Solid Oxide Membranes

Brent Shambaugh
Justin Brady
Travis Spain
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

1 - Thomas G12/07-N rotary pump
2 - Heat Exchangers
3 - Oxygen Membrane
4 - Lithium Ion Batteries
5 - Mixing Point, Electrode Location
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.
A new Nusselt Number correlation was given by Choi et. al for flow of nitrogen in microchannels

\[
Nu = 0.00972 \text{Re}^{1.17} \text{Pr}^{\frac{1}{3}} \quad \text{Re} < 2000
\]

Or Wu & Little:

\[
Nu = 0.00222 \text{Re}^{1.09} \text{Pr}^{0.4} \quad \text{Re} > 3000
\]
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 1 psi 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.
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 the heat exchanger to allow for maximum heat transfer between the streams.
Microchannel Heat Exchangers

T_{O2, in} = 831.15K
T_{air, in} = 294.35K
T_{O2, out} = 298.15K
T_{air, out} = 831.14K

Number of channels = 315
Diameter of each channel = .07mm

Flow rate air = 5.36 L/min, Flow rate O2 = 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

- 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**
  - $\text{Bi}_2\text{Cu}_{0.1}\text{V}_{0.9}\text{O}_{5.35}$

- **Crystal Structure**
  - Tetragonal v. Orthorhombic
  - $\text{Bi}_2\text{O}_2^{2+}$ interleaved with anion-deficient perovskite-like sheets $\text{V}_{0.9}\text{Cu}_{0.1}\text{O}_{3.5}$

- **Thermal Expansion**
  - $10^{-5}/\text{K}$

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 diatomic Oxygen
- Flux through the membrane

\[ N_i = \frac{P_i}{l} \text{(driving force)} \]
## Membrane Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of plates</td>
<td>208</td>
<td>source</td>
</tr>
<tr>
<td>Temperature</td>
<td>550</td>
<td>C</td>
</tr>
<tr>
<td>total volumetric flow rate of permeate</td>
<td>5</td>
<td>L/min</td>
</tr>
<tr>
<td>molar gas volume (STP)</td>
<td>24.04</td>
<td>L/mol</td>
</tr>
<tr>
<td>molar flow rate of permeate/plate</td>
<td>0.00002</td>
<td>mol/s/plate</td>
</tr>
<tr>
<td>electron stoichiometry</td>
<td>4</td>
<td>source</td>
</tr>
<tr>
<td>Faraday constant</td>
<td>96485</td>
<td>C/mol electrons</td>
</tr>
<tr>
<td>current</td>
<td>6.431</td>
<td>A</td>
</tr>
<tr>
<td>current density for BICUVOX.10</td>
<td>0.75</td>
<td>A/cm²</td>
</tr>
<tr>
<td>total plate area required</td>
<td>12.87</td>
<td>cm²</td>
</tr>
<tr>
<td>side length of square plates</td>
<td>1.41</td>
<td>in</td>
</tr>
<tr>
<td>thickness of plates</td>
<td>0.3</td>
<td>cm</td>
</tr>
<tr>
<td>air gap height</td>
<td>0.5</td>
<td>cm</td>
</tr>
<tr>
<td>electrode height</td>
<td>0.2</td>
<td>cm</td>
</tr>
<tr>
<td>total cell stack height</td>
<td>287.24</td>
<td>cm</td>
</tr>
<tr>
<td>number of columns</td>
<td>4</td>
<td>spec</td>
</tr>
<tr>
<td>height per column</td>
<td>6.65</td>
<td>in</td>
</tr>
<tr>
<td>electrical potential for each cell</td>
<td>0.057</td>
<td>V</td>
</tr>
<tr>
<td>total potential for stack</td>
<td>11.923</td>
<td>V</td>
</tr>
<tr>
<td>power required</td>
<td>76.675</td>
<td>W</td>
</tr>
</tbody>
</table>

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

Feed air
Oxygen
Nitrogen

Cell Membrane Stack

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

<table>
<thead>
<tr>
<th>Unit</th>
<th>Wattage</th>
<th>Hours</th>
<th>Watt-Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>76.7</td>
<td>4</td>
<td>306.8</td>
</tr>
<tr>
<td>Heating Element, Unsteady</td>
<td>29325.54</td>
<td>.00055</td>
<td>16.12905</td>
</tr>
<tr>
<td>Heating Element, Steady</td>
<td>0.61</td>
<td>0.166667</td>
<td>0.101667</td>
</tr>
<tr>
<td>2 Pumps</td>
<td>4.6</td>
<td>4</td>
<td>18.4</td>
</tr>
</tbody>
</table>

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 in³ (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/m²K
- 2.5 in. thickness
  - Outside T=77°F
- Membrane Size
  - 12.1 x 9.4 x 12.1
## Equipment Sizing

### Sizes (in inches & pounds)

<table>
<thead>
<tr>
<th>Component</th>
<th>Height</th>
<th>Width/Diameter</th>
<th>Length</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane Stack</td>
<td>12.1</td>
<td>9.4</td>
<td>12.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Pump 1</td>
<td>2.25</td>
<td>4.45</td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>Pump 2</td>
<td>2.25</td>
<td>4.45</td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>Heat Exchanger – O2</td>
<td>2.756</td>
<td>0.1005</td>
<td>2.756</td>
<td>0.22</td>
</tr>
<tr>
<td>Heat Exchanger - LA</td>
<td>2.756</td>
<td>0.0918</td>
<td>2.756</td>
<td>0.22</td>
</tr>
<tr>
<td>Battery</td>
<td>2.75</td>
<td>2</td>
<td>9.5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Final Size</strong></td>
<td><strong>15.2</strong></td>
<td><strong>9.5</strong></td>
<td><strong>12.2</strong></td>
<td><strong>9.94</strong></td>
</tr>
</tbody>
</table>
Unit Design

- Dimensions
  - Height – 15.2”
  - Width – 9.5”
  - Length – 12.2”

- Weight
  - 9 lbs

- Membrane
  - 81% of Volume

- Battery
  - 55% of Weight
Panel View

**Power On/Off**
- Standby
- On/Ready

**System Warnings**
- Low Oxygen
- High Temperature
- Low Flow
- Check System

**Battery Power**

**Microphone Warning**

**Oxygen Supply**
Connect Nasal Cannula Here
Safety

**Issues**
- High Temperature of System
- High Temperature Exit Streams
- Low O₂ Concentration
- Low Flow in Exit Streams

**Solutions**
- Insulation & Casing
- Temperature Sensors & Alarms
- Concentration Controls
- Flow Controls
Control System

Instrument List

<table>
<thead>
<tr>
<th>Displayed Text</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>Analyzer Alarm</td>
</tr>
<tr>
<td>FF</td>
<td>Feed Forward</td>
</tr>
<tr>
<td>FA</td>
<td>Flow Alarm</td>
</tr>
<tr>
<td>TA</td>
<td>Temperature Alarm</td>
</tr>
<tr>
<td>TC</td>
<td>Temperature Controller</td>
</tr>
<tr>
<td>TS</td>
<td>Temperature Sensor</td>
</tr>
</tbody>
</table>
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

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

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

\( d_1 = \) 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

\( \beta = \) the beta function

\( \alpha = \) the alpha function

\[ p_1 d_1 + p_2 d_2 = Y \]

\( Y = \) the total money available in the market $315 M
Beta Function

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

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

$H_c = \text{the happiness of the competitor’s product}$

$H_i = \text{the happiness of the product being sold}$

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

From the portable unit:

Happiness vs. Noise

\[ H = -0.0197N + 1 \]

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: \[ H_h = -0.1829h + 1 \]

For width: \[ H_w = -0.4886W + 1 \]

For length: \[ H_l = -0.3735l + 1 \]
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:

\[ H_I = 0.3 \times H_N + 0.05 \times H_p + 0.3 \times H_w \\
+ 0.1 \times H_h + 0.1 \times H_w + 0.15 \times H_l \]

• Beta value = 0.865
Alpha Function

- The $\alpha$ 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:
- $y = \text{the advertising rate}$
- $t = \text{time}$
Alpha Function (cont.)

Alpha Function vs. Time

Alpha Function

Time (yr)

Low
Medium
High
Solving the Demand Model

• Solve these two equations simultaneously:

\[ \beta p_1 d_1 = \alpha p_2 d_2 \left( \frac{d_1^\alpha}{d_2^\beta} \right) \]  \hspace{1cm} \text{(equation 1)}

\[ p_1 d_1 + p_2 d_2 = Y \]  \hspace{1cm} \text{(equation 2)}

• Solve for at constant \( \alpha, \beta, Y, p_1, \) and \( p_2 \)

• 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:

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

$$d_1 = f(d_1)$$

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.

\[ d_1 = \left( \frac{\beta}{\alpha} \right)^{1-\alpha} \left( D - d_1 \right)^{1-\beta} \]

instead of

\[ d_1 = \left( \frac{\alpha p_2 (d_2)^{1-\beta}}{\beta p_1} \right)^{1/\alpha} \]
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.

\[
\begin{align*}
    d_1 &= 9.5 \\
    d_2 &= 6650.65
\end{align*}
\]
• When using the development for scenario 1, the following results are achieved (Selling Price = $5500, $\beta = 0.55$):
Results at $5500

Demand vs. Alpha at $5500

- Beta = 0.909
- Beta = 0.864
- Beta = 0.7
- Beta = 0.5
- Beta = 0.1
Demand at Different Selling Prices

Note: Production cost per unit ($\beta=0.865, $5500) = $3600
Time Dependence of Demand

Demand vs. Time

- \( y = 1 \)
- \( y = 3 \)
- \( y = 5 \)

\[ \text{Beta} = 0.909 \]
### NPW calculation

<table>
<thead>
<tr>
<th>Year</th>
<th>$\beta(t,H)$</th>
<th>$\alpha(y,t)$</th>
<th>Demand</th>
<th>Sales</th>
<th>Product Cost</th>
<th>Gross Earnings</th>
<th>Depreciation</th>
<th>Taxes</th>
<th>Net Profit</th>
<th>Cash Flow $Cf/(1+i)^t$</th>
<th>NPW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>0.83</td>
<td>3.6E+03</td>
<td>2.65E+07</td>
<td>1.85E+07</td>
<td>8.08E+06</td>
<td>5.55E+06</td>
<td>2.83E+06</td>
<td>2.92E+06</td>
<td>5.25E+06</td>
<td>4.86E+06</td>
</tr>
<tr>
<td>2</td>
<td>0.75</td>
<td>0.91</td>
<td>4.1E+03</td>
<td>3.13E+07</td>
<td>1.89E+07</td>
<td>1.24E+07</td>
<td>5.55E+06</td>
<td>4.33E+06</td>
<td>2.49E+06</td>
<td>8.04E+06</td>
<td>6.89E+06</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>0.94</td>
<td>4.0E+03</td>
<td>3.23E+07</td>
<td>1.90E+07</td>
<td>1.33E+07</td>
<td>5.55E+06</td>
<td>4.64E+06</td>
<td>3.07E+06</td>
<td>3.61E+06</td>
<td>6.84E+06</td>
</tr>
<tr>
<td>4</td>
<td>0.75</td>
<td>0.95</td>
<td>4.3E+03</td>
<td>3.28E+07</td>
<td>1.90E+07</td>
<td>1.37E+07</td>
<td>5.55E+06</td>
<td>4.80E+06</td>
<td>3.37E+06</td>
<td>3.92E+06</td>
<td>6.55E+06</td>
</tr>
<tr>
<td>5</td>
<td>0.75</td>
<td>0.96</td>
<td>4.3E+03</td>
<td>3.31E+07</td>
<td>1.91E+07</td>
<td>1.40E+07</td>
<td>5.55E+06</td>
<td>4.90E+06</td>
<td>3.56E+06</td>
<td>9.10E+06</td>
<td>6.19E+06</td>
</tr>
<tr>
<td>6</td>
<td>0.75</td>
<td>0.97</td>
<td>4.4E+03</td>
<td>3.33E+07</td>
<td>1.91E+07</td>
<td>1.42E+07</td>
<td>5.55E+06</td>
<td>4.97E+06</td>
<td>3.68E+06</td>
<td>9.23E+06</td>
<td>5.81E+06</td>
</tr>
<tr>
<td>7</td>
<td>0.75</td>
<td>0.97</td>
<td>4.3E+03</td>
<td>3.34E+07</td>
<td>1.91E+07</td>
<td>1.43E+07</td>
<td>5.55E+06</td>
<td>5.02E+06</td>
<td>3.77E+06</td>
<td>9.32E+06</td>
<td>5.44E+06</td>
</tr>
<tr>
<td>8</td>
<td>0.75</td>
<td>0.98</td>
<td>4.4E+03</td>
<td>3.36E+07</td>
<td>1.91E+07</td>
<td>1.44E+07</td>
<td>5.55E+06</td>
<td>5.05E+06</td>
<td>3.84E+06</td>
<td>9.39E+06</td>
<td>5.07E+06</td>
</tr>
<tr>
<td>9</td>
<td>0.75</td>
<td>0.98</td>
<td>4.3E+03</td>
<td>3.37E+07</td>
<td>1.91E+07</td>
<td>1.45E+07</td>
<td>5.55E+06</td>
<td>5.08E+06</td>
<td>3.89E+06</td>
<td>9.44E+06</td>
<td>4.72E+06</td>
</tr>
<tr>
<td>10</td>
<td>0.75</td>
<td>0.98</td>
<td>4.4E+03</td>
<td>3.37E+07</td>
<td>1.91E+07</td>
<td>1.46E+07</td>
<td>5.55E+06</td>
<td>5.11E+06</td>
<td>3.94E+06</td>
<td>9.48E+06</td>
<td>4.39E+06</td>
</tr>
</tbody>
</table>

| P2 = 2.16E+03 | P1 = 8.0E+03 | H2/H1 = 5.00E+00 |
| D = 1.40E+04 | i = 8.00E-02 | y = 3.00E+00 |
## Determining Equipment Price

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Use</th>
<th>Size</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage Tank</td>
<td>Bismuth Oxide</td>
<td>50 m³</td>
<td>33373</td>
</tr>
<tr>
<td>Storage Tank</td>
<td>Vanadium Oxide</td>
<td>50 m³</td>
<td>33373</td>
</tr>
<tr>
<td>Storage Tank</td>
<td>Magnesium Oxide</td>
<td>50 m³</td>
<td>33373</td>
</tr>
<tr>
<td>conveyor system</td>
<td>Plant Automation</td>
<td>200 m, .4 m width</td>
<td>254627</td>
</tr>
<tr>
<td>roller conveyor</td>
<td>Finished Product</td>
<td>21 m, .5 m width</td>
<td>6180</td>
</tr>
<tr>
<td>mixer, high solids</td>
<td>Bismuth Vanadate</td>
<td>1.5 m³</td>
<td>12361</td>
</tr>
<tr>
<td>mixer, high solids</td>
<td>MgO Slurry</td>
<td>1 m³</td>
<td>12361</td>
</tr>
<tr>
<td>welder/brazing equipment</td>
<td>Heat Exchanger</td>
<td></td>
<td>1483265</td>
</tr>
<tr>
<td>high temperature press</td>
<td>Membrane Sintering</td>
<td>2000 kW, 100 Mpa</td>
<td>741633</td>
</tr>
<tr>
<td>high temperature press</td>
<td>Mgo Sintering</td>
<td>2000 kW, 100 Mpa</td>
<td>741633</td>
</tr>
<tr>
<td>high precision cutter</td>
<td>Copper Cutting</td>
<td>Rotary cutter 10kg/s</td>
<td>2224898</td>
</tr>
<tr>
<td>oven</td>
<td>Sealant Annealing</td>
<td>1m³</td>
<td>61803</td>
</tr>
<tr>
<td>grinder 100 mesh</td>
<td>uniform particle</td>
<td>1.3 kg/s</td>
<td>282202</td>
</tr>
<tr>
<td>automation equipment</td>
<td>Plant Automation</td>
<td></td>
<td>7416327</td>
</tr>
</tbody>
</table>

**Equipment Price** 13337409
**Capital Investment**

- Based on percent of purchased equipment

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Measurement Criteria</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchased equipment</td>
<td>100</td>
<td>13337409</td>
</tr>
<tr>
<td>Installation</td>
<td>45</td>
<td>6001834</td>
</tr>
<tr>
<td>Instrumentation (installed)</td>
<td>18</td>
<td>2400734</td>
</tr>
<tr>
<td>Piping</td>
<td>16</td>
<td>2133985</td>
</tr>
<tr>
<td>Electrical systems (installed)</td>
<td>10</td>
<td>1333741</td>
</tr>
<tr>
<td>Buildings (including services)</td>
<td>68</td>
<td>9069438</td>
</tr>
<tr>
<td>Yard improvements</td>
<td>15</td>
<td>2000611</td>
</tr>
<tr>
<td>Service facilities</td>
<td>40</td>
<td>5334964</td>
</tr>
<tr>
<td><strong>Total Direct Cost</strong></td>
<td></td>
<td>41612717</td>
</tr>
<tr>
<td><strong>Indirect Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engineering and Supervision</td>
<td>33</td>
<td>4401345</td>
</tr>
<tr>
<td>Construction expenses</td>
<td>39</td>
<td>5201580</td>
</tr>
<tr>
<td>Legal expenses</td>
<td>4</td>
<td>533496</td>
</tr>
<tr>
<td>Contractor's fee</td>
<td>17</td>
<td>2267360</td>
</tr>
<tr>
<td>Contingency</td>
<td>35</td>
<td>4668083</td>
</tr>
<tr>
<td><strong>Total Indirect Cost</strong></td>
<td></td>
<td>17071894</td>
</tr>
</tbody>
</table>

FCI                                      | 440                  | 58684600     |
Working Capital                          | 78                   | 10403179     |
TCI                                      | 518                  | 69067779     |

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

NPW vs. Beta at $5500

Advertising correction:

\[ Cost = TPC + \left( \frac{y}{100} \right) \times TPC \]

Alpha constraint, \( y = 5 \)
NPW vs. Selling Price

NPW vs. Selling Price at Beta = 0.864

NPW vs. Selling Price at Beta = 0.864

-2.50E+08
-2.00E+08
-1.50E+08
-1.00E+08
-5.00E+07
0.00E+00

Selling Price

NPW

TPC dominates
WC dominates
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.)

Selling Price vs. NPW at Beta = 0.72

[Graph showing the relationship between Selling Price and NPW at Beta = 0.72]
Break Even Analysis

Breakeven Chart

Break Even Point

- **sales**
- **TPC**
Optimum Selling Price

Alpha vs. Demand at Beta = 0.72

Demand

Alpha
Conclusions

- Selling Price $5500
- Maximum Selling Price $12000
- NPW of $3 \times 10^6$
- 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

Effect of Selling Price with Advertising

\[ \text{Cost} = TPC + \left( \frac{y}{100} \right) \times TPC \]
Pump Performance

Output Pressure vs. Flowrate

F = -0.0204P^2 + 0.1752P + 4.6309

<table>
<thead>
<tr>
<th>Compressor Performance LPM @ PSI</th>
<th>0</th>
<th>1</th>
<th>1.5</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>50316</td>
<td>20</td>
<td>18.5</td>
<td>17</td>
<td>14.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum Pressure (PSI)</th>
<th>Continuous</th>
<th>Intermittent</th>
<th>Restart</th>
</tr>
</thead>
<tbody>
<tr>
<td>50316</td>
<td>4.4</td>
<td>11.6</td>
<td>0</td>
</tr>
</tbody>
</table>
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**
  - $a = b \neq c$
  - $\alpha = \beta = 90^\circ$, $\gamma = 120^\circ$

- **Orthorhombic**
  - $a \neq b \neq c$
  - $\alpha = \beta = \gamma = 90^\circ$
Membrane Stack

\[ I_m = \frac{4QF}{n} \]  
\text{(Current)}

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

\[ P_M = E_M \times I_M \]  
\text{(Wattage)}

Specifications

<table>
<thead>
<tr>
<th>Number of Plates</th>
<th>208</th>
<th>Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>685</td>
<td>°C</td>
</tr>
<tr>
<td>Total Volumetric Flow Rate of Permeate</td>
<td>5</td>
<td>L/min</td>
</tr>
<tr>
<td>Molar Gas Volume (STP)</td>
<td>24.04</td>
<td>L/mol</td>
</tr>
<tr>
<td>Molar Flow Rate of Permeate/Plate</td>
<td>0.00002</td>
<td>mol/s/plate</td>
</tr>
<tr>
<td>Electron Stoichiometry</td>
<td>4</td>
<td>mol electrons/mol D₂</td>
</tr>
<tr>
<td>Faraday Constant</td>
<td>96485</td>
<td>C/mol electrons</td>
</tr>
<tr>
<td>Current Density for BIEVOX.10</td>
<td>0.75</td>
<td>A/cm²</td>
</tr>
<tr>
<td>Total Plate Area Required</td>
<td>9</td>
<td>cm²</td>
</tr>
<tr>
<td>Side Length of Square Plates</td>
<td>3</td>
<td>cm</td>
</tr>
<tr>
<td>Thickness of Plates</td>
<td>0.36</td>
<td>cm</td>
</tr>
<tr>
<td>Air Gap Height</td>
<td>0.4</td>
<td>cm</td>
</tr>
<tr>
<td>Electrode Height</td>
<td>0.2</td>
<td>cm</td>
</tr>
<tr>
<td>Total Cell Stack Height</td>
<td>287.24</td>
<td>cm</td>
</tr>
<tr>
<td>Number of Columns</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Height Per Column</td>
<td>14.14</td>
<td>in</td>
</tr>
<tr>
<td>Total Potential for Stack</td>
<td>11923</td>
<td>V</td>
</tr>
<tr>
<td>Power Required</td>
<td>76675</td>
<td>W</td>
</tr>
<tr>
<td>Oxygen Recovery from Feed</td>
<td>0.80</td>
<td>%</td>
</tr>
<tr>
<td>Calculations</td>
<td>Cell</td>
<td>Formula</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>----------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>number of plates</td>
<td>208</td>
<td>source plates</td>
</tr>
<tr>
<td>Temperature</td>
<td>550</td>
<td>source C</td>
</tr>
<tr>
<td>total volumetric flow rate of permeate</td>
<td>5</td>
<td>spec L/min</td>
</tr>
<tr>
<td>molar gas volume (STP)</td>
<td>24.04</td>
<td>calc L/mol</td>
</tr>
<tr>
<td>molar flow rate of permeate/plate</td>
<td>0.00002</td>
<td>calc mol/s/plate</td>
</tr>
<tr>
<td>electron stoichiometry</td>
<td>4</td>
<td>source mol electrons/mol O₂</td>
</tr>
<tr>
<td>Faraday constant</td>
<td>96485</td>
<td>source C/mol electrons</td>
</tr>
<tr>
<td>current</td>
<td>6.431</td>
<td>calc A</td>
</tr>
<tr>
<td>current density for BICUVOX.10</td>
<td>0.75</td>
<td>source A/cm²</td>
</tr>
<tr>
<td>total plate area required</td>
<td>9</td>
<td>calc cm²</td>
</tr>
<tr>
<td>side length of square plates</td>
<td>3.00</td>
<td>calc cm</td>
</tr>
<tr>
<td>thickness of plates</td>
<td>0.38</td>
<td>source cm</td>
</tr>
<tr>
<td>air gap height</td>
<td>0.40</td>
<td>source cm</td>
</tr>
<tr>
<td>electrode height</td>
<td>0.2</td>
<td>source cm</td>
</tr>
<tr>
<td>total cell stack height</td>
<td>287.24</td>
<td>calc cm</td>
</tr>
<tr>
<td>number of columns</td>
<td>4</td>
<td>spec cm</td>
</tr>
<tr>
<td>height per column</td>
<td>28.27</td>
<td>calc in</td>
</tr>
<tr>
<td>electrical potential for each cell</td>
<td>0.055</td>
<td>calc V</td>
</tr>
<tr>
<td>total potential for stack</td>
<td>11.436</td>
<td>calc V</td>
</tr>
<tr>
<td>power required</td>
<td>73.548</td>
<td>calc W</td>
</tr>
</tbody>
</table>