing

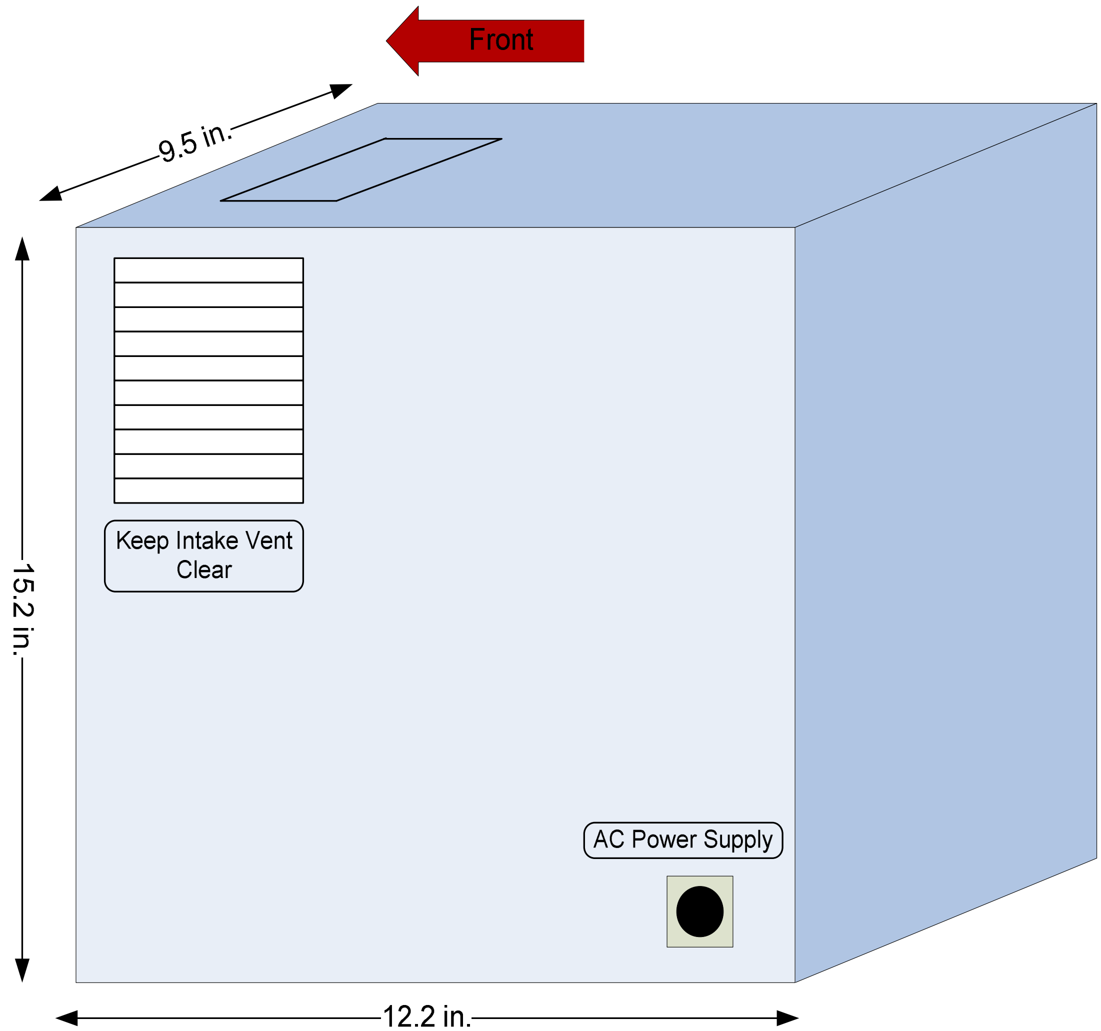
Sizes (in inches & pounds)				
Component	**Height**	**Width/Diameter**	**Length**	**Weight**
Membrane Stack	12.1	9.4	12.1	2.4
Pump 1		2.25	4.45	0.55
Pump 2		2.25	4.45	0.55
Heat Exchanger – O2	2.756	0.1005	2.756	0.22
Heat Exchanger - LA	2.756	0.0918	2.756	0.22
Battery	2.75	2	9.5	5
Final Size	***15.2***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

Unit Design

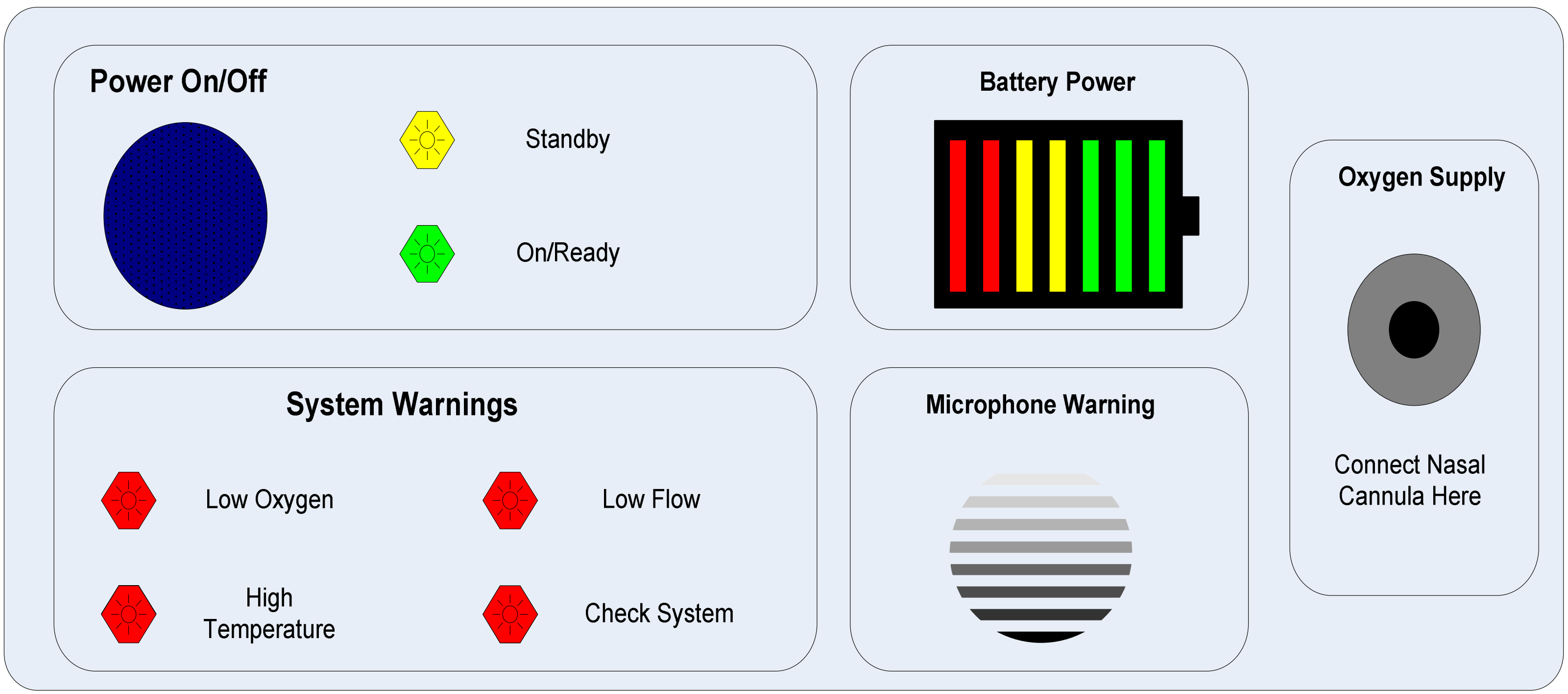


- Dimensions
  - Height – 15.2″
  - Width – 9.5″
  - Length – 12.2″
- Weight
  - 9 lbs
- Membrane
  - 81% of Volume
- Battery
  - 55% of Weight

3-D View


Front
9.5 in.
15.2 in.
Keep Intake Vent Clear
AC Power Supply
12.2 in.

Panel View


Power On/Off
Standby
On/Ready
Battery Power
Oxygen Supply
Connect Nasal Cannula Here
System Warnings
Low Oxygen
Low Flow
High Temperature
Check System
Microphone Warning

Safety

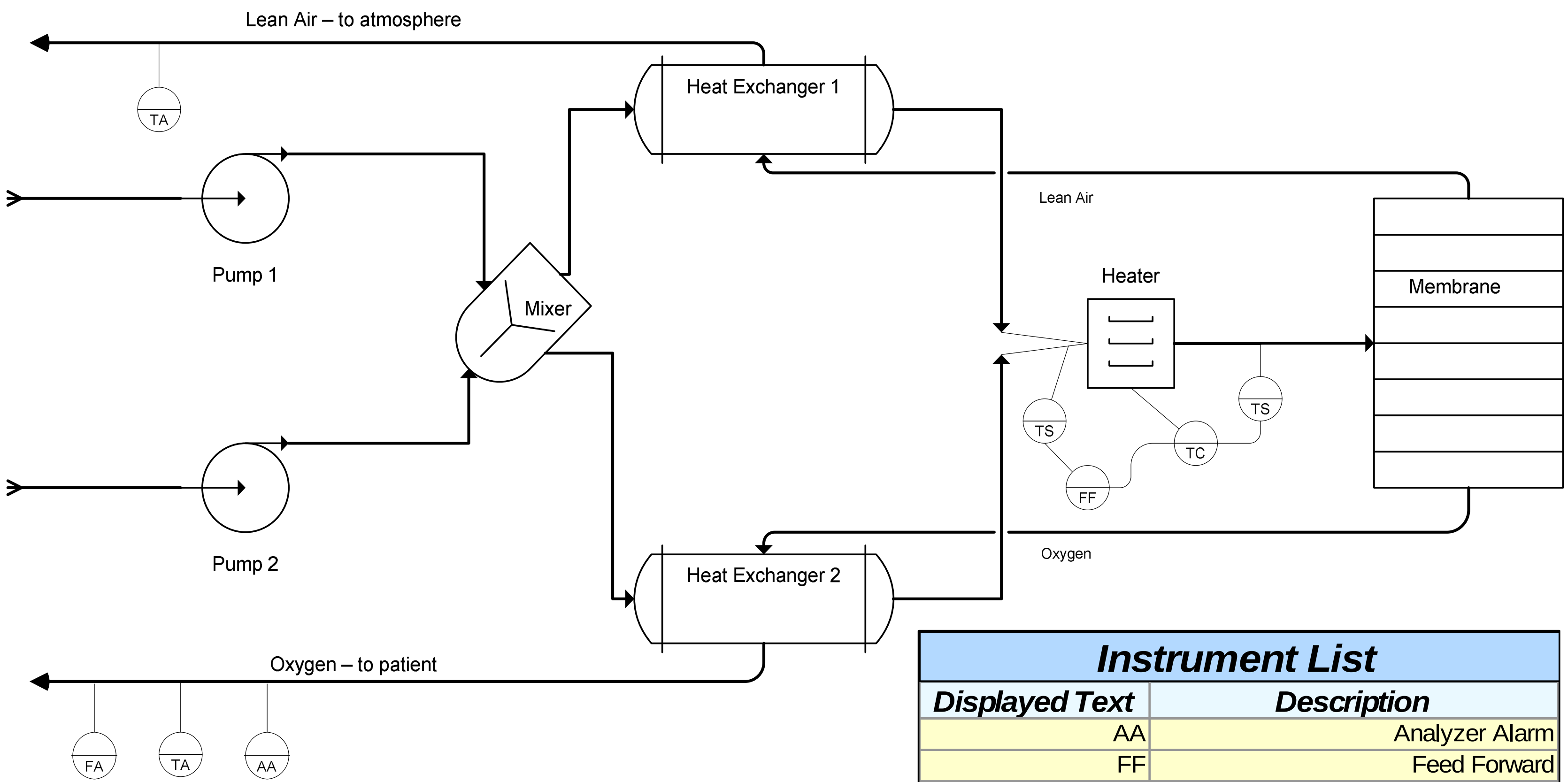
<u>Issues</u>

- High Temperature of System
- High Temperature Exit Streams
- Low O_2 Concentration
- Low Flow in Exit Streams

<u>Solutions</u>

- Insulation & Casing
- Temperature Sensors & Alarms
- Concentration Controls
- Flow Controls

Control System



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

Business Plan

Nature of Business

- Our business will begin as a partnership between Brent Shambaugh and Justin Brady
- For additional funding as we grow, we will seek private investment

Comparison with Competition

	AirSep Lifestyle	Inogen One	Our Product
Avg. Noise (Db)	55	40	13
Power (watts)	35	38	341
weight (lb)	9.75	9.7	9.8
length (ft)	1.36	0.97	1.017
width (ft)	0.60	0.50	0.95
height (ft)	0.46	1.03	1.034
cost $	3899	5495	5500

Plant Location

- The market for oxygen is considered homogeneous in the United States
- Due to shipping expenses, it would best if we were centrally located
- The location that we have chosen is Denver, Colorado

  - According to Forbes magazine, it has one of the lowest tax rates in the nation

Objective

- Investigate how the NPW is affected by demand and price changes of our product
- Investigate the major factors affecting demand
- Consider three different scenarios: an in-car unit, an in-house unit, and a portable unit
- Focus on portable unit

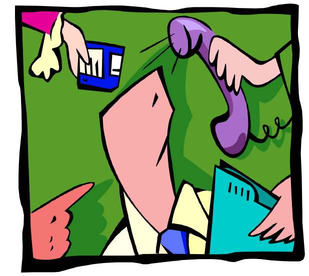
Justification for Portable Unit

- There are only two main competitors in this market, verses a total of four competitors for the in-house unit

- The in-car unit is not practical since it is limited to a car

- Our microchannel heat exchangers allow for the unit to be small. This small size is not needed for an in-house unit

Demand Model



- Governed by two equations:

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

(equation 1)

$$p_1 d_1 + p_2 d_2 = Y$$

(equation 2)

d_1= the demand for our product

d_2 = the demand for the competitor's product

p_1= the price for our product

p_2 = the price for the competitor's product

Y = the total money available in the market $315 M

β = the beta function

α = the alpha function

Beta Function

The β value is a ratio which describes how much happier the consumer is with product of interest compared to the competition.

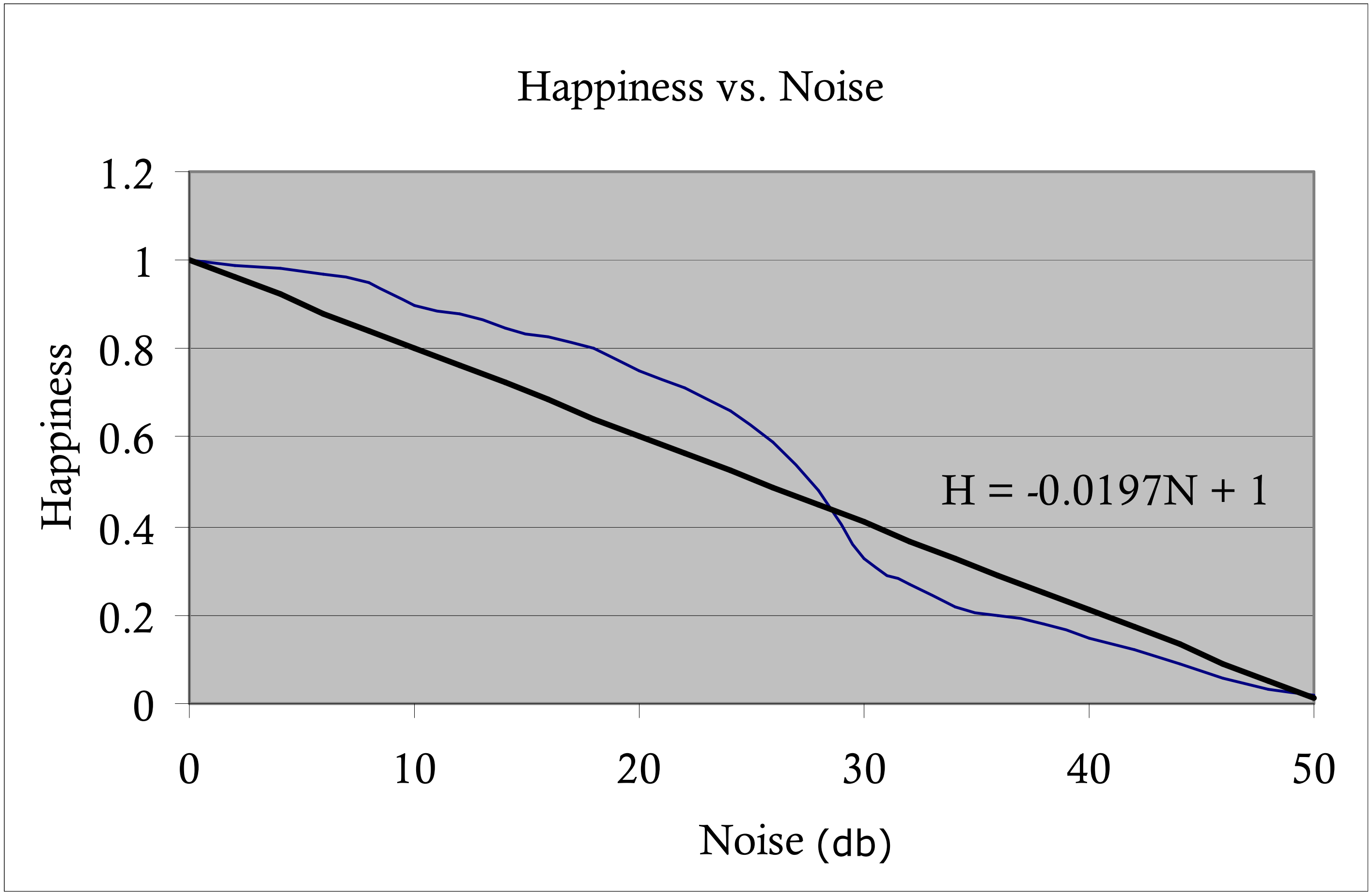
$$\beta = \frac{H_c}{H_I}$$

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

Constraint: $0 < \beta < 1$, larger β acceptable with lower selling price

Happiness Determination

From the portable unit:



http://www.josaka.com/Content/2000/Decibel-Chart.htm

Happiness Determination

For the Portable Unit:

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

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

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

For height: $H_h = -0.1829h + 1$ 100%, 2ft :0%, 3ft

For width: $H_w = -0.4886W + 1$ 100%, <8in : 0%, 2ft

For length: $H_l = -0.3735l + 1$ 0%, 1ft

Happiness Determination

$$H_I = \sum_i w_i y_i$$

Where:

w_i = the weight of each variable
y_i = happiness function for each variable

The sum of all weights must equal one

Overall Happiness Function

For the Portable Unit:

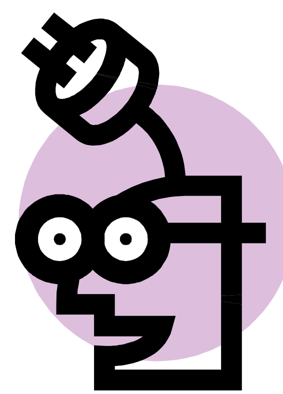
$$H_I = 0.3 * H_N + 0.05 * H_p + 0.3 * H_w + 0.1 * H_h + 0.1 * H_w + 0.15 * H_l$$

- Beta value = 0.865

Alpha Function

- The α value is an expression of how well the general public knows product being sold
- It may be expressed in terms of advertising rate and time

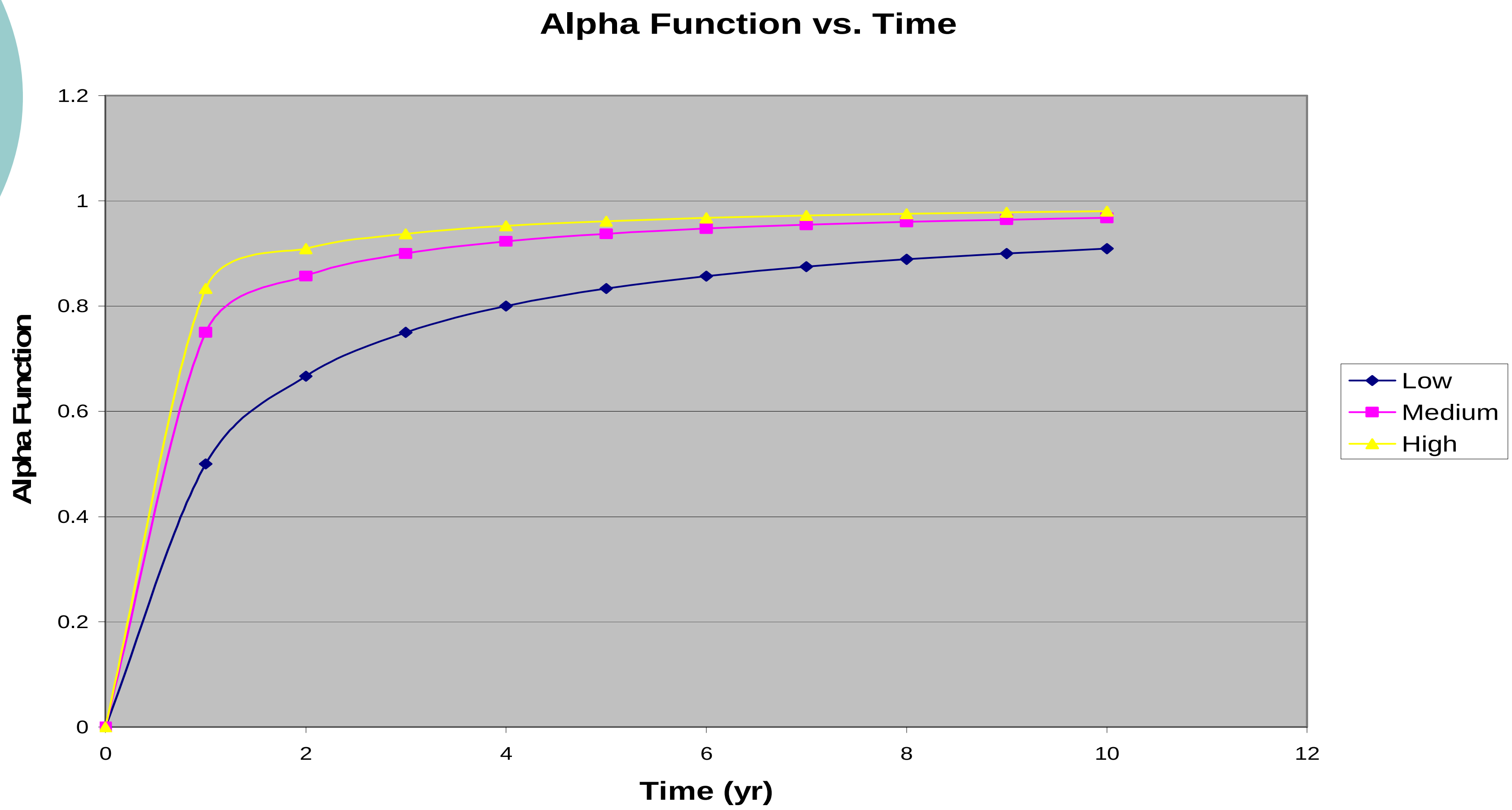
$$\alpha = \frac{yt}{1 + yt}$$



Where:

y = the advertising rate
t = time

Alpha Function (cont.)



Solving the Demand Model

- Solve these two equations simultaneously:

$$\beta p_1 d_1 = \alpha p_2 d_2 \left(\frac{d_1^{\alpha}}{d_2^{\beta}} \right) \qquad \text{(equation 1)}$$

$$p_1 d_1 + p_2 d_2 = Y \qquad \text{(equation 2)}$$

- Solve for at constant α, β, Y, p1, and p2
- Use one of two methods, an iterative method or a graphical method

Iterative Method for the Demand Model

Rearrange Equation 1 for d_1:

$$d_1 = \left(\frac{\alpha p_2 (d_2)^{1-\beta}}{\beta p_1} \right)^{\frac{1}{1-\alpha}}$$

Rearrange Equation 2 for d_2:

$$d_2 = \frac{Y - p_1 d_1}{p_2}$$

Substitute Equation 2 into 1:

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

$$d_1 = f(d_1)$$

Iterate d_1 for solution

Iterative Method

- Assume that the customer base is captivated to buy the product, so the total demand existing in the market is completely satisfied.

- The total demand is therefore the sum of the demand for the product of interest and the competitors:

$$D = d_1 + d_2$$

Iterative Method

- The American Lung Association says that 90,000 people will develop Chronic Obstructive Pulmonary Diseases (COPD) each year, and 15% of these have the need for oxygen. This gives a total demand of 14,000.

- In the case that the demand equation gives a demand that exceeds the total demand an alternate form of equation 1 needs to be used.

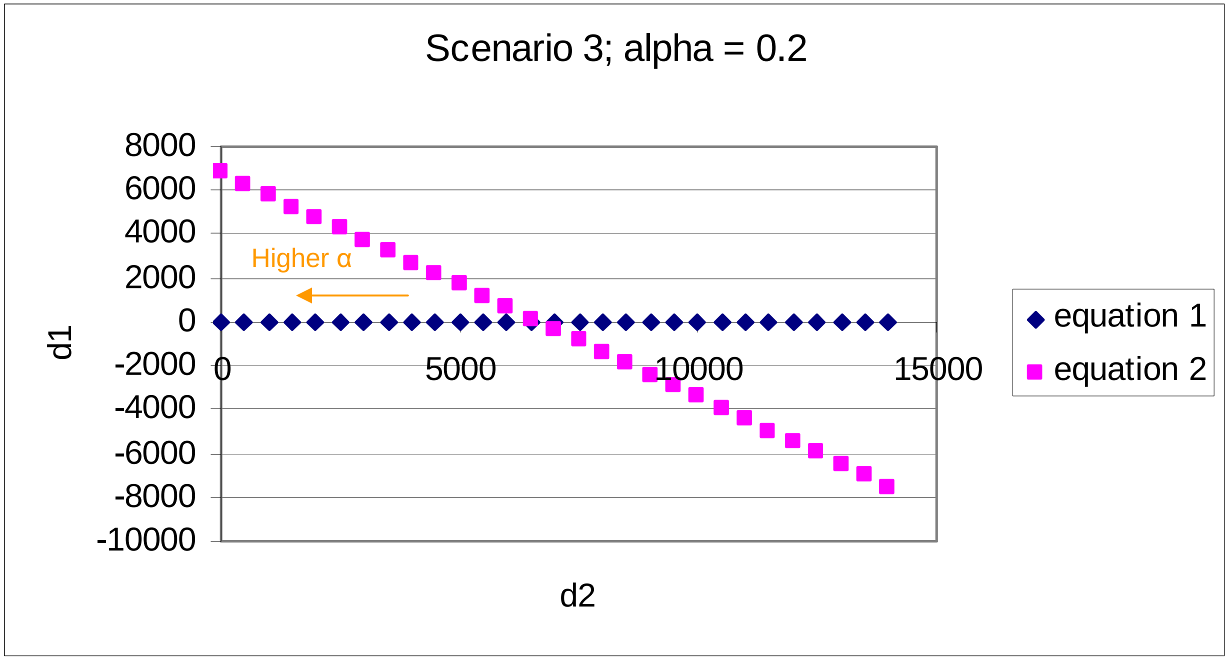
$$d_1 = \left(\frac{\beta}{\alpha}\right)^{1-\alpha} \left(D - d_1\right)^{\frac{1-\beta}{1-\alpha}} \quad \text{instead of} \quad d_1 = \left(\frac{\alpha p_2 \left(d_2\right)^{1-\beta}}{\beta p_1}\right)^{\frac{1}{1-\alpha}}$$

Graphical Method

- Rearrange equations 1 & 2 for d_1 and plot d_1 vs. d_2.
- For total demands greater than the market demand, use the same formula as given for the iterative method

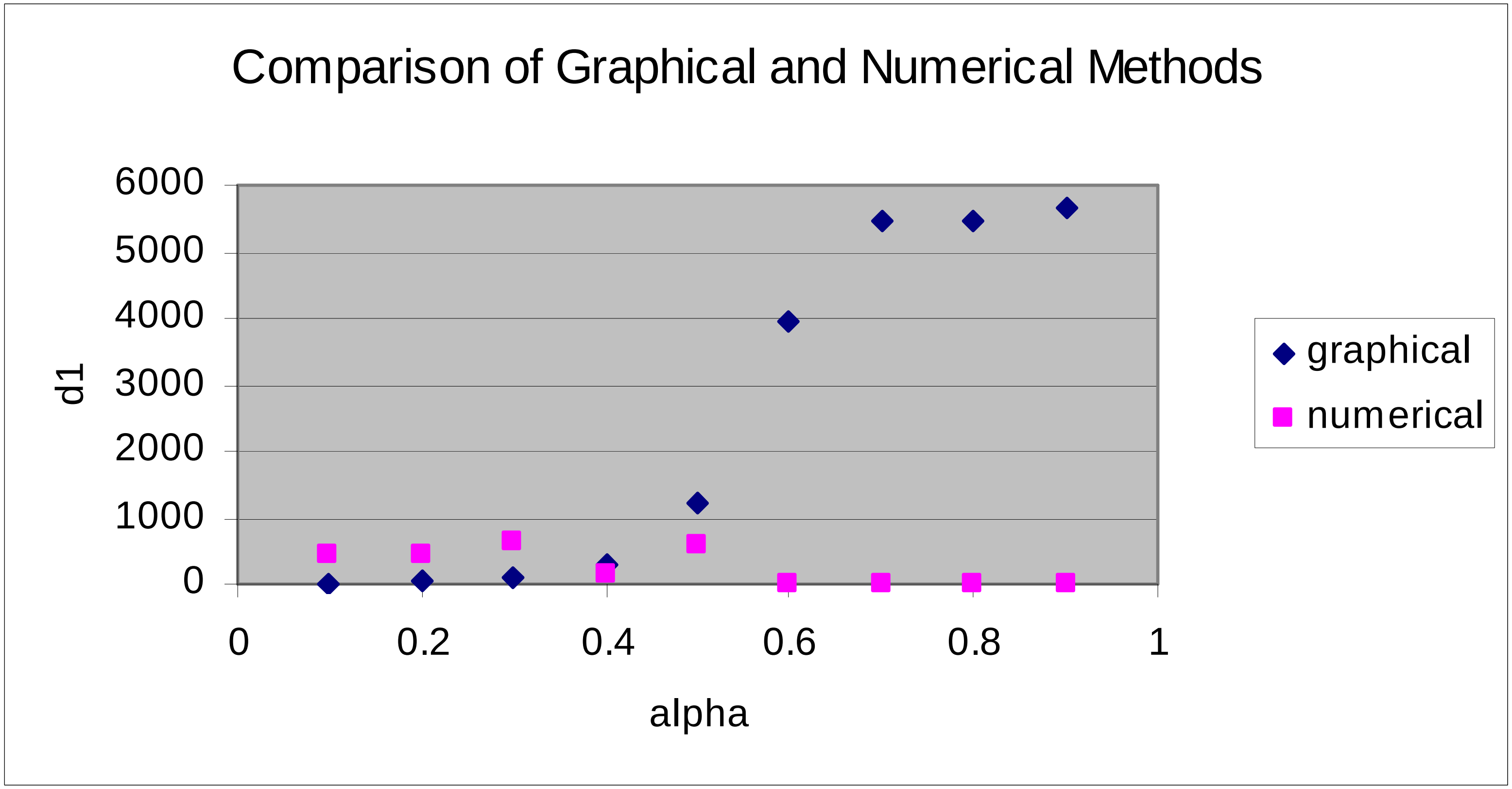
$d_1 = 9.5$

$d_2 = 6650.65$

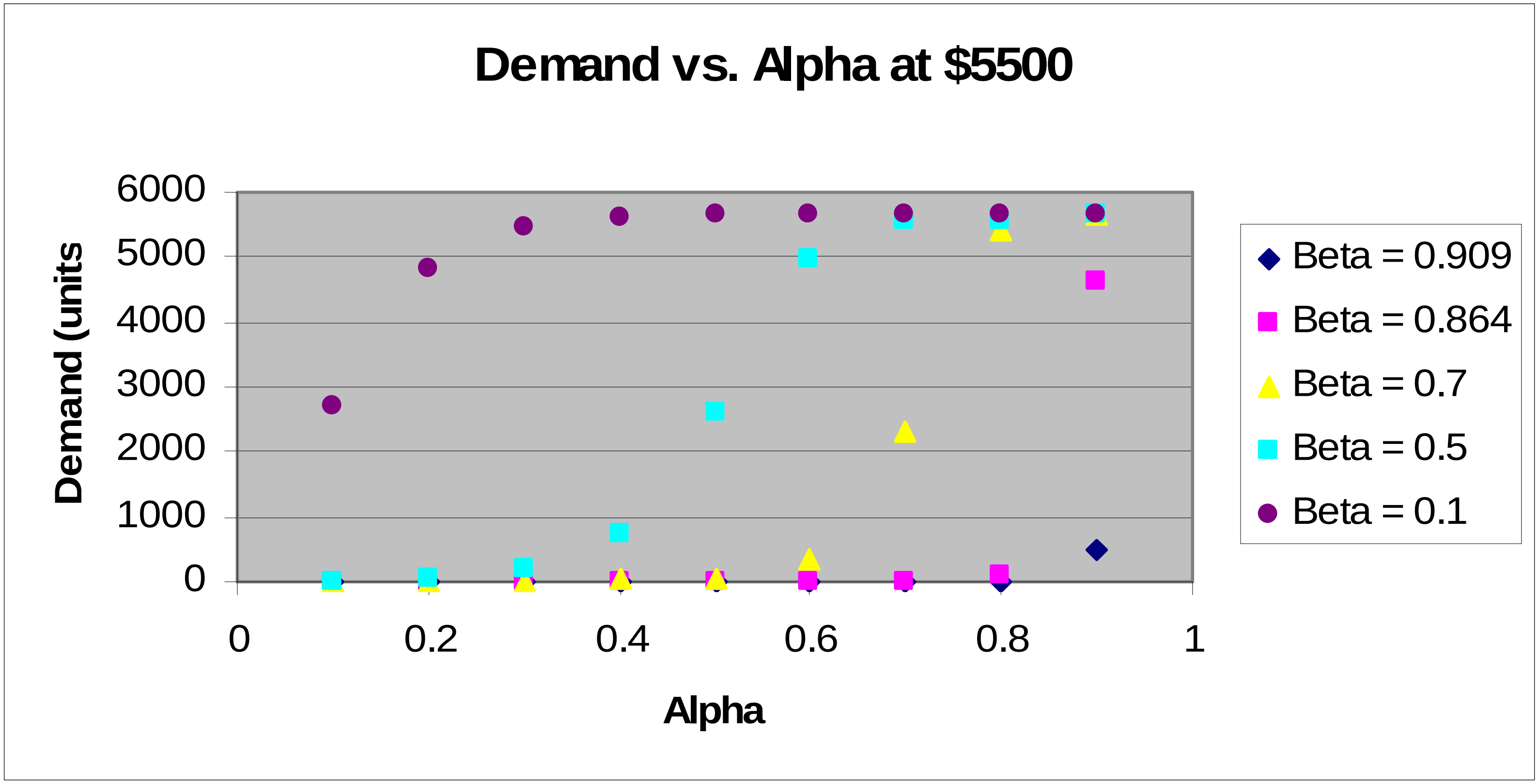


Iterative vs. Graphical

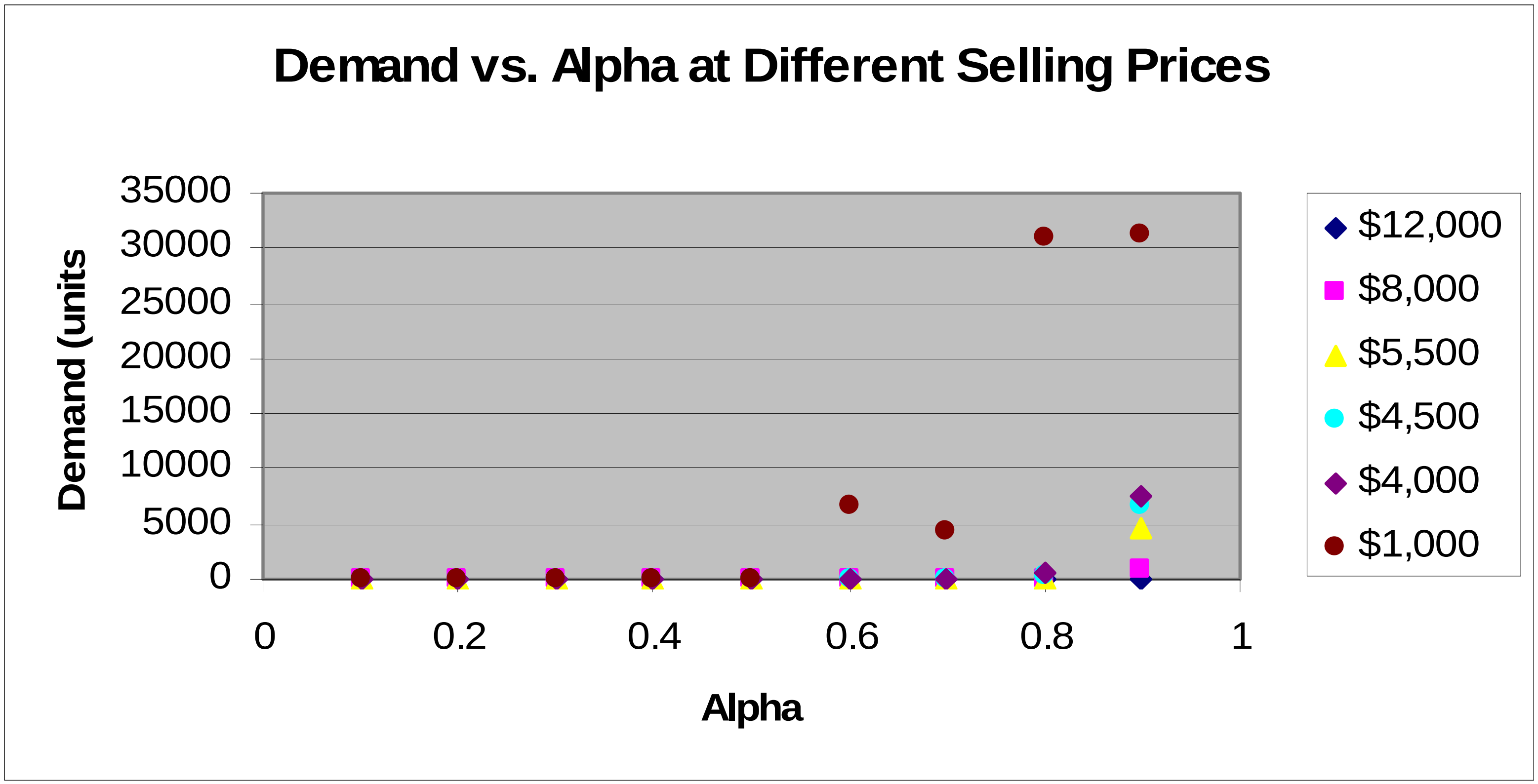
• When using the development for scenario 1, the following results are achieved (Selling Price = \$5500, $\beta = 0.55$):



Results at $5500

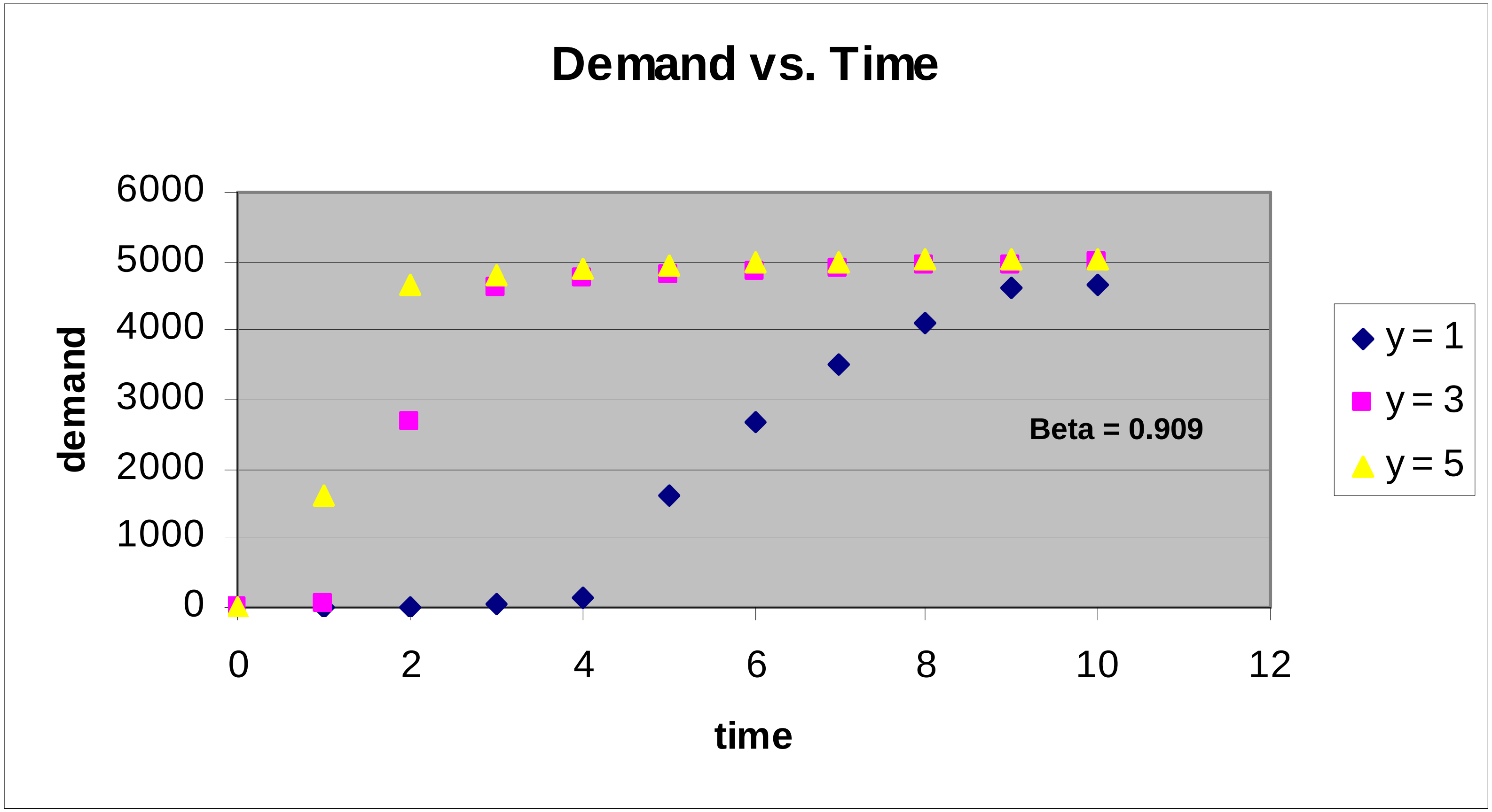


Demand at Different Selling Prices



Note: Production cost per unit (β=0.865,$5500) = $3600

Time Dependence of Demand



NPW calculation

						P2=	2.16E+03	P1=	8.E+03	H2/H1=	5.00E+00
Manufacturing Heat exchangers only						D=	1.40E+04	i=	8.00E-02	y	3.00E+00
Year	**β(t,H)**	**α(y,t)**	**Demand**	**Sales**	**Product Cost**	**Gross Earnings**	**Depreciation**	**Taxes**	**Net Profit**	**Cash Flow**	**$Cf_i/(1+i)^k$**
1	0.75	0.83	3.E+03	2.65E+07	**1.85E+07**	8.08E+06	5.55E+06	2.83E+06	-2.92E+05	5.25E+06	4.86E+06
2	0.75	0.91	4.E+03	3.13E+07	1.89E+07	1.24E+07	5.55E+06	4.33E+06	2.49E+06	8.04E+06	6.89E+06
3	0.75	0.94	4.E+03	3.23E+07	1.90E+07	1.33E+07	5.55E+06	4.64E+06	3.07E+06	8.61E+06	6.84E+06
4	0.75	0.95	4.E+03	3.28E+07	1.90E+07	1.37E+07	5.55E+06	4.80E+06	3.37E+06	8.92E+06	6.55E+06
5	0.75	0.96	4.E+03	3.31E+07	1.91E+07	1.40E+07	5.55E+06	4.90E+06	3.56E+06	9.10E+06	6.19E+06
6	0.75	0.97	4.E+03	3.33E+07	1.91E+07	1.42E+07	5.55E+06	4.97E+06	3.68E+06	9.23E+06	5.81E+06
7	0.75	0.97	4.E+03	3.34E+07	1.91E+07	1.43E+07	5.55E+06	5.02E+06	3.77E+06	9.32E+06	5.44E+06
8	0.75	0.98	4.E+03	3.36E+07	1.91E+07	1.44E+07	5.55E+06	5.05E+06	3.84E+06	9.39E+06	5.07E+06
9	0.75	0.98	4.E+03	3.37E+07	1.91E+07	1.45E+07	5.55E+06	5.08E+06	3.89E+06	9.44E+06	4.72E+06
10	0.75	0.98	4.E+03	3.37E+07	1.91E+07	1.46E+07	5.55E+06	5.11E+06	3.94E+06	9.48E+06	4.39E+06
										NPW=	6.E+06

Determining Equipment Price

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

Capital Investment

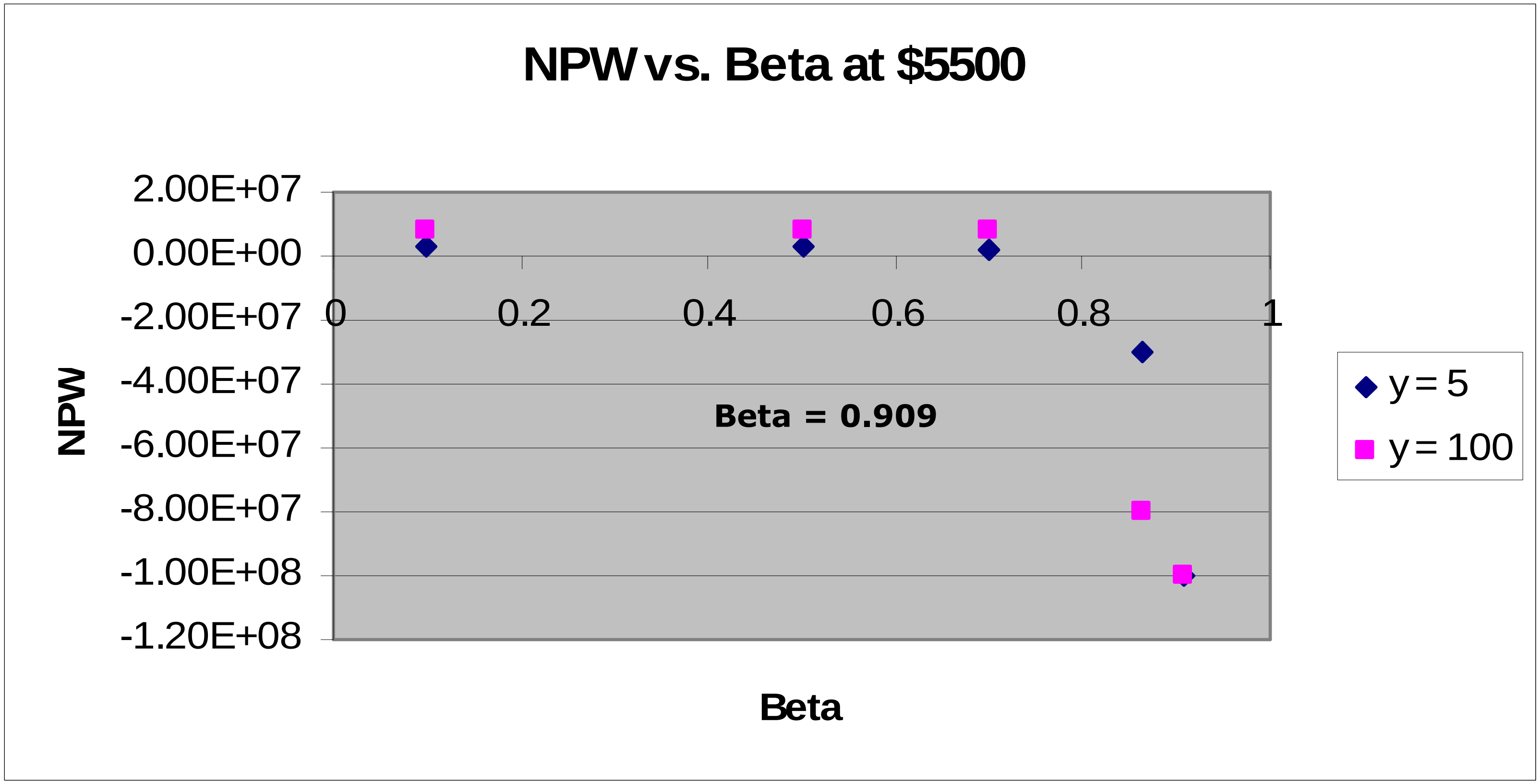
- Based on percent of purchased equipment

Cost Item	Measurment Criteria	Amount
Direct Costs		
Purchased equipment	100	13337409
Installation	45	6001834
Instrumentation (installed)	18	2400734
Piping	16	2133985
Electrical systems (installed)	10	1333741
Buildings (including services)	68	9069438
Yard improvements	15	2000611
Service facilities	40	5334964
Total Direct Cost		41612717
Indirect Costs		
Engineering and Supervision	33	4401345
Construction expenses	39	5201590
Legal expenses	4	533496
Contractor's fee	17	2267360
Contingency	35	4668093
Total Indirect Cost		17071884
FCI	440	58684600
Working Capital	78	10403179
TCI	518	69087779

Changed value → (Buildings)

Based on Table 6-9
Plant Design and Economics
Peters, Timmerhaus & West

NPW Beta Dependence

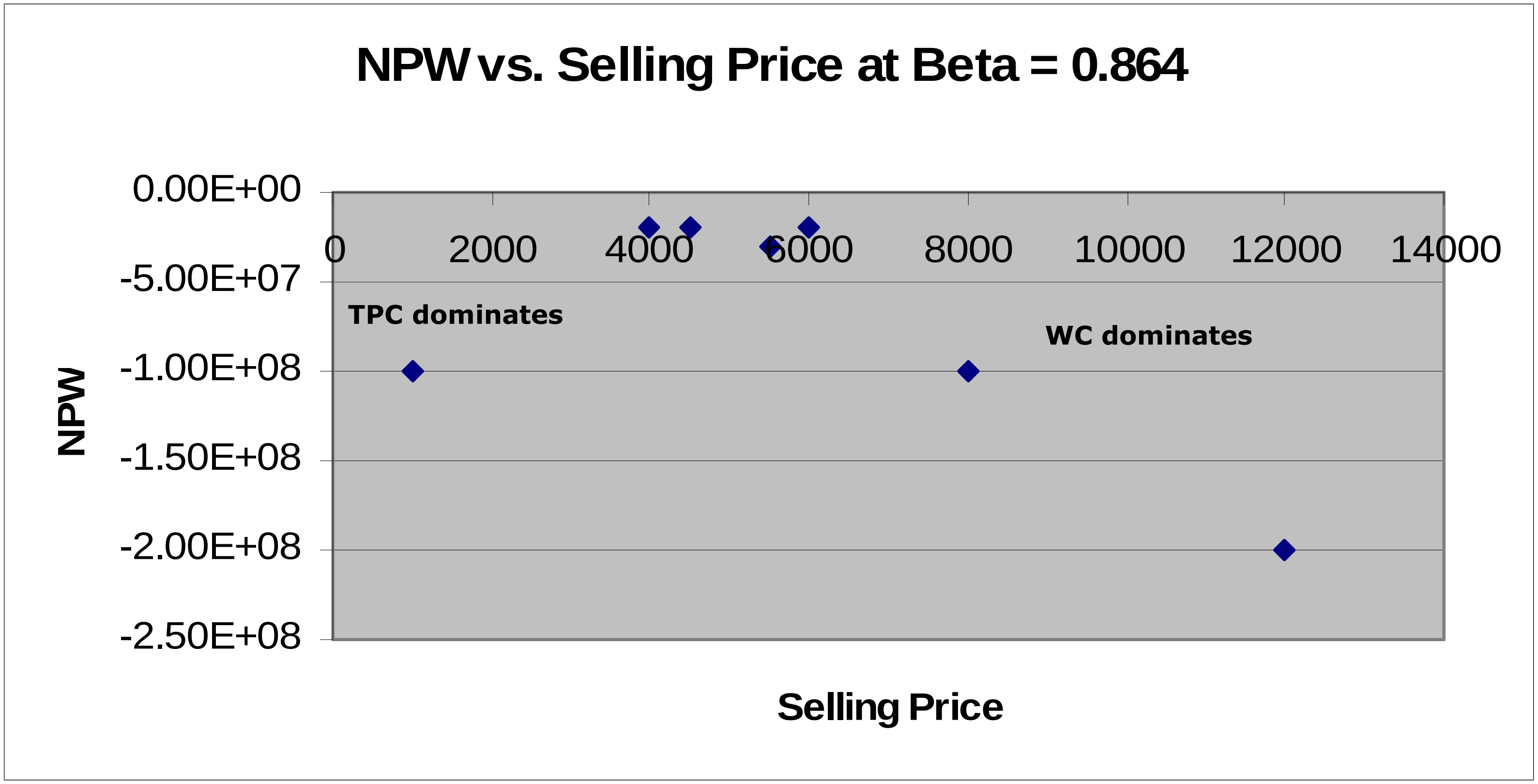


Advertising correction:

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

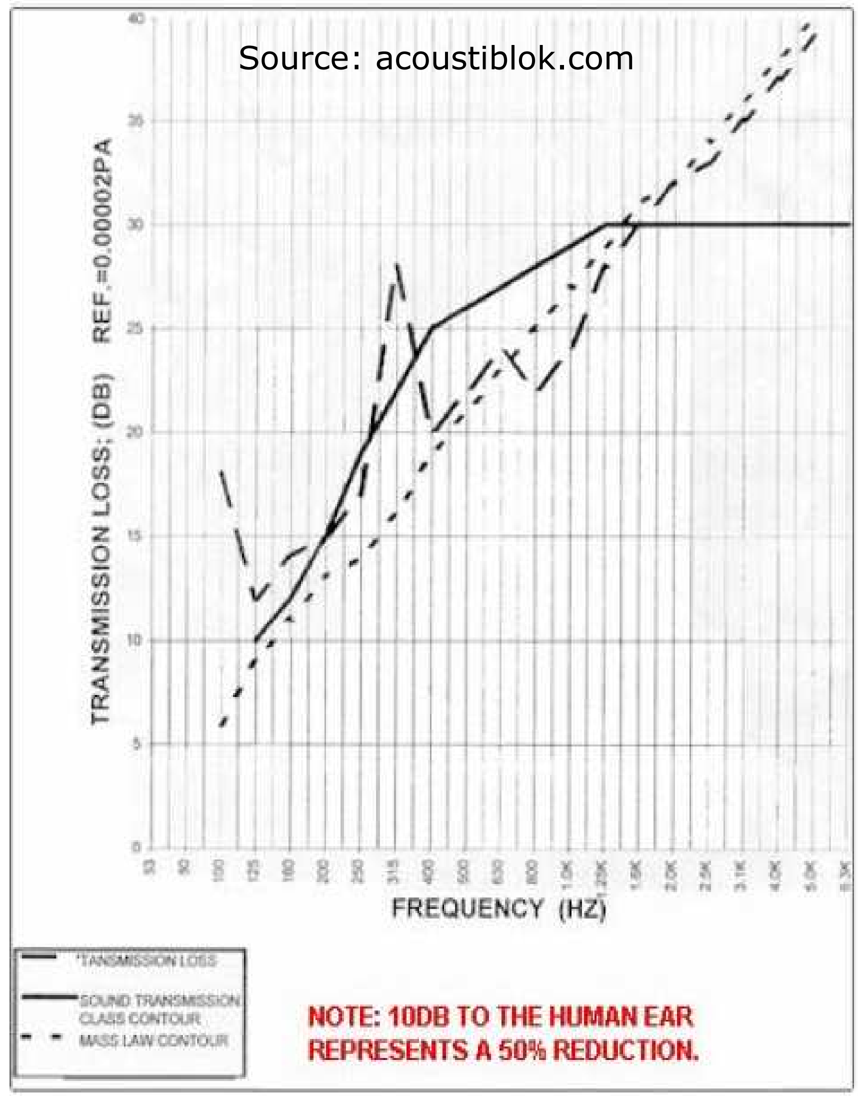
Alpha constraint, y = 5

NPW vs. Selling Price



Properties of Acoustiblok

- Thickness = 0.11 inches
- Weight/Sq. Ft. = 1 lb
- Estimate = $10/Sq ft.

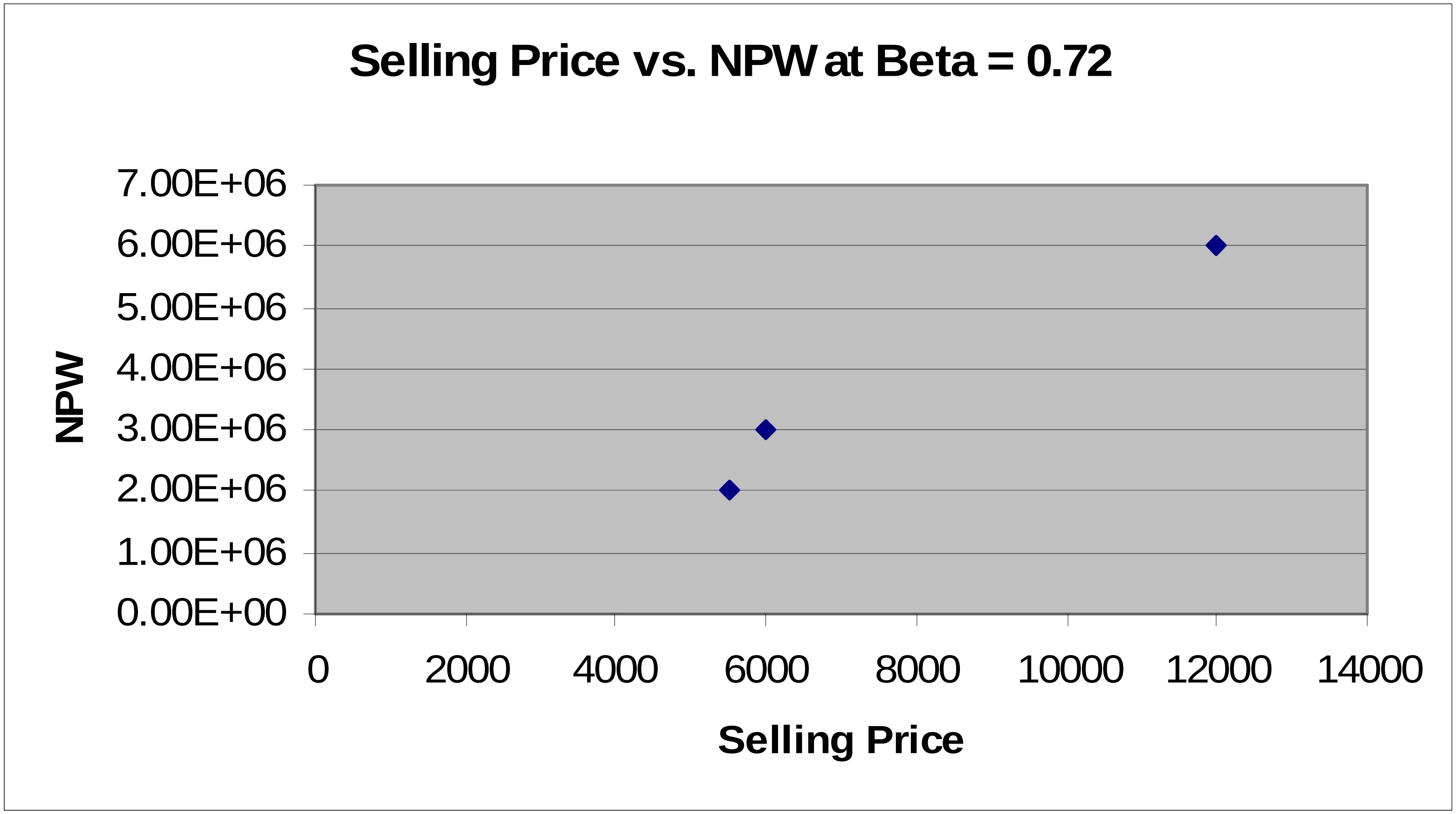


Optimal Design

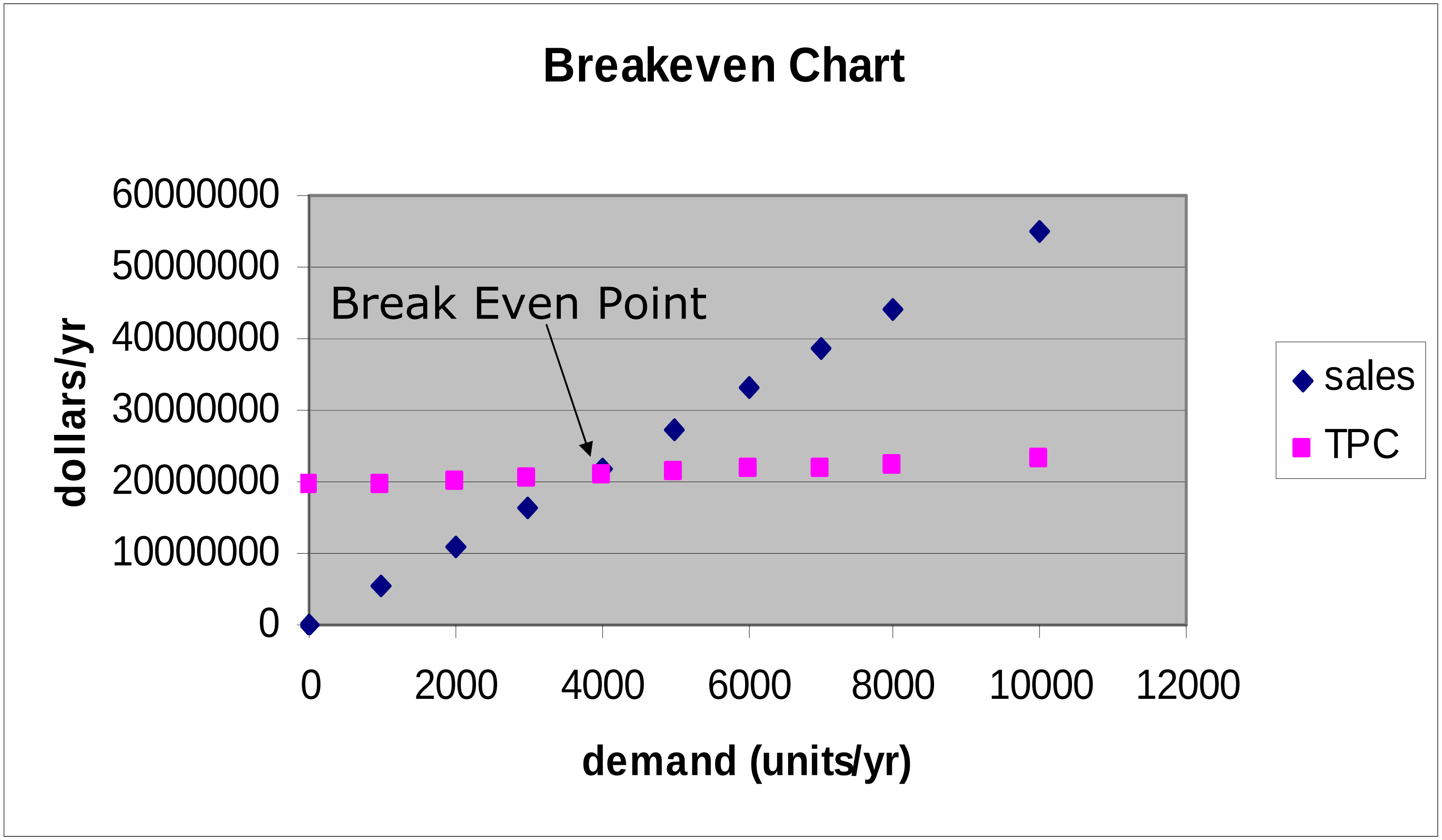
Avg. Noise (Db)	13
Power (W)	341
weight (lb)	9.94
length (ft)	1.017
width (ft)	0.95
height (ft)	1.034
cost $	5500

B-value: 0.75

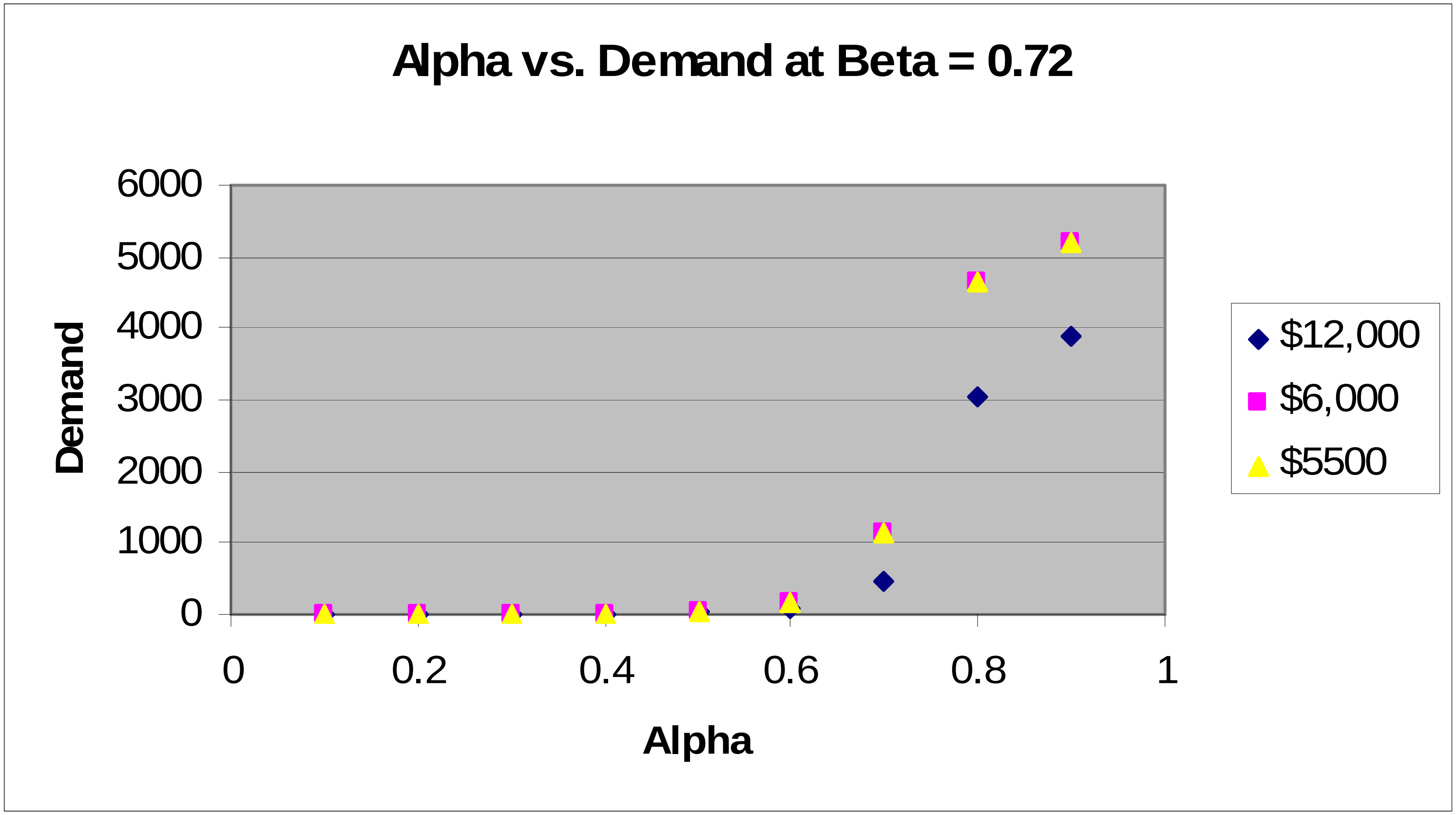
Optimal Design (cont.)



Break Even Analysis



Optimum Selling Price

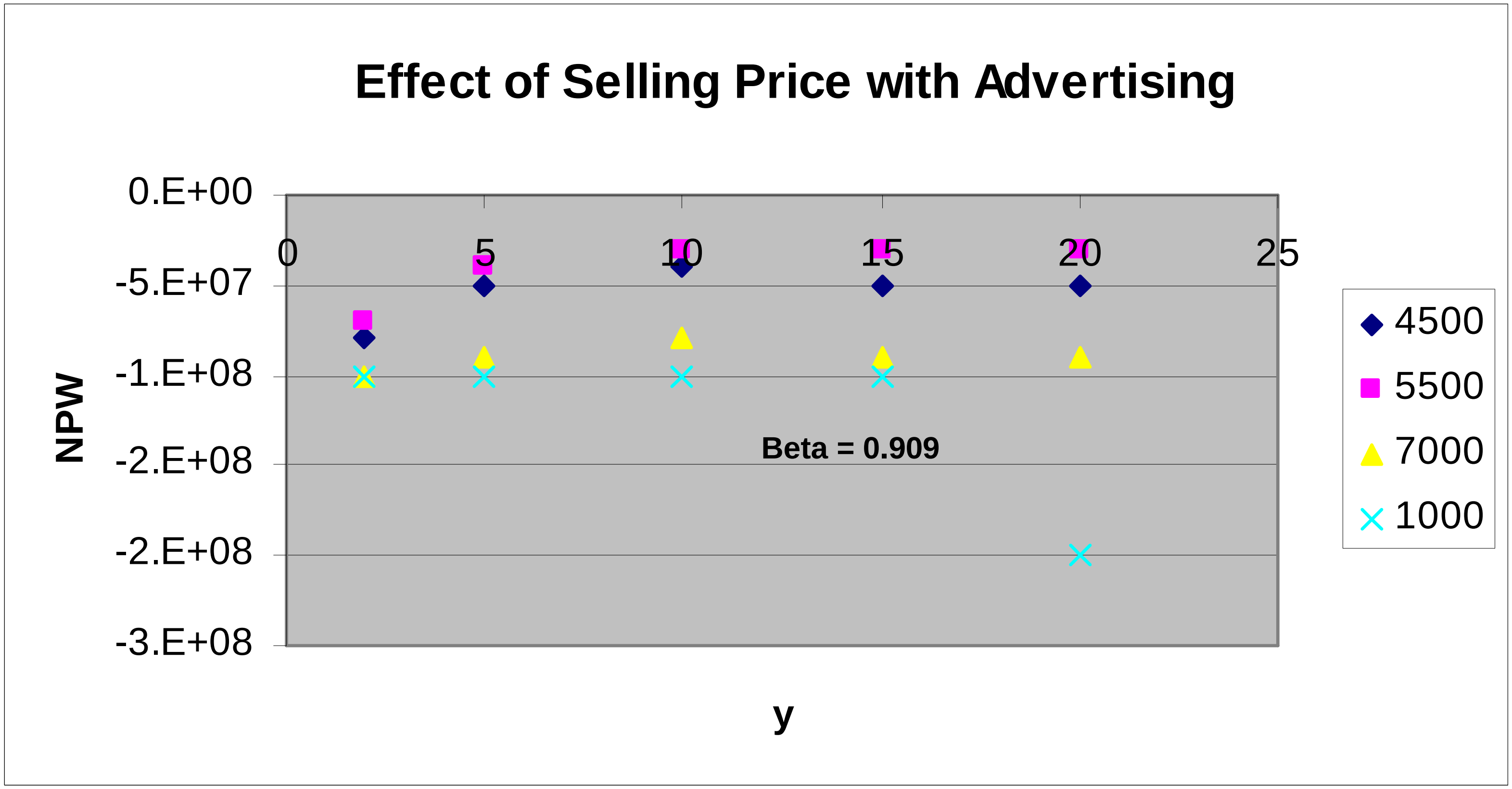


Conclusions

- Selling Price $5500
- Maximum Selling Price ~ $12000
- NPW of $3x10^6$
- Min. Production rate of 4000 units/yr
- Economic Model is not very efficient, and does not consider advertising costs

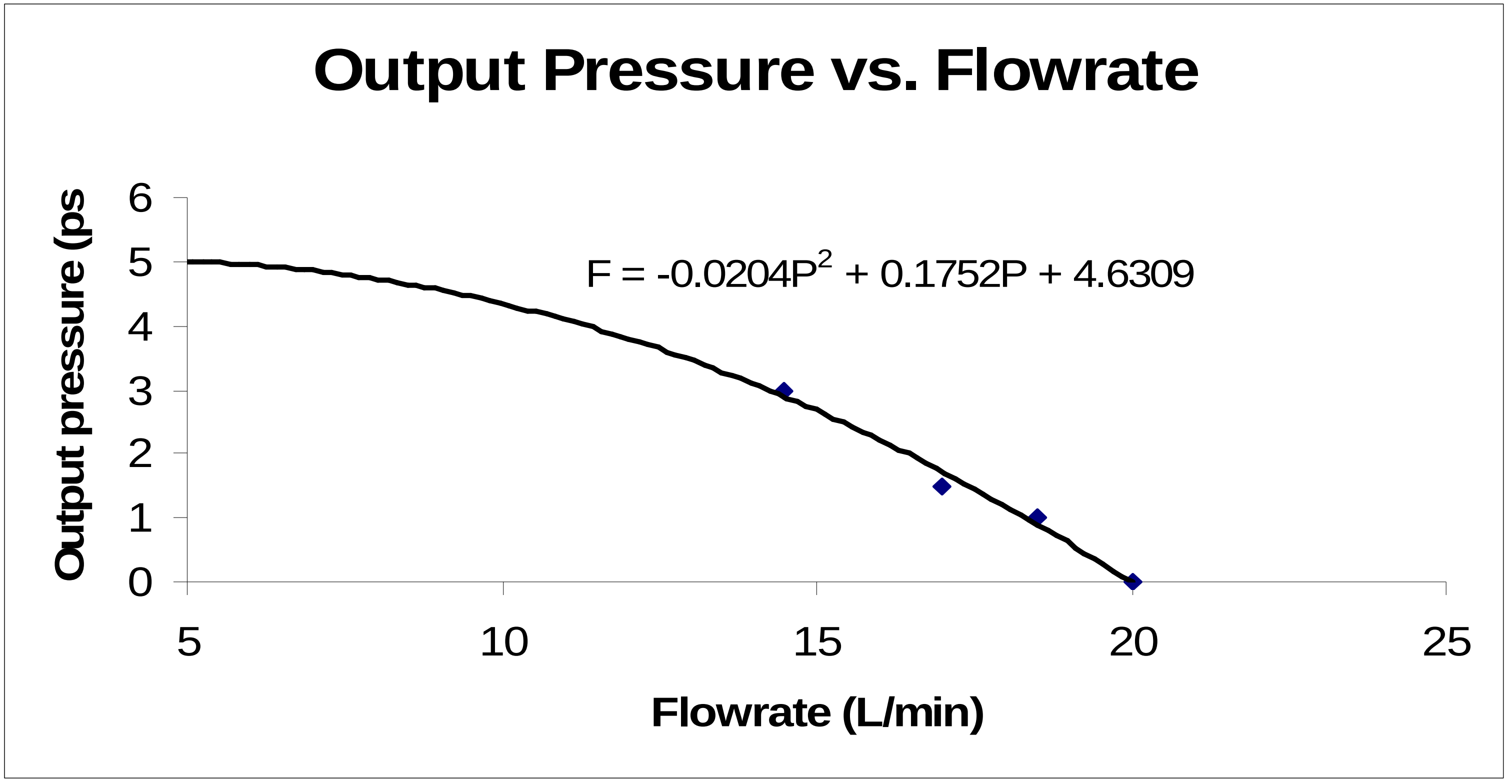
Any Questions?

NPW as a Function of Advertising Rate



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

Pump Performance



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

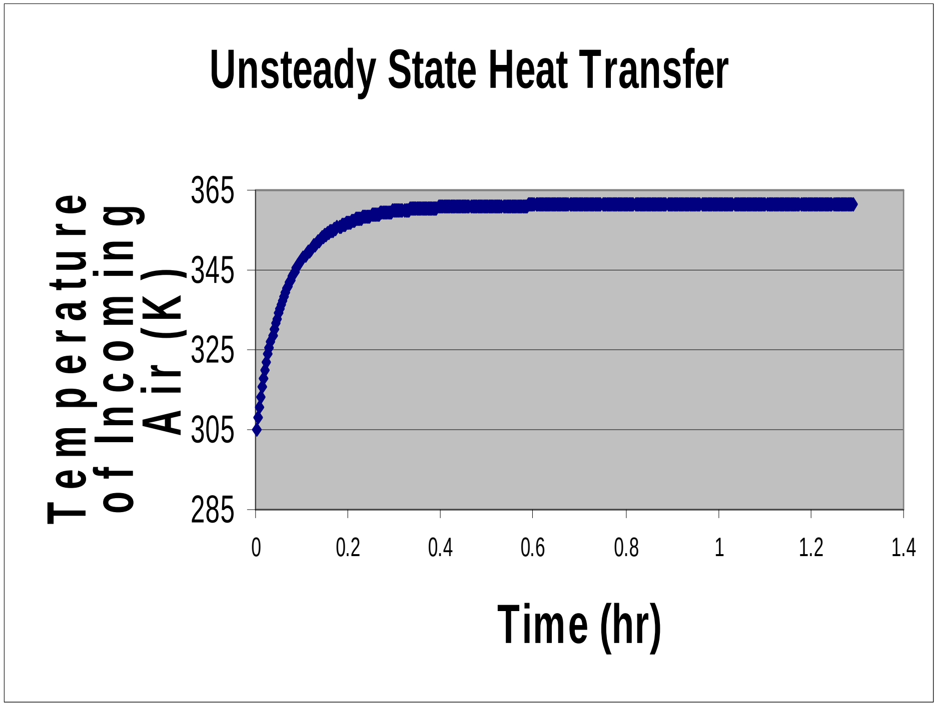
Unsteady State Assumptions

- During the time that the nichrome wire is heating up, there is negligible deviation of the bulk air temperature from the ambient

- The time for the system to heat up is limited by the time for the heat exchangers to reach steady state

Unsteady State Heat Transfer

- Assumed
  - "Plug Flow"
  - Heat is not transferred from exit of wire to beginning of HX
  - Instantaneous wire heating
- Space-time of .52 s
- Pulsed heating model
  - Model does not predict convergence.



Tetragonal v. Orthorhombic

- Tetragonal
  - $a = b \neq c$
  - $\alpha = \beta = 90°, \gamma = 120°$
- Orthorhombic
  - $a \neq b \neq c$
  - $\alpha = \beta = \gamma = 90°$

Membrane Stack

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

$$E_M = \frac{RT}{zF} \ln \frac{y_{O_2,h}}{y_{O_2,l}}$$ (Voltage)

$$P_M = E_M \times I_M$$ (Wattage)

Specifications

number of plates	208	plates
Temperature	585	C
total volumetric flow rate of permeate	5	L/min
molar gas volume (STP)	24.04	L/mol
molar flow rate of permeate/plate	0.00002	mol/s/plate
electron stoichiometry	4	mol electrons/mol O_2
Faraday constant	96485	C/mol electrons
Current	6.431	A
current density for BICUVOX.10	0.75	A/cm^2
total plate area required	9	cm^2
side length of square plates	3	cm
thickness of plates	0.38	cm
air gap height	0.4	cm
electrode height	0.2	cm
total cell stack height	287.24	cm
number of columns	8	
height per column	14.14	in
total potential for stack	11.923	V
power required	76.675	W
oxygen recovery from feed	0.80	%

Calculations				Cell	Formula
number of plates	208	*source*	plates	B7	
Temperature	550	*source*	C	B8	
total volumetric flow rate of permeate	5	*spec*	L/min	B9	
molar gas volume (STP)	24.04	*calc*	L/mol	B10	
molar flow rate of permeate/plate	0.00002	*calc*	mol/s/plate	B11	B9/B10/60/B7
electron stoichiometry	4	*source*	mol electrons/mol O_2	B12	
Faraday constant	96485	*source*	C/mol electrons	B13	
current	6.431	*calc*	A	B14	B11*B12*B13
current density for BICUVOX.10	0.75	*source*	A/cm^2	B15	
total plate area required	9	*calc*	cm^2	B16	B14/B15
side length of square plates	3.00	*calc*	cm	B17	SQRT(B16)
thickness of plates	0.38	*source*	cm	B18	
air gap height	0.40	*source*	cm	B19	
electrode height	0.2	*source*	cm	B20	
total cell stack height	287.24	*calc*	cm	B21	B7*B18+(B7+1)*B20+2*B7*B19
number of columns	4	*spec*		B22	
height per column	28.27	*calc*	in	B23	B21/(B22*2.54)
electrical potential for each cell	0.055	*calc*	V	B27	8.314*(B8+273)/2/B13*LN(0.99/0.21)
total potential for stack	11.436	*calc*	V	B28	B27*B7
power required	73.548	*calc*	W	B29	B28*B14