Portable Oxygen Generating Device Design

Membrane and Pressure Swing Adsorption Technology Alternatives and Market Analysis

Oxygen Design Group

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Introduction and Motivation

Oxygen Therapy

- Hypoxemia: Lungs provide insufficient oxygen to bloodstream
- Oxygen treatment prescribed by a physician
- Elderly and disabled persons are most frequent users of portable oxygen devices
- Oxygen flow rates range from 0.5-8 L/min

Existing Technologies

- Compressed Oxygen Tanks
- Liquid Oxygen
- Oxygen Concentrators

Compressed Oxygen

- Compressed oxygen is delivered tc patient in pressurized tanks
- No electricity, lightweight, high flow rates (>5 L/min)
- High purity
- Limited life of tanks
- Frequent tank replacement
- High-pressure tanks are hazardous

Liquid Oxygen

- Large, stationary tank at home
- User can fill smaller, lightweight (5-13 lbs) portable tank
- No electricity, high flow rates, quiet
- High purity
- Stationary tank must be refilled frequently by technician
- Liquid oxygen will evaporate over time

Oxygen Concentrators

- Electric oxygen system
- Provides oxygen by extracting it from the air
- Generally use pressure swing adsorption with zeolites
- Unlimited oxygen supply while connected to power source
- No refilling needed

Oxygen Concentrators

- Most are not portable
  - Size of a large suitcase
  - Weight is greater than 50 lbs.
- Requires 250-400 W of power
- Motor increases electricity costs
- Motor is loud (>50 decibels)
- Requires backup power

Oxygen Concentrators

- Oxygen purity ranges from 90-95%
- Flow rates range from 1-5 L/min
- Unable to achieve high oxygen flow rates (>5 L/min)
- Cost from $3,000-$5,000

Oxygen Concentrators

- *Lifestyle* portable oxygen concentrator is currently on the market
- Uses molecular sieve technology combined with an oxygen conserving technology
- Dimensions are 5.5 in x7.5 in x16.5 in
- Weighs 9.5 lbs
- AC, DC (automobile), and battery powered

Oxygen Concentrators

- Flow rates range from 1-5 L/min
- Only 90% ± 3% oxygen purity
- Produces 55 decibels
- Battery life only 50 minutes
- Takes 2-2.5 hours to charge battery
- Costs approximately $5,000
- Recalled, but still on market

Product Goals

- Current portable oxygen devices must be improved to increase performance and reliability
- Solid-oxide membrane and pressure-swing adsorption technologies will be investigated
- Develop a new portable oxygen device measuring 12”x7”x7” capable of achieving a 5 liter/minute flow rate and 94-99% oxygen purity

Product Goals

- 6 hour battery life
- 40,000 hour service life
- Less than 10 lb. in weight
- Low noise output
- Less than $2,000 unit production cost

Pressure Swing Adsorption Design

Pressure Swing Adsorption

- System of two packed columns with component-selective zeolite
- Two stages in alternation:
  1. Adsorption/Production
  2. Blowdown/Purge
- Turn two batch-phase processes into one continuous production process
- Requires compression of feed stream

Nitrogen Removal Design Equations

- Multi-Component Adsorption Isotherm (Langmuir-Freundlich)

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

Nitrogen Removal Design Equations

- Equilibrium-dominated (assume very fast mass transfer)

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

- Q_F = volumetric flow rate of feed
- c_F = concentration of solute in feed
- t_x = time front has traveled at L_x
- q_F = loading per mass of adsorbent in equilibrium with the feed concentration
- S = total mass of adsorbent in the bed
- L_x = position in the bed, less than or equal to total bed length
- L_b = length of bed

Specifications

- Production time of no less than fifteen seconds (total cycle time of thirty seconds)
- Column diameter of 2.5”

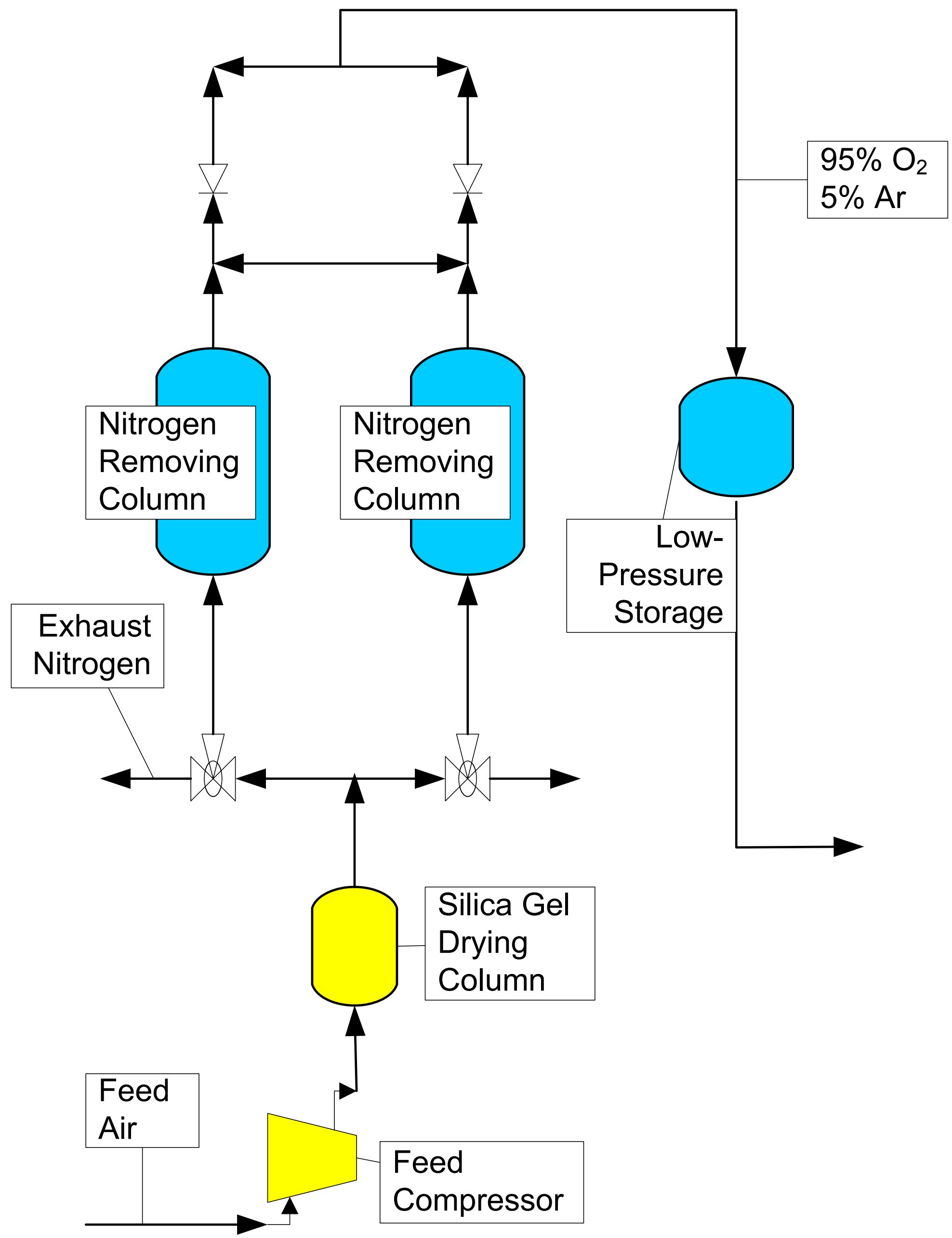
Results

- 2.1 lbs. Oxysiv 5 (13-X zeolite) adsorbent per column
- 2 columns of 2.5” diameter & 1.5 ft. height
- Product: 95% O_2 + 5% Ar
- Removal of argon still required to achieve 99% purity

Air Drying

- Moisture in air acts as poison to Oxysiv 5
- Water cannot be desorbed in the same cycle as nitrogen
- Silica gel used to remove moisture from air
- Gel regenerated by heat

Nitrogen Removal



Argon Removal Options

1. Equilibrium based PSA

2. Kinetic based PSA

Equilibrium-based PSA

- Feed of 95% O_2 + 5% Ar @ 10 atm
- Increase purity to 99.7% O_2 with Argon adsorption on silver mordenite (AgM)
- Requires moderate heating (30 C)
- Low selectivity necessitates longer beds or longer cycle times
- Approximately 20% recovery

Langmuir-Freundlich Adsorption Isotherms on AgM

$$T = 30^\circ\ \text{C.:}\ n_{Ar} = \frac{8.875 C_{Ar}}{1 + 0.0041 C_{Ar}}\ ;\ n_{O_2} = \frac{7.363 C_{O_2}}{1 + 0.00307 C_{O_2}}$$

$$T = 60^\circ\ \text{C.:}\ n_{Ar} = \frac{5.222 C_{Ar}}{1 + 0.0025 C_{Ar}}\ ;\ n_{O_2} = \frac{4.155 C_{O_2}}{1 + 0.00166 C_{O_2}}$$

$$T = 90^\circ\ \text{C.:}\ n_{Ar} = \frac{3.206 C_{Ar}}{1 + 0.00117 C_{Ar}}\ ;\ n_{O_2} = \frac{2.629 C_{O_2}}{1 + 0.00108 C_{O_2}}$$

Rate-difference based PSA

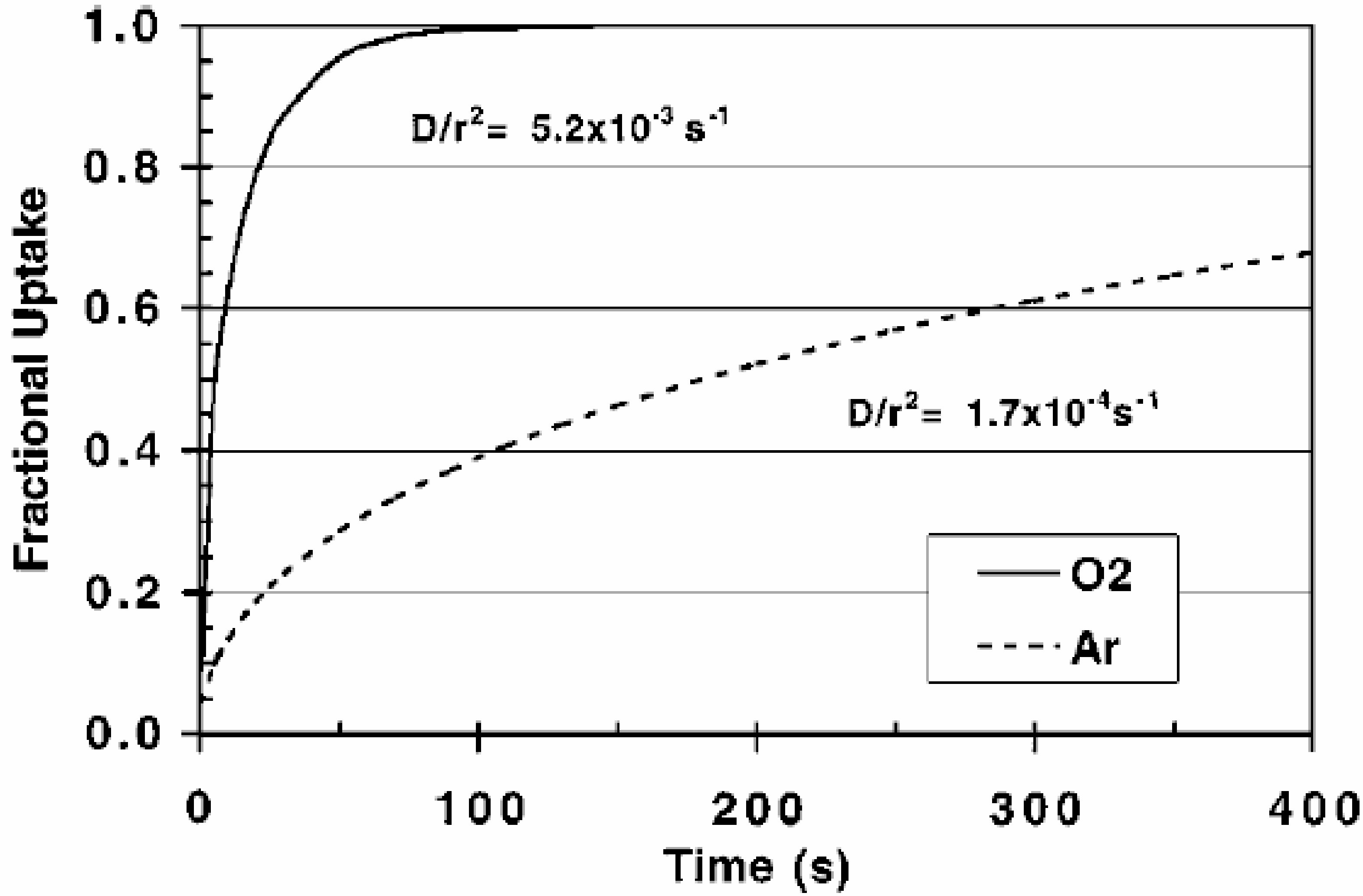
- Use carbon molecular sieve to adsorb oxygen
- Rate of adsorption of oxygen onto adsorbate is much faster than argon
- High purity oxygen obtained from blowdown step

Kinetic Separation Design Equations

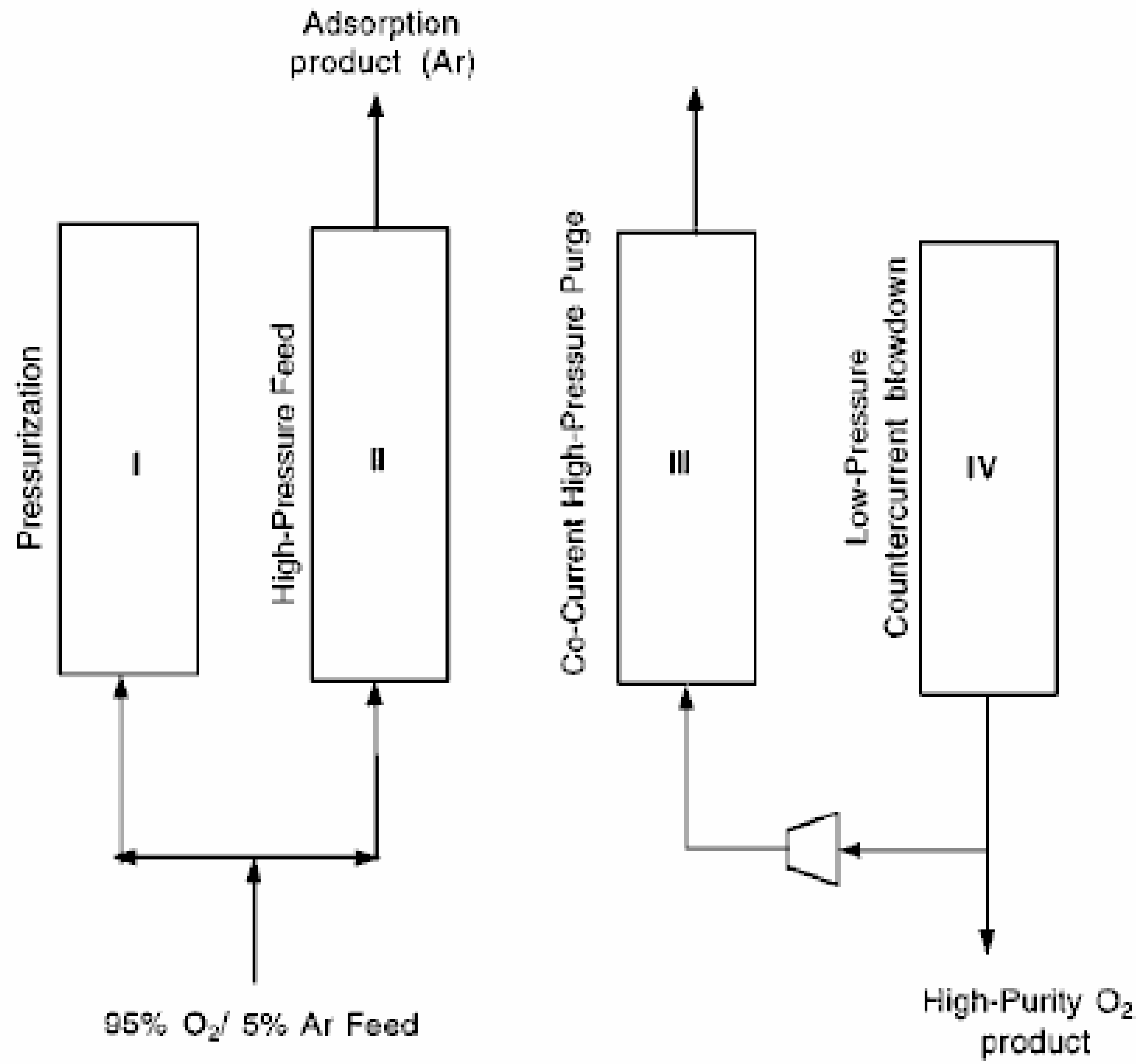
- Linear Driving Force Model

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

- t = time
- D_e = effective intraparticle diffusivity
- R_p = radius of particle
- q_{Rp} = loading at particle surface
- $\bar{q}$ = average loading of component on the adsorbent



1.0
0.8
0.6
0.4
0.2
0.0
Fractional Uptake
0
100
200
300
400
Time (s)
D/r²= 5.2x10⁻³ s⁻¹
D/r²= 1.7x10⁻⁴s⁻¹
O2
Ar



Adsorption
product (Ar)
Pressurization
I
High-Pressure Feed
II
Co-Current High-Pressure Purge
III
Low-Pressure
Countercurrent blowdown
IV
95% O2/ 5% Ar Feed
High-Purity O2
product

Operating Conditions

- Adsorption at 2 atm
- Blowdown at 0.2 atm
- 99.0% pure oxygen
- 55% recovery
- 0.01157 kg product/hr / kg adsorbent

Adsorption Data

Run No.	P_H (atm)	P_L (atm)	Interstitial feed velocity U_F (m/s)	Interstitial purge velocity U_P, (m/s)	Adsorption product (O_2) % purity	Adsorption product (O_2) % recovery	Adsorption product (O_2) throughput (kg of product/h/kg of adsorbent) $\times 10^3$
1	1.0	0.1	0.8	0.20	97.86	82.52	10.08
2	1.0	0.1	0.8	0.60	98.93	63.99	7.78
3	1.0	0.1	0.8	1.00	99.33	43.17	5.23
4	1.0	0.2	0.8	0.20	97.81	76.36	8.62
5	1.0	0.2	0.8	0.60	98.87	55.71	6.27
6	1.0	0.2	0.8	1.00	99.30	32.98	3.69
7	2.0	0.2	1.0	0.10	97.75	70.29	17.58
8	2.0	0.2	0.8	0.60	99.07	52.22	11.57
9	2.0	0.2	1.0	0.80	99.30	36.64	8.98

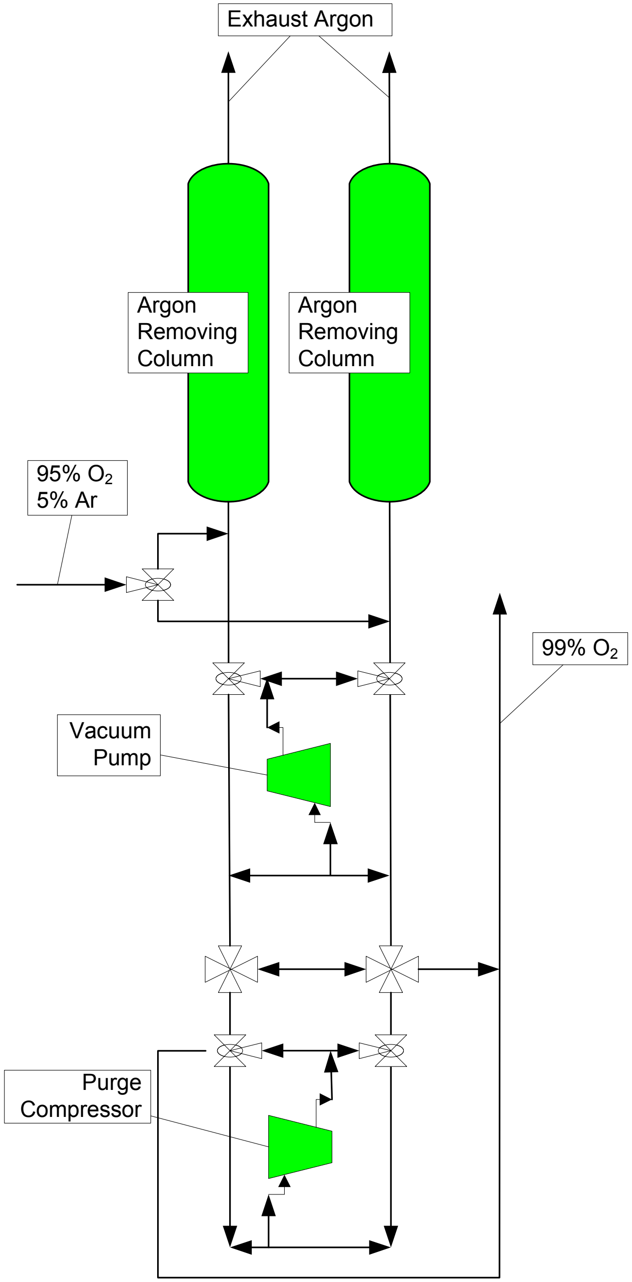
Equilibrium or Kinetic?

- Carbon molecular sieve separation will yield acceptably pure oxygen with a higher recovery than AgM equilibrium based PSA.
- Molecular sieve separation will also be less energy intensive (smaller pressure change, no heating required)
- Molecular sieve separation is the most attractive option for PSA based oxygen & argon separation

Results from Kinetic Separation

- 74 lbs. adsorbent per column required for 5 L/min
- 2 columns of 6” diameter and 4.5 ft height
- Feed rate of 9.9 L/min
- Product rate of 5 L/min, 99% O_2 at 1 atm.

Argon Removal



Impact on Nitrogen Removing Section

- Required production of 9.9 L/min
- Assuming 10% of product used as purge, requires initial air feed rate of 79.2 L/min
- Feed compressed initially to 45 psia.
- Product pressure let down to 2 atm before entering argon removing section

PROBLEM!

- Device is too heavy and too large to be portable
- No demand for non-portable device that only provides for one user
- Device must be modified to be useful to oxygen patients

Solution: Compressed Oxygen

- Patients use small cylinders filled with highly compressed 99% pure oxygen

Compressed Oxygen

- Cylinders (E-size) filled to 2200 psi and provide oxygen without power source
- Can provide any flow rate
- At flow of 5 L/min, 1 cylinder lasts about 205 minutes

Compressed Oxygen

- Cylinders are not reusable
- Patient has new cylinders delivered by company
- Patient must work around delivery schedule
- Patient limited by number of cylinders delivered

Market Niche

- Currently, no device exists that allows patient to refill cylinders with 99% pure oxygen
- An un-fulfilled demand exists for a modified version of our device that allows in-home cylinder bottling
- Eliminates need for delivery company

Modified Device

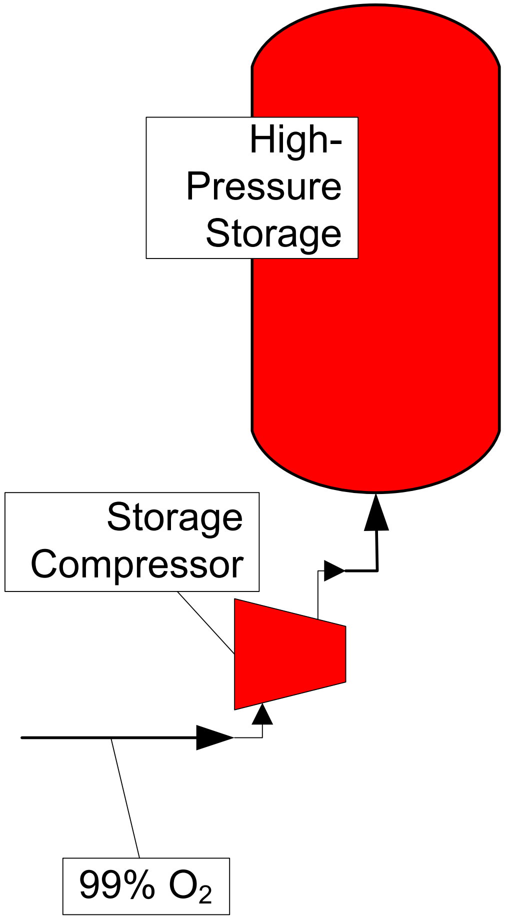
- Must pressurize product
- Product stored in high-pressure storage tank to allow rapid filling of cylinders
- Storage tank capable of filling 2 cylinders at a time

High-Pressure Storage

- H-size aluminum cylinder
- Volume: 58 L
- Initial pressure: 3021 psi
- Final pressure: 2500 psi
  - Allows small amount of emergency oxygen
  - Ensures higher pressure than small cylinder

High-Pressure Storage

- Tank connected to cylinder by ¼” diameter 6” long smooth pipe
- Fill times:
  - 1st cylinder: 5.1 seconds
  - 2nd cylinder: 5.2 seconds



High Pressure Storage

User needs

- So long as user does not breathe more than 5 L/min continuously for 413 minutes (6 hrs 53 minutes), device can produce as fast as user consumes

Breathing rate (L/min)	5.0	4.0	3.0	2.0
Minutes to use up small tank	206.5	258.2	344.2	516.3
Hours to use up small tank	3.4	4.3	5.7	8.6
Minutes to use up both tanks	413.1	516.3	688.4	1032.7
Deadtime for device	0.0	103.3	275.4	619.6

Final Product

- Produces 99% pure medical O_2
- Allows user to refill E-size oxygen cylinders 2 at a time (based on average continuous consumption of 5 L/min or less)
- Non-portable, A/C powered
- Enough silica gel to dry one bottling cycle
- Gel regenerated by heating element embedded in canister

Power Requirements

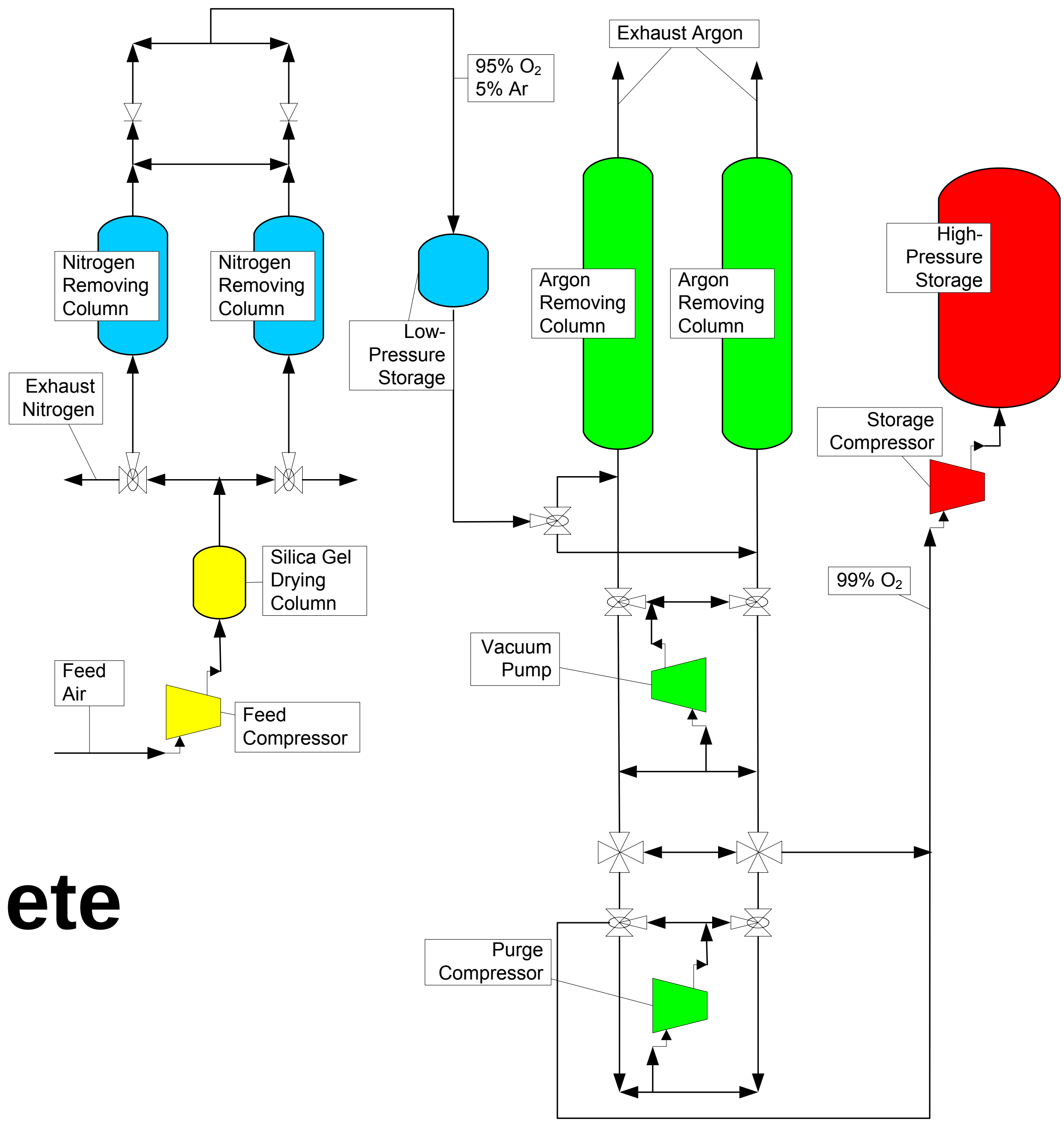
- 4 Compressors

	Flow rate (L/min)	Inlet Pressure (psi)	Outlet Pressure (psi)	Duty (hp)
Feed Compressor	80	14.7	45	0.5
Purge Vacuum	7.987	29.4	2.94	0.0248
Purge Compressor	2.987	14.7	29.4	0.1429
Storage Compressor	5	14.7	3021	3

Power Requirements

- Total Power Consumed: 2.74 kW (3.67 hp)
- Assume device is producing only 12 hours per day
- Monthly power consumption: 1018 kWh
- **Operating cost per month: $76.03**
  - Much less than $300/month charged by delivery companies

Complete PFD

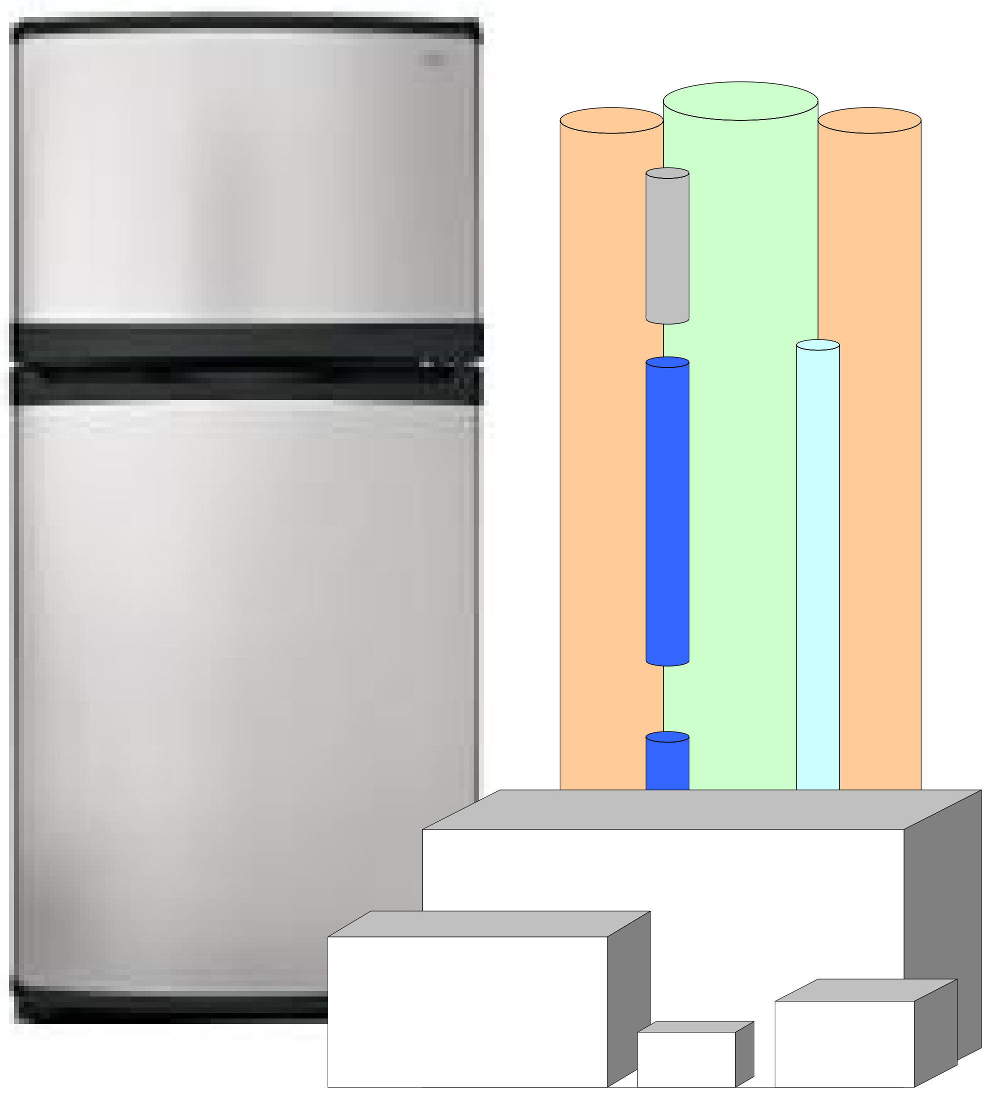


Parts Breakdown	Weight	N2 removal	Ar removal	Combined Weights
Metal	lb/ft2	ft2	ft2	Total Weight (lbs)
Adsorption Columns (Sch. 40 Aluminum)	1.5	2.13	14.88	25.51
Low Pressure Storage Tank (Sch. 40 Alum	1.5	1.13		1.70
Dryer canister (Sch 40 Aluminum)	1.5	2.30		3.45
Frame (Steel)	3	10.00		30.00
Piping	lb/ft	ft	ft	Total Weight (lbs)
1/2" Sch. 40 Copper	0.75	3	6	6.75
Packing	lb/column	columns	columns	Total Weight (lbs)
Oxysiv 5 adsorbent	2.1	2		4.20
CMS packing	74		2	148.00
Silica Gel drying gel	4.9	1		4.90
Items	lb/item	Number of items	Number of items	Total Weight (lbs)
Feed Compressor	45	1		45.00
Vacuum Pump	2		1	2.00
Purge Compressor	11		1	11.00
Tank fill Compressor	85		1	85.00
High Pressure Storage Tank	135		1	135.00
Fan	0.5	2	2	2.00
3-way solenoid valve	1.5	2	2	6.00
Check valve	1.5	2	2	6.00
Computer	1	1		1.00
Casing	8	1		8.00
Total Final Weight				**525.51**

Parts Breakdown	Price	N2 removal	Ar removal	Combined Costs
Metal	$/ft2	ft2	ft2	Total Cost
Adsorption Columns (Aluminum)	1.5	2.13	14.88	$ 25.51
Low Pressure Storage Tank (Aluminum)	1.5	1.13		$ 1.70
Dryer canister (Aluminum)	1.5	2.30		$ 3.45
Frame (Steel)	2	30.00		$ 60.00
Piping	$/ft	ft	ft	Total Cost
1/2" Sch. 40 Copper	3.6125	3	6	$ 32.51
Packing	$/lb	lb	lb	Total Cost
Oxysiv 5 adsorbent	5.5	4.21		$ 23.16
CMS packing	3		148	$ 444.00
Silica Gel drying gel	2	4.9		$ 9.80
Items	$/item	Number of items	Number of items	Total Cost
Feed Compressor	230	1		$ 230.00
Vacuum Pump	100		1	$ 100.00
Purge Compressor	150		1	$ 150.00
Tank fill Compressor	2500		1	$ 2,500.00
High Pressure Storage Tank	150		1	$ 150.00
Fan	5	2	2	$ 20.00
3-way solenoid valve	86	2	2	$ 344.00
Check valve	20	2	2	$ 80.00
Computer	20	1		$ 20.00
Casing	40	1		$ 40.00
Total Final Cost				**$ 4,234.13**

Final Sizes

- Compressor box
  - Height: 15”
  - Width: 30”
  - Depth: 25”
- Column Tower
  - Height: 55”
  - Width: 21”
  - Depth: 12”
- Complete Device
  - Height: 55”
  - Width: 30”
  - Depth: 37” (base), 12” (tower)
- Slightly smaller than a regular freezer/refrigerator



Membrane Design

Membranes

- Semi-permeable barriers
- Use the differences in the abilities of the components to pass through the membrane
- Permeate
  - Passes through the membrane
  - Enriched in the fast component
- Retentate
  - Does not pass through the membrane
  - Enriched in the slow component

Membrane General Equation

- The general equation for flux of component *i* through a membrane is given by

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

  - P_i is the permeability of component *i* through the membrane material
  - *l* is the thickness of the membrane
  - the driving force required to induce the flux varies for membrane applications and materials

Membranes for Gas Permeation

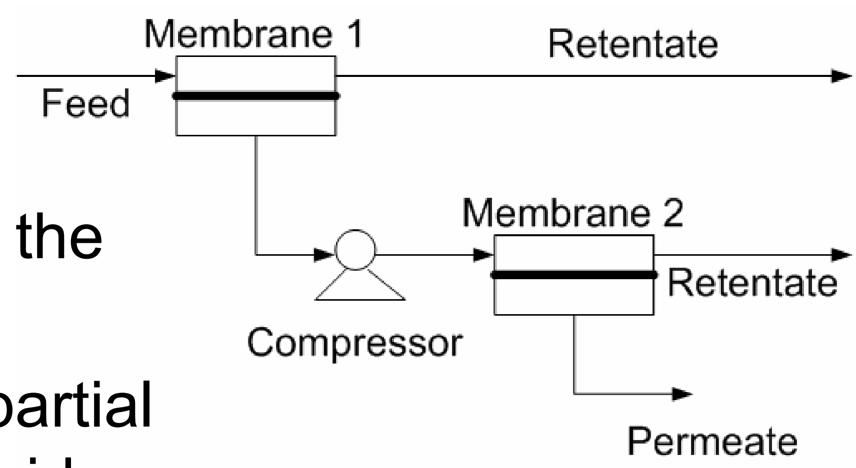
- Polymers
  - Used industrially to produce N_2 from air
- Ceramic Oxides
  - Can produce a high purity oxygen stream at high temperatures
  - Mixed Conducting
    - Conducts ions and electrons
  - Ionic
    - Transports ions

Polymers for Oxygen Separation from Air

- Polycarbonate is very selective membrane material (7.47 $0_2/N_2$) with permeability of 1.36E-10 cm^3(STP) cm/ cm^2 s cmHg
- For 100% recovery of O_2, the maximum concentration is 88%
- For a portable sized device, recovery of oxygen is ~10%
- Countercurrent permeate stream ~40% oxygen
- The feed flow rate requirement can be reduced if concentration is decreased
- Design is a tradeoff between oxygen concentration and feed flow rate

Design Enhancement Options

- Cascades can be used to increase composition
- The size of the design increases significantly with the each series module
- Purge stream can reduce partial pressure on the permeate side
- The purge stream enhances the flux of oxygen but contaminates the permeate stream



Polymers for Argon Separation from 95% Oxygen PSA Stream

- TMPC and PPO
  - Oxygen permeability: 3.98E-10 and 1.14E-09 cm^3(STP) cm/cm^2 s cmHg
  - Oxygen/argon selectivity: 2.43 and 2.28
- The operating pressures are 3 atm on the feed side and 1 atm on the permeate side
- 40 micron membrane thickness

Polymers for Argon Separation from 95% Oxygen PSA Stream

- Using a single membrane module, the highest permeate oxygen concentration is 97.35% using TMPC
- The concentration is limited by the low partial pressure difference, i.e, both concentration and pressure differences are low
- The permeation rate is low so recovery is small
- For a module with diameter of 7.48 in. and height of 10.24 in., 1300 lpm of feed are required to produce 5 lpm of oxygen product
- The device size increases as the feed flow rate is decreased

Ideal Polymer Membranes

- Hypothetical membrane with permeability of TMPC selectivity of 7.75 for oxygen, then 99% purity could be obtained in a single module
- Flow rate considerations are still a factor
- For a reasonable feed flow rate of 15 lpm, the device should be 8.2 ft. in diameter and 3,281 ft. long which is approximately 2.5 times the height of the Empire State Building

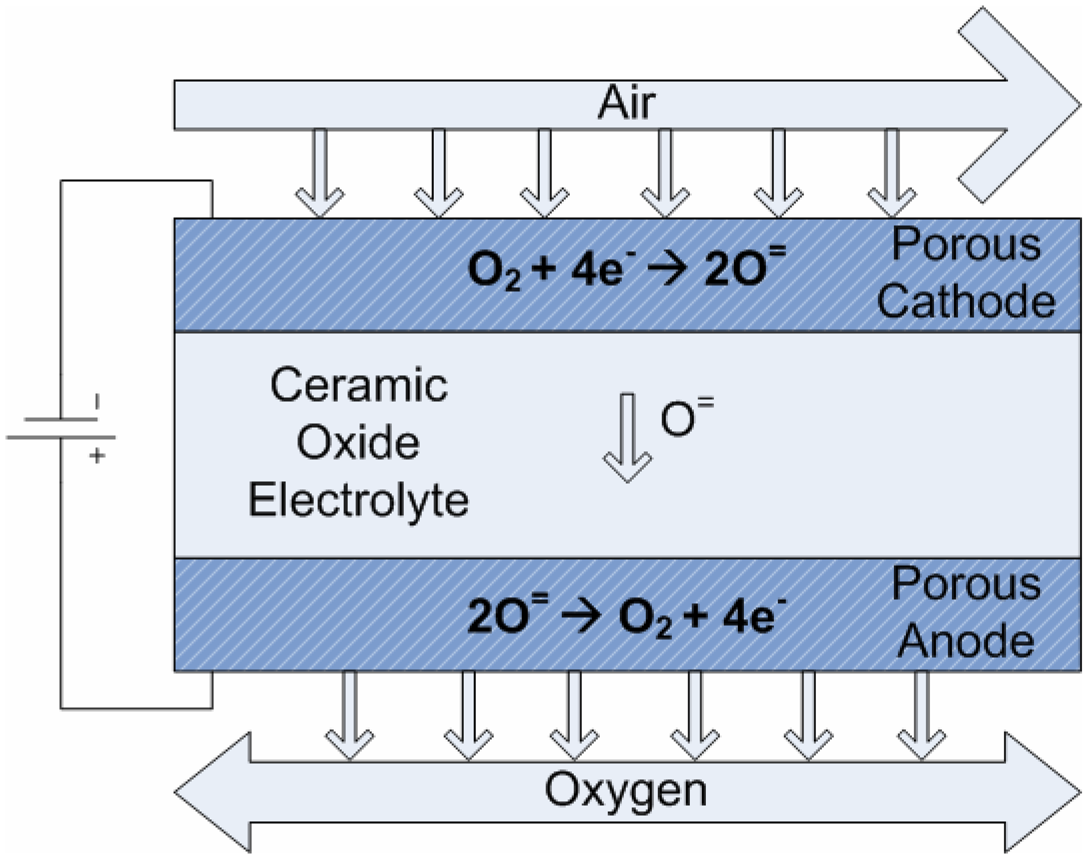
Mixed Conducting Membranes

- LSCF ceramic
- Feed pressure of 1 atm
- Vacuum pressure of 0.01 atm
- Operating temperature 1273 K
- Oxygen permeate flux is 0.00225 mol m^{-2} s^{-1}
- Oxygen recovery from the feed is 95%
- Need 16,500 cm^2 membrane area to produce 5 lpm

Ionic Ceramic Oxide Membranes

- Electrically driven by an external voltage source
- High temperatures
- Only allow oxygen flux
- Driving force is independent of the pressure

Ionic Ceramic Oxide Membrane Operating Principle



Ionic Conducting Ceramic Materials

- Yttria-stabilized zirconia (YSZ)
  - most commonly used
  - temperature range is 800-1000^{o}C
- Doped ceria
- Oxygen-deficient perovskites
- BIMEVOX ceramics
  - bismuth vandates with metals such as zinc, copper, and cobalt substituted for portions of the vanadium
  - oxygen flux similar to YSZ
  - temperature range is 400-600^{o}C
  - reduces the requirements for heating the cells, cooling the exhaust streams, and insulating the apparatus

BIMEVOX

- Boivin, et al studied the performance of different BIMEVOX electrolytes
  - BICUVOX
  - BICOVOX
  - BIZNVOX
  - all three exhibit current densities up to 1 A/cm^2
- Xia, et al report that BICUVOX.10 ionic conductivities are 50-100 times higher than other solid electrolytes
- BICUVOX.10 is chosen as the electrolyte material

Modeling of Membrane Performance

- Used experimental results for BICUVOX
- Electrochemistry equations used to design the membrane
- Specified the desired volumetric flow rate of oxygen
- Chose number of membrane plates and their thickness

Membrane Current

- Faraday relationship used to determine the current requirement

$$I = \frac{4QF}{n}$$

  - 4 is the number moles of electrons required to dissociate 1 mole of oxygen molecules
  - Q is the molar flow rate of the oxygen permeate
  - F is the Faraday constant, 96485 C/mol electrons
  - n is the number of membrane sheets.

Membrane Area

- Area required is based on the current density of the membrane material
- BICUVOX.10 at 585°C has a current density of approximately 0.75 cm^2/A
- The current multiplied by the current density gives the membrane area required
- Total membrane area is divided by the number of sheets gives the area of each sheet
- The model equations assume that each sheet is square

Membrane Voltage

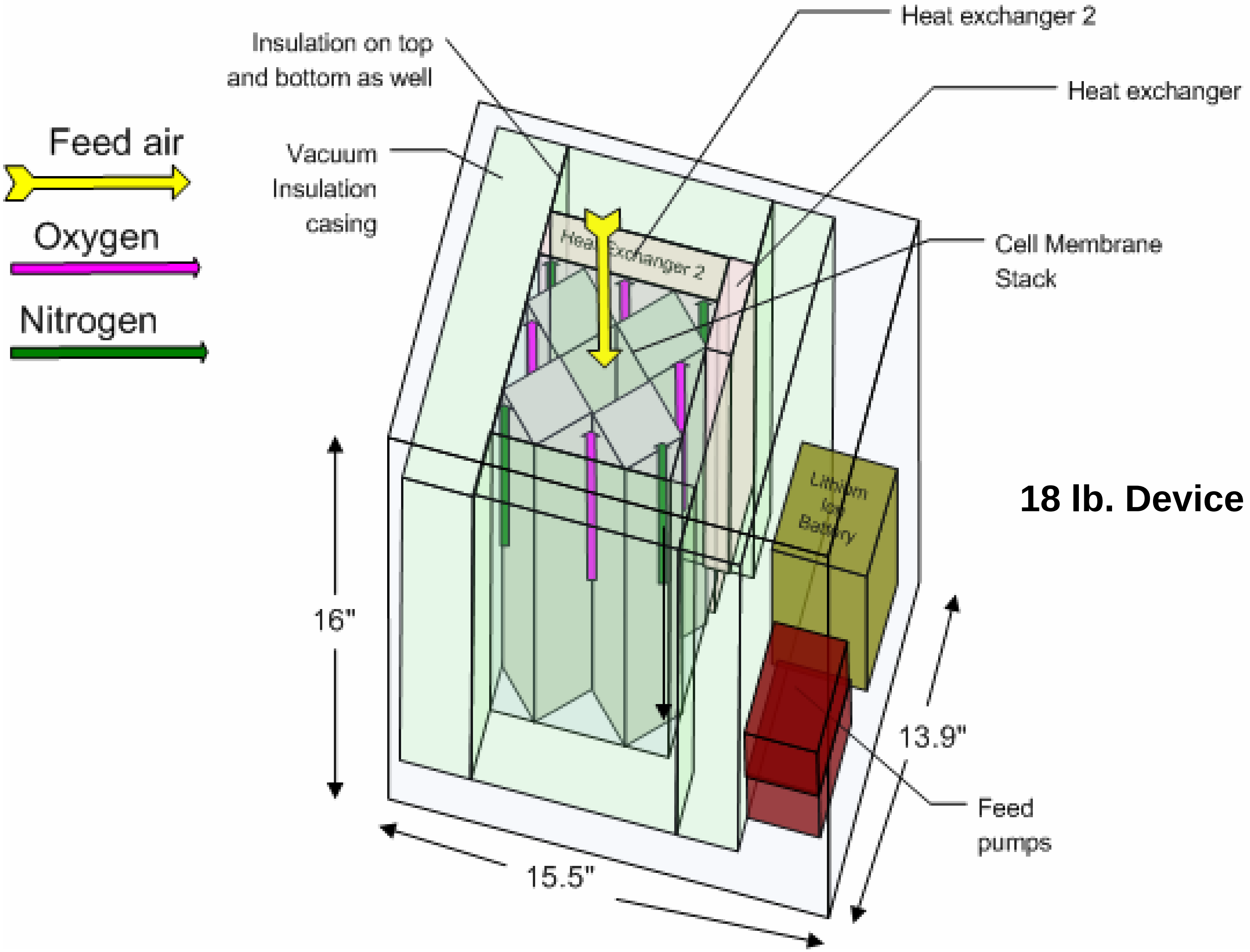
- The voltage drop across each membrane, *E*, is calculated using the Nernst potential,

$$E = \frac{RT}{zF} \ln \frac{y_{O_2,h}}{y_{O_2,l}}$$

  - *R* is the ideal gas constant
  - *T* is the operating temperature
  - *z* is the number of electrons required per ion
  - *F* is the Faraday constant
  - y_{O2} is the concentration of oxygen
  - the subscripts *h* and *l* refer to the high and low concentration sides of the membrane

Total Device Components

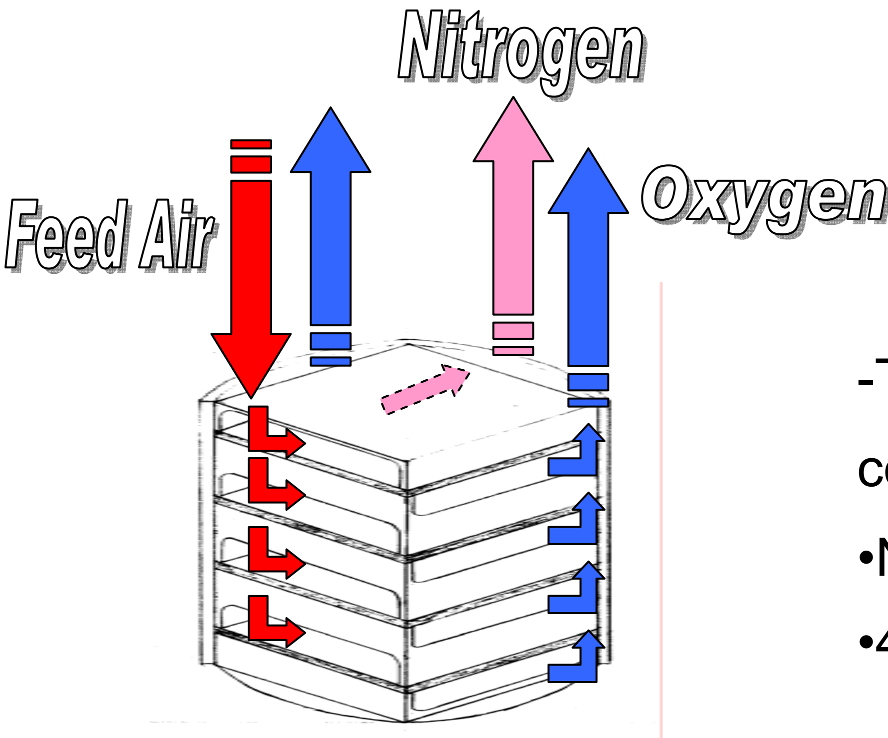
- Membrane Stack
- Heating Element
- Heat Exchangers
- Insulation
- Pumps
- Battery
- Sealant
- Case



Feed air
Oxygen
Nitrogen
Insulation on top and bottom as well
Vacuum Insulation casing
Heat exchanger 2
Heat exchanger 1
Heat Exchanger 2
Cell Membrane Stack
Lithium Ion Battery
Feed pumps
16"
15.5"
13.9"

18 lb. Device

Membrane Design



•Initial design: 9 plates (5.5" x 5.5")

- •Current = 149 A
- •Voltage = 0.52 V
- •Power = 76.7 W

$$\boxed{I_M = \frac{4QF}{n}}$$

-To reduce the amps, a different configuration was suggested.

•New design: 48 plates (2.4" x 2.4")

•4 stacks with 12 cells per stack

- •Current = 28 A
- •Voltage = 2.75 V

Membrane Design

Calculations		
number of plates	48	plates
total volumetric flow rate of permeate	5	L/min
molar gas volume (STP)	24.04	L/mol
electron stoichiometry	4	mol electrons/mol O_2
current	27.868	A
current density for BICUVOX.10	0.75	A/cm^2
thickness of plates	0.38	cm
air gap height	0.75	cm
electrode height	0.2	cm
number of columns	4	
height per column	9.85	in
volume of plates	41.36	in^3
density of ceramic*	0.21	lb/in^3
mass of ceramic	8.60	lb
total potential for stack	2.751	V
power required	76.675	W
oxygen recovery from feed	0.80	
feed flow rate	30	L/min

Additional Design Criteria

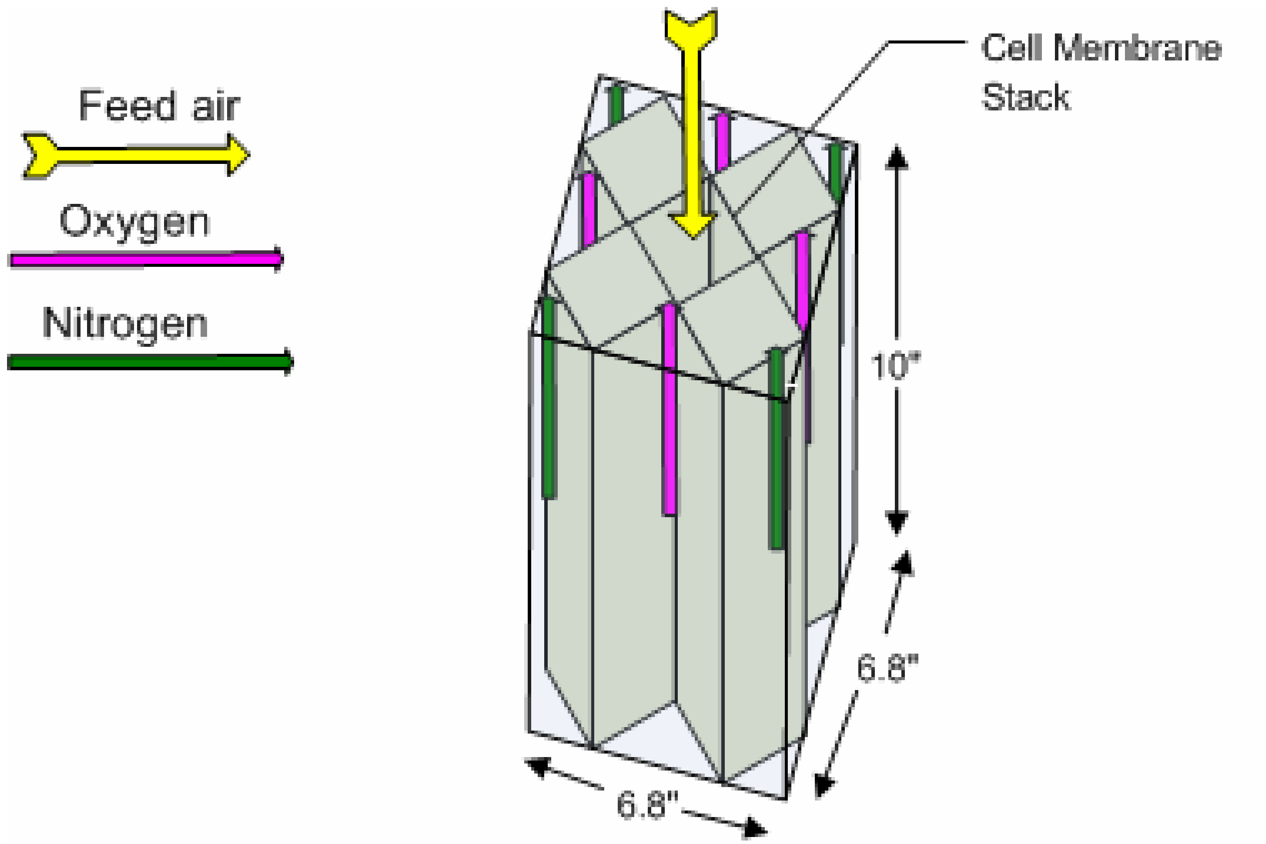
$$I_M = \frac{4QF}{n}$$

$$E = \frac{RT}{zF}\ln\frac{y_{O_2,h}}{y_{O_2,l}}$$

Nernst equation determines voltage across each membrane

The density of Bicuvox was estimated at 5.75 g/cm^3 based on the densities of the similar ceramic materials Y-TZP, Vanadium Carbide, and Zirconia.

Cell Stack Design



- Magnesium Oxide Housing

Heating Element

- The ionic conduction membrane begins conducting at 585 ^{o}C
- Nichrome-60 heating element
- 3 wires 4.8” long located in inlet air stream
- Heating element power is 66 W

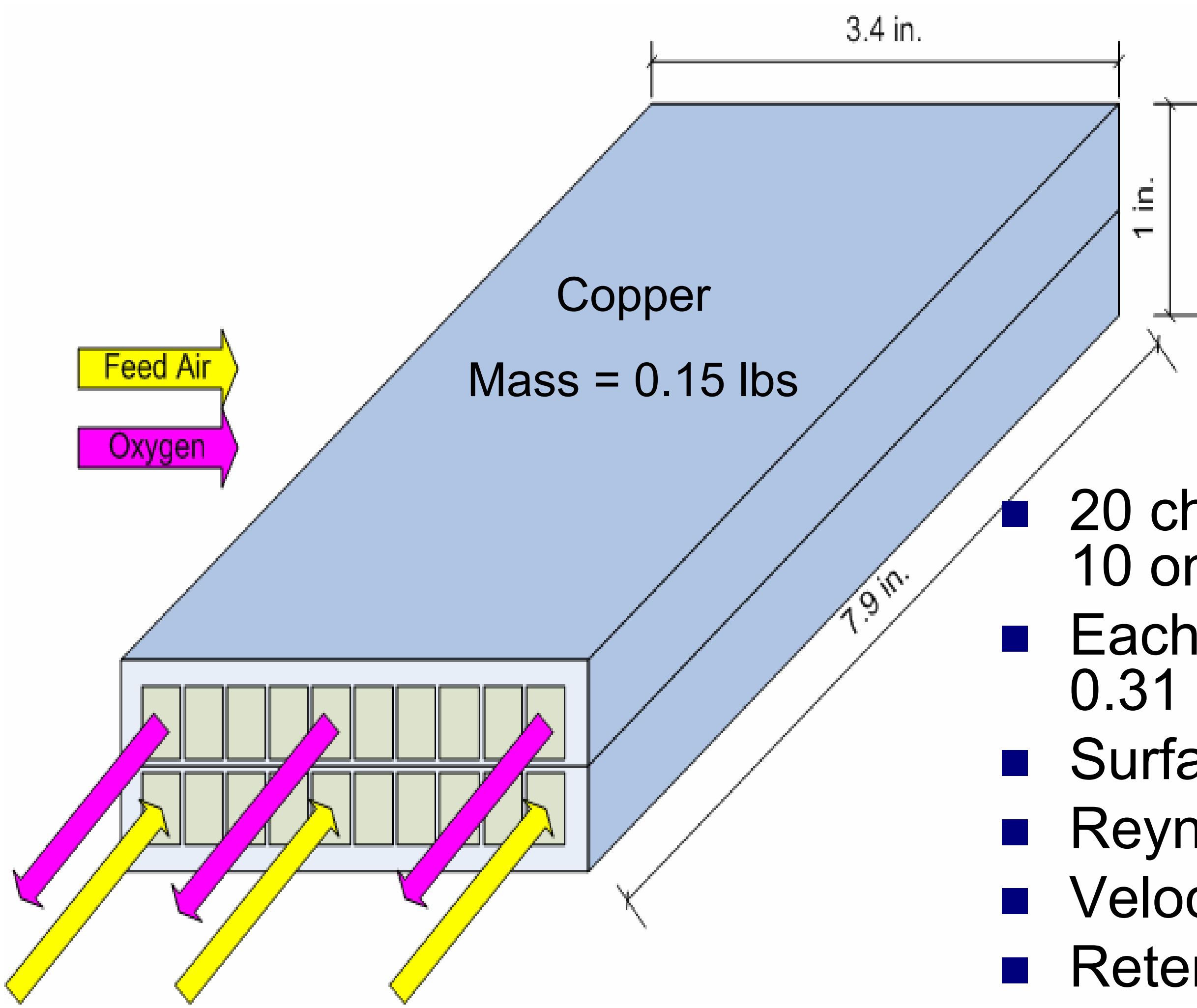
Heating Element Criteria

wire design: 3 vertical wires along the feed stream		
wire length/air entry point	4.80	in
current/length of wire to heat wires to 585 C	4.58	A/ft
current for 3 parallel sets of resistors in parallel, I_H	5.50	A
resistance/length of wire	1.82	ohm
resistance of each wire	0.7276	ohm
price/length of wire	0.80	$/ft
price of wires	0.96	$
weight/volume of wire	0.30	lb/in^3
diameter of 24 gauge wire	0.20	in
total weight of wires	0.36	lb
equivalent resistance of 3 wires in parallel, R_H	2.18	ohm
assume start up time	20	min

Heat Exchanger

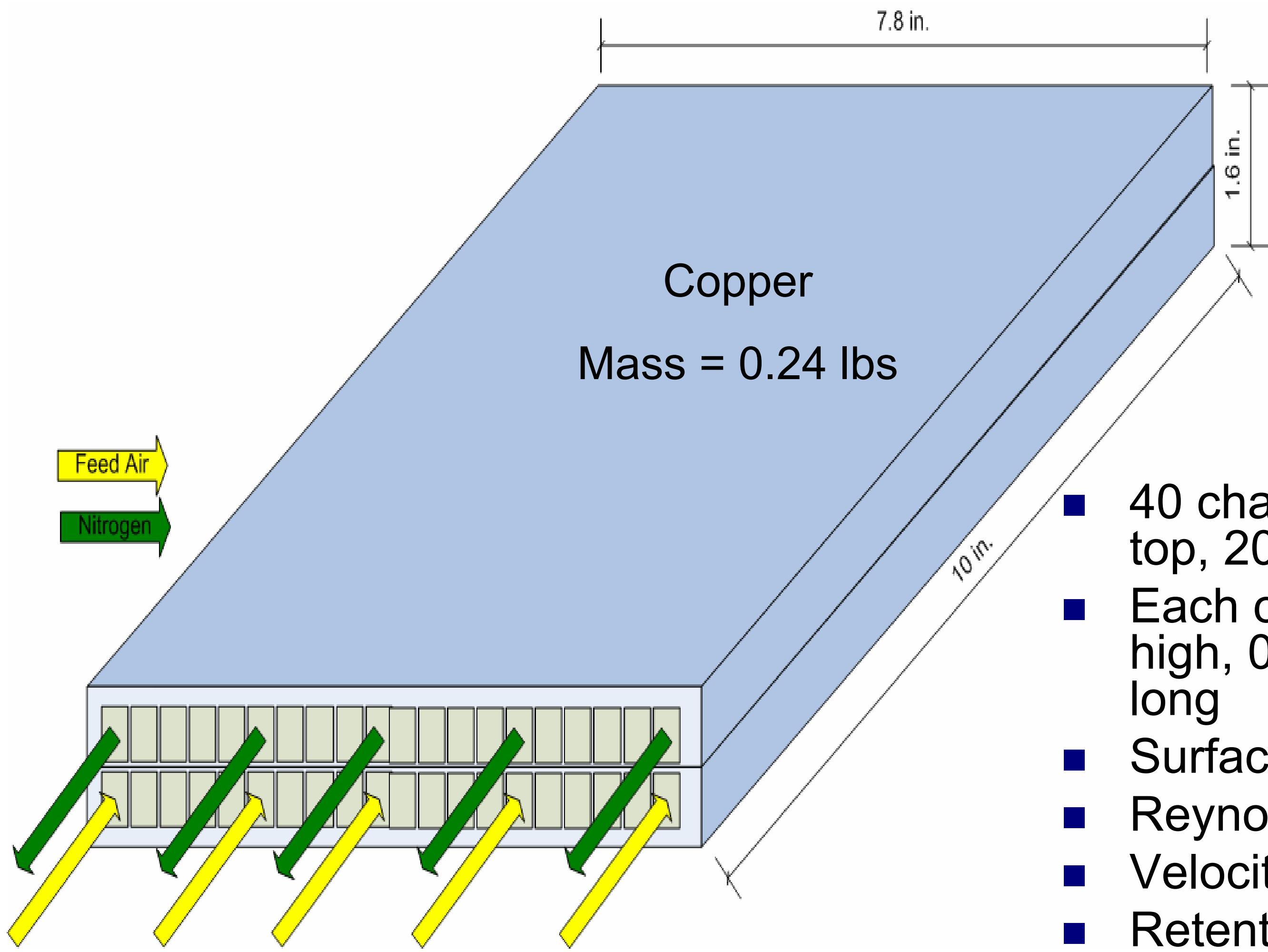
- Membrane stack operates at 600ºC
- Incoming 30 L/min feed air stream used to cool exiting 5 L/min oxygen and 25 L/min nitrogen streams
- Two microchannel heat exchangers needed
- Oxygen and nitrogen streams both exit the exchangers at 41ºC, and the feed enters the stack at 580ºC

Oxygen & Air Exchanger



- 20 channels total (10 on top, 10 on bottom)
- Each channel is 0.4 in. high, 0.31 in. wide, 7.9 in. long
- Surface area = 0.56 ft^2
- Reynolds number = 19
- Velocities = 10.4 cm/s
- Retention time = 1.9 sec.

Nitrogen & Air Exchanger



- 40 channels total (20 on top, 20 on bottom)
- Each channel is 0.7 in. high, 0.37 in. wide, 10 in. long
- Surface area = 2.9 ft^2
- Reynolds number = 34
- Velocities = 12.9 cm/s
- Retention time = 1.9 sec.

Method

- Required heat transfer area was found from double-pipe exchanger overall heat transfer coefficient
  - Air and oxygen = 0.11 ft^2
  - Air and nitrogen = 1.8 ft^2
- Dimensions of each exchanger were found by varying the length, width, and height of each channel while simultaneously varying the number of channels to achieve the required surface area for each device
- Outer wall thickness set at 2.5mm
- Middle layer thickness set at 0.5mm
- Width between each channel also specified as 0.18mm

Pressure Drop

- Correlation for laminar flow in rectangular ducts

$$\Delta P = \frac{4kL\dot{m}^2}{2\,\mathrm{Re}\,d_{eq}A_c^2\rho}$$

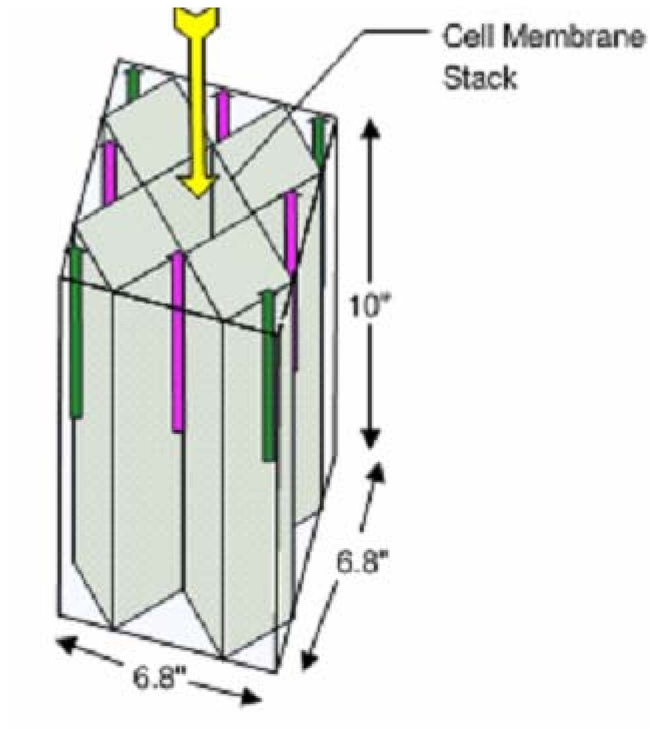
$$k = f\,\mathrm{Re} = 24(1 - 1.3553\alpha + 1.9467\alpha^2 - 1.7012\alpha^3 + 0.9564\alpha^4 - 0.2537\alpha^5)$$

$$\alpha = \frac{channel\ height}{channel\ width}$$

- Total stream pressure drops negligible~10^{-4} psi

Sealant

- Purpose
  - Separation of gas streams in membrane stack
- Required attributes
  - No harmful vapors
  - Must withstand operating temperatures
  - Thermal expansion properties



Sealant

- Resbond 907GF
  - No known health effects
  - Usable temp. range up to 1288ºC
  - Thermal expansion elongation, 5%
    - closely matches expansion of housing and cells
    - prevents leaks
  - Electrically insulating; high resistivity

Insulation

- Heat Shielding
  - Metal foil
  - Location: between cell membranes and housing
  - Purpose: negate radiative heat transfer
    - 97 to 99% effective
- Membrane Stack Insulating
  - Vacuum panels: for low thermal conductivity
  - Location: external face of heat exchanger housing
  - Purpose: insulate unit from membrane cell stack operating temperatures

Vacuum Panel Insulation

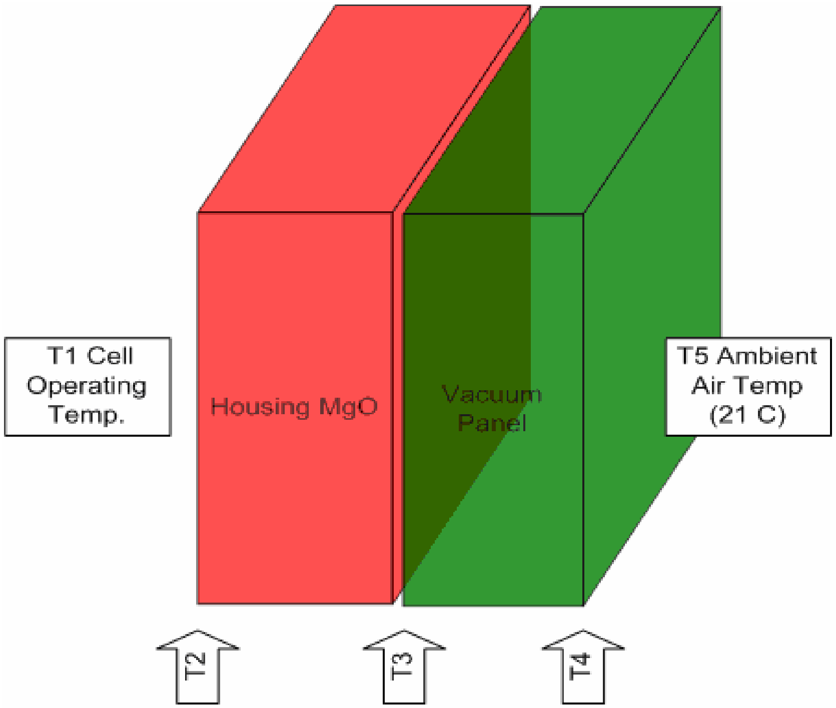
- Vacupor by Porextherm
  - Core material: fumed silica
    - Necessary to prevent panel collapse
    - Prevents out-gassing at low pressures
    - No degradation of vacuum
  - No health issues associated with conventional insulation
  - Low thermal conductivity constant:
    - k = 0.0048 W/mK

Vacuum Panel Insulation

- Fourier Eq.

$$q = \frac{T_1 - T_5}{\left[\left(\frac{x_{MgO}}{A \times k_{MgO}}\right) + \left(\frac{x_{vac}}{A \times k_{vac}}\right) + \left(\frac{2}{h_{air}}\right)\right]}$$

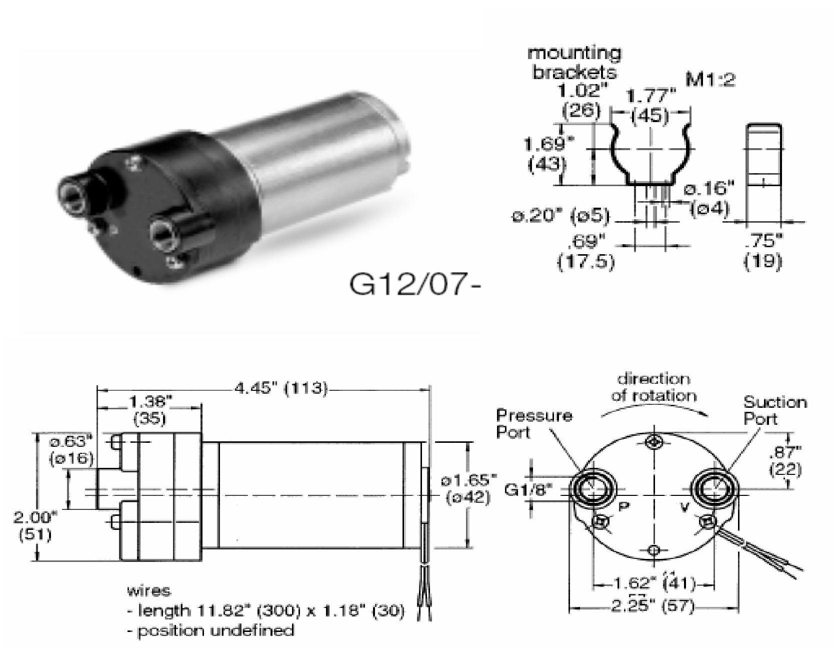
  Newton's Law of cooling
  - k_{MgO} = 30 W/mK
  - $k_{Vac\ pnl}$ = 0.0048 W/mK
  - Housing: 0.5cm thick
  - Vacuum panel thickness: 7.5cm
    - Hot face temp: 585ºC
    - Gives cold face temp. of 27.1ºC (80.7ºF)



Feed Compressors

- Provides feed air to the membrane stack
- Desired Attributes
  - Feed Air Requirements
    - 28 L/min to achieve 5L/min oxygen flow
  - Low power requirements
  - Steady flow
  - Small size
  - Low weight
  - No particle/lubricant emissions

Thompson Compressor



<u>G12/07-N Rotary Vane</u>

- **18.5L/min flow rate @ 1.0psi**
  - **-2 pumps combined flow: 37L/min**
- **12V DC**
- **Weight: 1.1 lb.**
- **Oil-less**
- **No pulsation**
- **Low vibration**
- **2.00 x 4.45 x 2.25 inches**

Power Supply

- Lithium-Ion battery
  - 12V DC
  - Full charge operating time: 4 hr
  - Complete recharge in 3 hrs
    - 95% charge in 1.5 hrs
  - High energy density: 400 Wh/L
    - Results in low weight and volume
      - 1.81 lbs
      - 0.31L

Controls and Alarms

- Safety and Product Stream Quality
  - Temp Alarms
    - High product stream temp
  - Flow Rate Control
    - Regulation of the oxygen stream for patient activity level
  - Low Voltage Alarm: battery low warning
  - Audio and Visual Alarms: for audio or visually impaired users

External Casing

- Aluminum
  - Low cost
  - Low density: lower unit weight
  - High durability to impacts, corrosion
  - No health concerns associated with plastics
    - Heat exposure

Prototype Cost

Component	**Cost ($)**	**Basis**
Inconel electrodes	30.00	assuming one lb per unit; based on raw material cost
Batteries	150.00	hardware store cost
Battery charger	50.00	actual cost
Resistance heating wires	1.00	$0.80 / ft
Vacuum insulation	50.00	estimate from conventional insulation
Foil radiation shielding	0.50	$100 per 1000 ft^2
Heat exchanger	1000.00	estimate
External Casing	50.00	estimated from manufactured aluminum cases
Controls and alarms	100.00	estimate
Pumps (2 ea)	468.00	Thompson pumps distributor; cost for two
Ceramic BICUVOX	500.00	pure estimate, based on manufacturing process
Total Unit Cost	**$2500**	

Regulations

Medical Coverage

- Costs range from $300-$500 per month for portable oxygen treatment
- Covered by most private insurance companies and HMOs
- Medicare covers 80% of costs if prescribed by a doctor
- Not covered by Medicare if used only during sleep or as supplement to stationary oxygen system

FDA Approval

- Sec. 868.5440 *Portable Oxygen Generator*
  - Releases oxygen for respiratory therapy by physical means or by a chemical reaction
- Class II device
- Subject to Pre-market Notification [510(k)]
- Class I and II devices must submit a 510 (k) at least 90 days before marketing in the United States
- Standard fee of $3,502
- Total average review time for fiscal year 2003 was 96 days (including wait time)

Pre-market Notification

- Must prove substantial equivalence (SE) to a previously approved similar device
- Must be as safe, effective, and intended for same use as similar device
- Device can be marketed in the U.S. once substantial equivalence is proven true by FDA

Pre-market Notification

- New Technology is considered SE if:
  - New device has same intended use, AND
  - Has new technology that could affect safety or effectiveness, AND
  - There are accepted scientific procedures for determining whether safety or effectiveness has been adversely affected, AND
  - There is data to prove that safety and effectiveness has not been diminished

FCI Estimation and Price Determination

Basic Economic Model

$$\alpha P_1 d_1 = \beta P_2 d_2$$

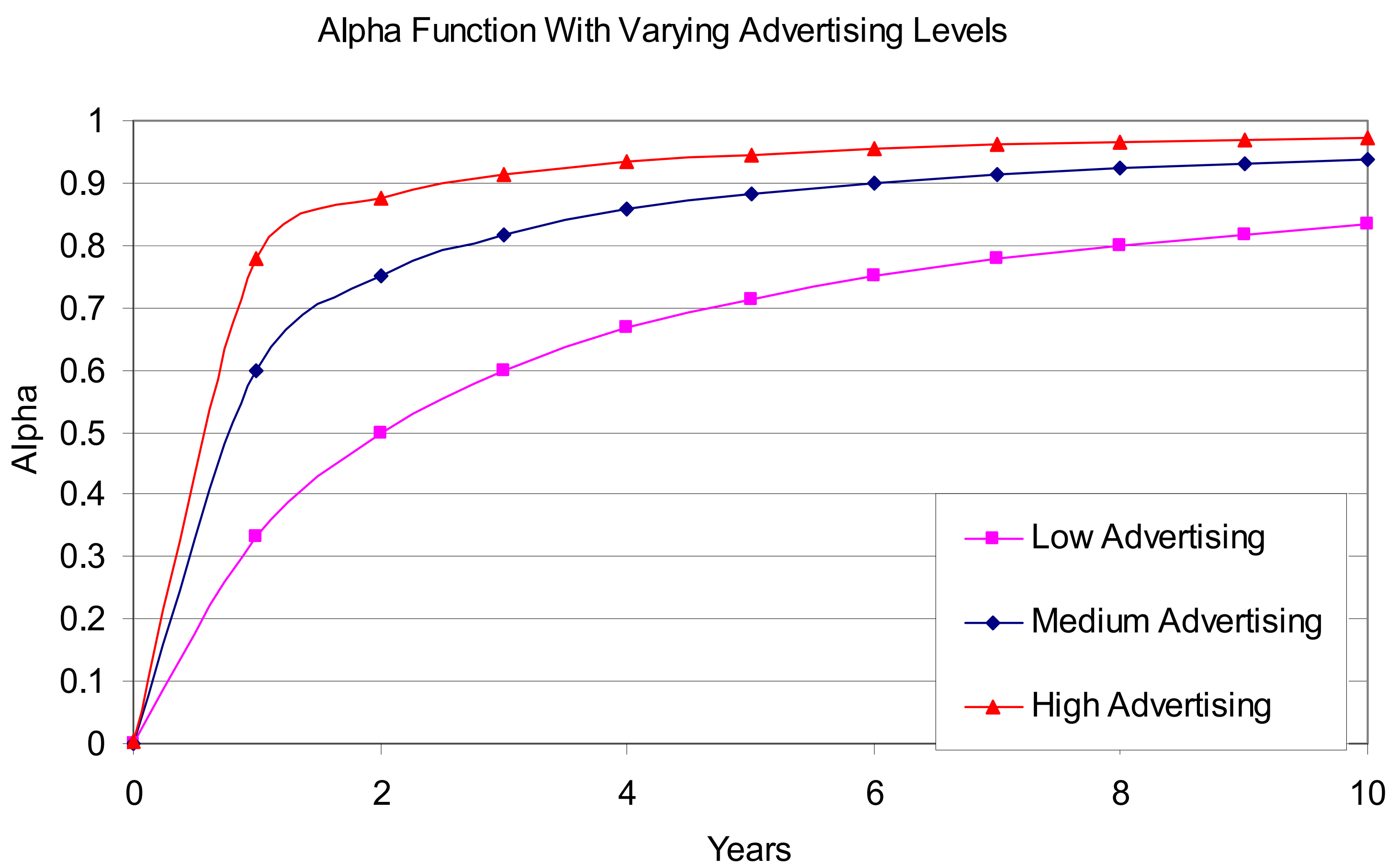
- P = Price
- d= Demand
- α = Fraction of our market that has knowledge of our product
- β = Based on happiness; fraction that will prefer our product

Alpha Function

- The alpha function describes how long it will take in order for our market to learn about our project
- Advertising, contracts with distributors and market type all are factors in the alpha function

$$\alpha(y,t) = 1 - \left(\frac{y * t}{y * t + 1} \right)$$

Effects of Advertising on The Alpha Function

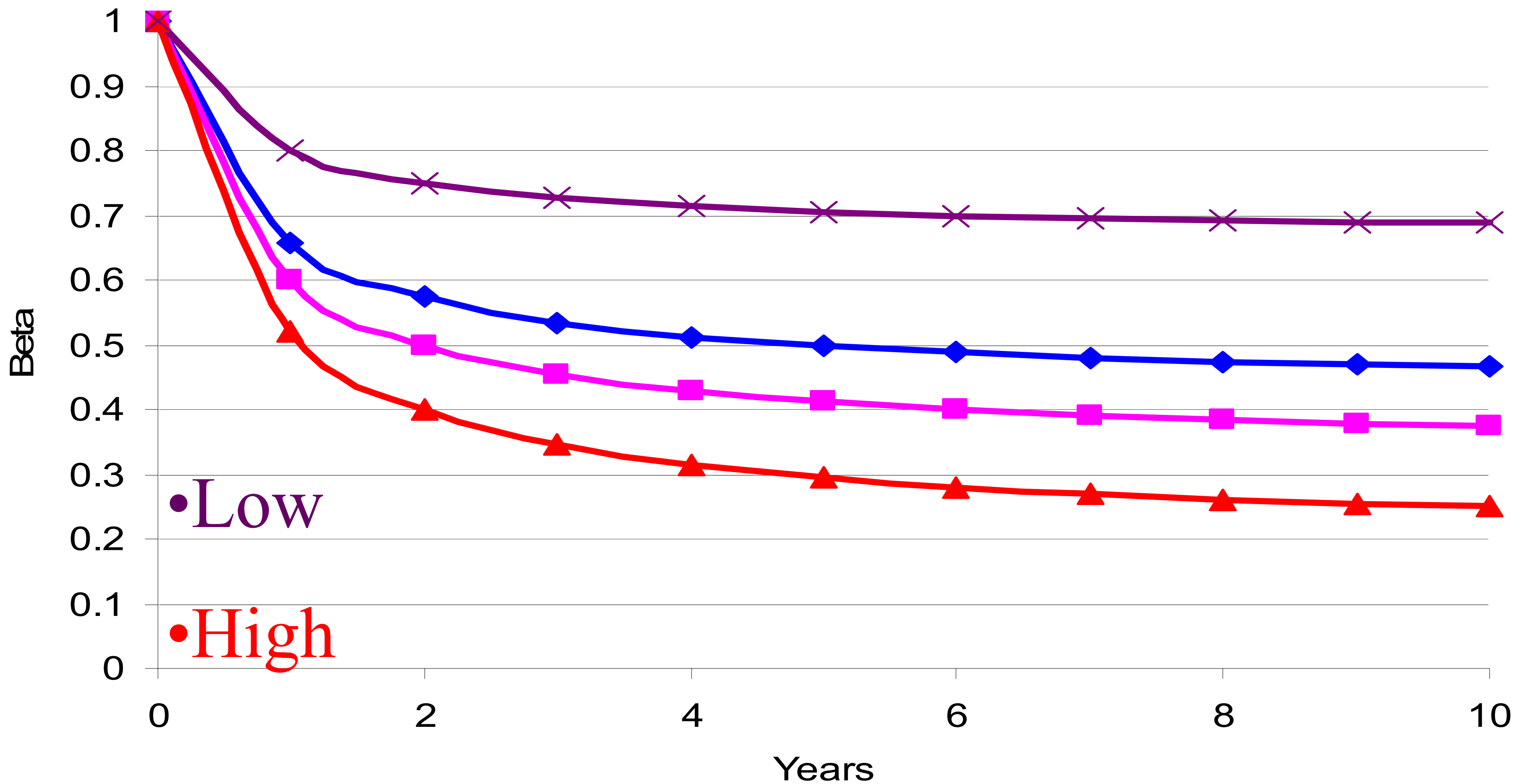


Beta Function

- The beta function describes the likelihood that a consumer will choose to buy our product.
- The happiness ratio of the two products and time are factors included in the beta function

$$B(k,t) = 1 - k_1 \left(\frac{Ht}{Ht+1} \right)$$

Effects of the Happiness Ratio on the Beta Function



Happiness Determination

- Happiness was found from a series of factors by comparing the properties of our products to their maximum or minimum values
- For example comparing battery life:

    Min acceptable life: 30 min

    Max possible before indifference: 6 hrs

    Membrane battery life: 5 hrs

Happiness Determination

Deviation from the minimum was found for each factor

Ex:

$$Dev = \frac{5hr - .5hr}{6hr - .5hr} = 0.81$$

Happiness Determination

- Deviations were weighted and summed

Competing with Airsep						
Happiness Factors	**Importance**	**normalized weight xi**	**our deviation yi**	**xiyi**	**competitor deviation**	**xiyi**
Reliability	10	0.147	0.600	0.088	0.000	0.000
Size	7	0.103	0.006	0.001	0.976	0.100
Weight	8	0.118	0.100	0.012	0.500	0.059
Portability	8	0.118	0.400	0.047	0.600	0.071
Durability	7	0.103	0.400	0.041	0.000	0.000
Noise	5	0.074	0.500	0.037	0.330	0.024
Purity of Air	9	0.132	1.000	0.132	0.000	0.000
Appearance	2	0.029	0.300	0.009	0.250	0.007
Battery life	8	0.118	0.667	0.078	0.166	0.020
Variable Flow-rates	4	0.059	1.000	0.059	0.500	0.029

Our Happiness	0.504
Competitor Happiness	0.310

Potential Demand

- The total demand for new consumers in need of the our products concentrators was estimated at 12,000 per year

Competitors

- Airsep Lifestyle

- Airsep Refiller (95%)

Price Determination

First setting $$\gamma = \frac{\beta}{\alpha}$$

and $$d_2 = D - d_1$$

and then solving for the expected demand for our product

$$d_1 = \frac{\gamma P_2 D}{P_1 + \gamma P_2}$$

Price Determination

- Price was adjusted and FCI and NPW was found for each price
- Plant capacity was found using the highest demand level
- The price resulting in the highest NPW was chosen as the selling price

TCI

TCI was found as a function of demand

Capital Investment for Portable Oxygen Device		
Direct Costs	**Percent of Equipment Cost**	
Purchased equipment delivered	100	$28,500,000
Purchased-equipment installation	45	$12,825,000
Instrumentation and controls	18	$5,130,000
Piping	16	$4,560,000
Electrical systems	10	$2,850,000
Buildings	25	$7,125,000
Yard Improvements	15	$4,275,000
Service facilities	40	$11,400,000
Total direct plant cost	269	$76,665,000
Indirect costs		
Engineering and supervision	33	$9,405,000
Construction expenses	39	$11,115,000
Legal expenses	4	$1,140,000
Contractor's fee	17	$4,845,000
Contingency	35	$9,975,000
Total indirect plant cost	128	$36,480,000
Fixed Capital Investment	397	**$113,145,000**
Working Capital (15% of total capital investment)	70	$19,966,765
Total Capital Investment	467	**$133,111,765**

Net Present Worth

- The NPW was calculated from TCI and demand for each selling price

Year,n	Demand	Sales ($/year)	Product Cost	Gross Earnings	Depriciation	Taxes	Net Profit	Cash Flow	CFn/((1+r)^n)
1	5	$62,449	$184,088	-$121,640	$110,103	$2,186	-$231,743	-$123,825	-$112,568
2	2,892	$36,150,577	$8,632,836	$27,517,741	$110,103	$1,265,270	$27,407,638	$26,252,471	$21,696,257
3	4,147	$51,838,293	$12,305,555	$39,532,738	$110,103	$1,814,340	$39,422,635	$37,718,398	$28,338,391
4	4,862	$60,770,652	$14,396,748	$46,373,904	$110,103	$2,126,973	$46,263,801	$44,246,931	$30,221,249
5	5,324	$66,553,383	$15,750,568	$50,802,815	$110,103	$2,329,368	$50,692,712	$48,473,447	$30,098,197
6	5,648	$70,605,882	$16,699,316	$53,906,566	$110,103	$2,471,206	$53,796,463	$51,435,360	$29,033,920
7	5,888	$73,604,595	$17,401,358	$56,203,238	$110,103	$2,576,161	$56,093,135	$53,627,077	$27,519,170
8	6,073	$75,913,616	$17,941,932	$57,971,684	$110,103	$2,656,977	$57,861,581	$55,314,707	$25,804,719
9	6,220	$77,746,497	$18,371,036	$59,375,461	$110,103	$2,721,127	$59,265,358	$56,654,333	$24,026,968
10	6,339	$79,236,822	$18,719,942	$60,516,879	$110,103	$2,773,289	$60,406,776	$57,743,591	$22,262,654
							Avg	**Avg**	**Sum**
							$45,097,836	$43,134,249	$216,626,303
	NPW	$223,989,101							

Straight line depreciation was assumed with an interest rate of 10%

Optimum Selling Prices

Limitations of the model

- The model is not accurate when the selling price of our product is much greater then average market selling price
- Solution: adjust beta function to lower demand faster at high prices

Adjustment of the Beta Function

- The beta function was adjusted to increase as the selling price approached and passed the twice the value of our competitors.
- If $\frac{p_1}{p_2} > 1.5$, then with k inversely related to happiness

$$B = B_o + p_1 / (k \times p_2)$$

Optimum Selling Prices

Device	95% Oxygen Concentrator	99% Oxygen Tank Filler	Membrane Concentrator
Selling Price	$1800	$18,500(Base) $27,000 (with electricity)	$11,000
TCI	$4.7 million	$80 million	$133 million
NPW (10 years)	$3.4 million	$105 million	$166 million

Suggested Improvements To Economic Model

- Offer to rent the tank filling device at a monthly rate
- Extensive market research should be conducted to improve happiness factors and weight ratios
- Price of advertising vs. benefit of advertising
- More accurate FCI calculations

Conclusions

- A 99% oxygen tank filling device using pressure swing adsorption technology was designed and would be more economical than home delivery
- A portable ceramic oxide membrane device was designed to give 5 lpm of 99% oxygen with 4 hours of battery operation

Conclusions

- Membrane concentrator is the best option based on purity and portability
- PSA tank filler offers an immediately viable alternative while membrane concentrator prototype undergoes testing and approval

Questions?