Vinyl Chloride Production
Senior Design Presentation

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Project Purpose

- To design an environmentally safe vinyl chloride production plant.

Questions:
- What is Vinyl Chloride?
- How is it being produced?
- How much does it cost to be environmentally friendly?
Vinyl Chloride

- 99% of VCM is used to manufacture polyvinyl chloride (PVC).
- PVC consumption is second to low density polyethylene.
- VCM production results in a number of unwanted by-products.
VCM Plant Emissions in the United States

1. Formosa-LA
2. OxyvinyIs-D-TX
3. Oxyvinyls-L-TX
4. Georgia Gulf-LA
5. Westlake Monomers-KY
6. Formosa-TX
7. Borden-LA
8. Dow-LA
9. Dow-TX
Manufacturing Methods

- Vinyl Chloride from Acetylene
- Vinyl Chloride from Ethane
- Vinyl Chloride from Ethylene (Direct Route)
- Vinyl Chloride from Ethylene (EDC)
Balanced Process for Vinyl Chloride Production

- **Direct chlorination**: \( \text{CH}_2\text{CH}_2 + \text{Cl}_2 \rightarrow \text{ClCH}_2\text{CH}_2\text{Cl} \) (EDC)
- **Oxychlorination**: \( \text{CH}_2\text{CH}_2 + 2 \text{ HCl} + \frac{1}{2} \text{ O}_2 \rightarrow \text{EDC} + \text{ H}_2\text{O} \)
- **EDC pyrolysis**: \( 2 \text{ EDC} \rightarrow 2 \text{ CH}_2\text{CHCl} \) (VCM) + 2 HCl

**Overall reaction**: \( 2 \text{ CH}_2\text{CH}_2 + \text{Cl}_2 + \frac{1}{2} \text{ O}_2 \rightarrow 2 \text{ CH}_2\text{CHCl} + \text{ H}_2\text{O} \)

- No generation of HCl
- 95% of the world’s VCM is produced utilizing the balanced process
Balanced Process for Vinyl Chloride Production

- Oxy-chlorination
- Direct chlorination
- Ethylene
- Cl₂
- Air or O₂
- HCl recycle
- EDC purification
- EDC pyrolysis
- EDC recycle
- VCM purification
- VCM
- Light ends
- Heavy ends
Direct Chlorination and Oxychlorination P&ID

CAUSTIC SCRUBBERS
Vinyl Chloride Plant Reactor Design

- Theoretical reactor design equations
- Literature kinetic data used to calculate rate constants
- Numerical Integration used to calculate specified parameters
Reactor Design

\[
\frac{dF_k}{dz} = W_k \frac{\pi d_t^2}{4}
\]

- \( F_k \) = molar flow rate
- \( z \) = tube length
- \( d_t \) = tube diameter
- \( W_k \) = \( \nu_i r_i \)
- \( r_i = k_f[C_k] - k_r[C_k] \)
Oxychlorination Chemistry

<table>
<thead>
<tr>
<th>Set</th>
<th>Reaction</th>
<th>Stoichiometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>DCE formation</td>
<td>$\text{C}_2\text{H}_4 + 2\text{CuCl}_2 \rightarrow \text{C}_2\text{H}_4\text{Cl}_2 + 2\text{CuCl}$</td>
</tr>
<tr>
<td>R-2</td>
<td>TCE formation</td>
<td>$\text{C}_2\text{H}_4 + 3\text{CuCl}_2 \rightarrow \text{C}_2\text{H}_4\text{Cl}_3 + 3\text{CuCl} + 0.5\text{H}_2$</td>
</tr>
<tr>
<td>R-3</td>
<td>$\text{C}_2\text{H}_4$ combustion</td>
<td>$\text{C}_2\text{H}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>R-4</td>
<td>CuCl oxidation</td>
<td>$2\text{CuCl} + 0.5\text{O}_2 \rightarrow \text{CuO-CuCl}_2 \rightarrow \text{CuO} + \text{CuCl}_2$</td>
</tr>
<tr>
<td>R-5</td>
<td>CuCl$\text{sub}_2$ regeneration</td>
<td>$\text{CuO} + 2\text{HCl} \rightarrow \text{CuCl}_2 + \text{H}_2\text{O}$</td>
</tr>
</tbody>
</table>

- Plus nine other main by product formation reactions
- Excel Reactor Model of Oxychlorination
# Oxychlorination Reactor Results

## Oxy Reactor Effluent Flow Rates (lb-mol/hr)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Flow Rate (lb-mol/hr)</th>
<th>Flow Rate (lb-mol/hr)</th>
<th>Flow Rate (lb-mol/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDC</td>
<td>1341</td>
<td>Chloral</td>
<td>0.25</td>
</tr>
<tr>
<td>Water</td>
<td>1341</td>
<td>CCl&lt;sub&gt;4&lt;/sub&gt;</td>
<td>1.25</td>
</tr>
<tr>
<td>TEC</td>
<td>1.26</td>
<td>Methyl Chloride</td>
<td>0.12</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>140</td>
<td>Chloroform</td>
<td>0.11</td>
</tr>
<tr>
<td>Ethylene</td>
<td>5.5</td>
<td>Chloroethane</td>
<td>0.11</td>
</tr>
<tr>
<td>Oxygen</td>
<td>2.76</td>
<td>Chloroprene</td>
<td>0.10</td>
</tr>
<tr>
<td>HCl</td>
<td>0.015</td>
<td>Vinyl Acetylene</td>
<td>0.09</td>
</tr>
<tr>
<td>Acetylene</td>
<td>0.13</td>
<td>Dichloromethane</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Oxychlorination Reactor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Temperature (°C)</td>
<td>305</td>
</tr>
<tr>
<td>Reactor Pressure (psig)</td>
<td>58</td>
</tr>
<tr>
<td>Reactor Volume (ft³)</td>
<td>461</td>
</tr>
<tr>
<td>Tube Diameter (in)</td>
<td>2</td>
</tr>
<tr>
<td>Tube Length (ft)</td>
<td>1320</td>
</tr>
<tr>
<td>Residence Time (hr)</td>
<td>0.05</td>
</tr>
</tbody>
</table>
# DC Reactor Modeling Results

## DC Reactor Kinetic Results

<table>
<thead>
<tr>
<th></th>
<th>Modeling Results</th>
<th>Literature Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion of ethylene</td>
<td>99.93%</td>
<td>99.94%</td>
</tr>
<tr>
<td>Selectivity to EDC</td>
<td>99.8%</td>
<td>99.4%</td>
</tr>
</tbody>
</table>

## DC Reactor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Temperature (°C)</td>
<td>120</td>
</tr>
<tr>
<td>Reactor Pressure (psig)</td>
<td>15</td>
</tr>
<tr>
<td>Reactor Volume (ft³)</td>
<td>90</td>
</tr>
<tr>
<td>Tube Diameter (in)</td>
<td>2</td>
</tr>
<tr>
<td>Tube Length (ft)</td>
<td>115</td>
</tr>
<tr>
<td>Residence Time (hr)</td>
<td>0.018</td>
</tr>
</tbody>
</table>
EDC Purification P&ID
EDC Pyrolysis Reactor Modeling Results

• Conversion of EDC per pass is maintained at 50-55%

• Increasing cracking severity beyond this level results in insignificant increase in conversion and a decrease in selectivity to VCM.

• Conversion can be increased by the addition of CCl₄

• Modeling results produced conversion equal to 60%

• Major by products of EDC pyrolysis: Acetylene, benzene, 1-3 butadiene, vinyl acetylene, chloroprene.
Heat Integration

Pinch Design Method
- Optimization method that reduces energy cost
- Utilizes process to process heat transfer
- Optimal pinch temperature → 316°F
Heat Integration

Grand Composite Curve

Temperature (F)

Duty (MMBtu/hr)

Pocket of Heat Recovery

$Q_{H_{\text{min}}}$

$Q_{C_{\text{min}}}$
Heat Integration Results

- Hot Utility 401 → 308 MM Btu/hr
- Cold Utility 251 → 158 MM Btu/hr

Energy Reduction Results in a savings of $2.4 Million/year!
Waste Stream Treatment
Location of Waste Streams

- EDC Purification/Pyrolysis
- Oxychlorination Reaction Section
- Direct Chlorination Caustic Scrubber
## Contents of Waste

### Liquid Waste
- Ethylene
- EDC
- $\text{C}_2\text{HCl}_3$
- VCM

### Vapor Waste
- Ethylene
- EDC
- Carbon Tetrachloride
- $\text{CHCl}_3$
- Dichloromethane
- $\text{C}_2\text{HCl}_3$
- $\text{C}_2\text{H}_2$
- VCM
- $\text{C}_2\text{HCl}_3\text{O}$
- Vinyl Acetylene
- Chloroethane
Types of Waste Treatment

- Condenser
- Catalytic Incinerator
- Absorber/Scrubber
- Thermal Incinerator
- Flare
Waste Treatment Selected

- Multiple Treatment Process Selected

- Consists of thermal incineration, absorption column, and caustic scrubbing unit
Treatment PFD

- Vapor Waste
- Liquid Waste
- Incinerator
- Cl₂, H₂O, HCl
- CO₂, NOₓ
- Absorption
- Water
- NaOH
- CO₂, NOₓ
- Caustic Scrubbing
- Cl₂
- Water + HCl
- Water + NaCl + NaOCl
Products of Waste Treatment

- Water and HCl (solution)
- Water, NaCl, and Sodium Hypochlorite (solution)
- Carbon Dioxide and Nitrous Oxides
Incineration Unit Design

Auxiliary Fuel Flowrate Needed ($Q_f$)

$$Q_f = Q_w \left(\frac{X}{Y}\right) \text{ where,}$$

$$X = 1.1C_{po}(T_c - T_r) - C_{pi}(T_i - T_r) - h_w$$

$$Y = h_f - 1.1C_{po}(T_c - T_r)$$

$$Q_f = 331 \text{ lb/hr}$$
Absorption Column Design

**Amount of Solvent (Water)**

\[ L = G^*(Y_i - Y_o)/(X_o - X_i) \]

\[ L = 154,000 \text{ lbs/hr} \]

**Column Diameter (\( D_t \))**

\[ D_t = \frac{4VM_v}{fU_f \pi (1 - A_d/A) \rho_v} \]

\[ D_t = 5.7 \text{ ft} \]
Absorption Column Design Cont’d

Number of Theoretical Stages (\( N_{OG} \))

\[
N_{OG} = \frac{\ln\{[(A-1)/A][(Y_i - KX_i)/(Y_o - KX_i)] + (1/A)\}}{(A-1)/A}
\]

\( N_{OG} = 20 \)

Overall Height of a Transfer Unit (\( H_{OG} \))

\( H_{OG} = G/K_yaS \)

\( H_{OG} = .75 \)
Absorption Column Design Cont’d

Packing Height

\[ H_{\text{pack}} = N_{\text{OG}} \times (H_{\text{OG}}) \]

\[ H_{\text{pack}} = 15 \text{ ft} \]
Caustic Scrubbing Design

Design

\[ L = 45,000 \text{ lbs/hr} \]
\[ D_T = 4.5 \text{ ft} \]
\[ N_{OG} = 12 \]
\[ H_{OG} = .83 \]
\[ H_{pack} = 10 \text{ ft} \]
Waste Water Treatment
## Waste Water Streams

<table>
<thead>
<tr>
<th></th>
<th>DC Caustic Scrubber (L/hr)</th>
<th>Water Wash Drum (L/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>280</td>
<td>41,000</td>
</tr>
<tr>
<td>NaCl</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>HCl</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td>Chloral</td>
<td>-</td>
<td>26</td>
</tr>
<tr>
<td>EDC</td>
<td>-</td>
<td>680</td>
</tr>
<tr>
<td>CCl$_4$</td>
<td>-</td>
<td>180</td>
</tr>
<tr>
<td>TCE</td>
<td>-</td>
<td>170</td>
</tr>
</tbody>
</table>
## Limits and Treatment Options

<table>
<thead>
<tr>
<th>Substance</th>
<th>EPA Limit (mg/L)</th>
<th>Treatment Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl</td>
<td>5</td>
<td>-GAC</td>
</tr>
<tr>
<td>Chloral</td>
<td>1</td>
<td>-Incinerator w/Afterburner -GAC</td>
</tr>
<tr>
<td>EDC</td>
<td>.005</td>
<td>-GAC -Boiling</td>
</tr>
<tr>
<td>CCl₄</td>
<td>.005</td>
<td>-GAC -Fluidized Bed Incineration</td>
</tr>
<tr>
<td>TCE</td>
<td>.005</td>
<td>-Incineration -GAC</td>
</tr>
</tbody>
</table>
Granular Activated Carbon

- EPA Recommended Control Technology
- Ability to remove > 99% of contaminants
- Simple design and operation
- No hazardous waste byproducts
- Ability to operate at low temperatures and pressures
GAC Operation

- Makeup Carbon In
- Effluent
- Water Flow
- Carbon Column
- Carbon Movement
- Influent
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Mass</td>
<td>21000 lb</td>
</tr>
<tr>
<td>Adsorber Volume</td>
<td>170 ft$^3$</td>
</tr>
<tr>
<td>Adsorber Area</td>
<td>36 ft$^2$</td>
</tr>
<tr>
<td>Velocity</td>
<td>7 ft/min</td>
</tr>
<tr>
<td>Contact Time</td>
<td>27 min</td>
</tr>
<tr>
<td>Equilibrium Saturation</td>
<td>19 days</td>
</tr>
</tbody>
</table>
HAZOP Studies- Safety Concern

- Purpose: Reduce risk at workplace
- Identify risks, prevent and reduce impact
- Subdivide into small sections
- Deviations, Causes, Consequences, Safe Guard and Actions
PFTR Reactor
Plant Location Location Factors

- Raw Materials
  - Distance
  - Abundance
- Total Tax
  - Corporate Income Tax
  - Sales Tax
  - Property Tax
- Wages
- Utilities
- Land Cost
- Total Tax

Corpus Christi, TX
Taft, LA
## Factor Rating Maximization

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight %</th>
<th>LA</th>
<th>TX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>30</td>
<td>3 miles</td>
<td>17 miles</td>
</tr>
<tr>
<td>Abundance</td>
<td>25</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Total Tax</td>
<td>20</td>
<td>32%</td>
<td>40%</td>
</tr>
<tr>
<td>Wages</td>
<td>12</td>
<td>0.95</td>
<td>1.03</td>
</tr>
<tr>
<td>Utilities</td>
<td>8</td>
<td>$2.7/MMBtu</td>
<td>$2.5/MMBtu</td>
</tr>
<tr>
<td>Land Cost</td>
<td>5</td>
<td>$1270/acre</td>
<td>$640/acre</td>
</tr>
</tbody>
</table>
Factor Rating Maximization

\[ \text{Weight } \% \times \text{Value } \% = \text{Factor Rating} \]

Taft, LA
- 0.64

Corpus Christi, TX
- 0.96
Plant Capacity

- Forecasting
  - Economic Analysis 4.09 billion lb/yr
  - Economic Analysis 6.44 billion lb/yr
  - Economic Analysis 10.5 billion lb/yr

- Risk & Probability Analysis

- Decision
Forecasting

Prices of Chlorine vs. Year

Find Mean Value & Std. Dev
Apply to Monte Carlo Simulation

\[ y = 2.112x - 4017.7 \]

\[ R^2 = 0.9548 \]
## Forecasting

<table>
<thead>
<tr>
<th>Year</th>
<th>Ethylene ($/ton)</th>
<th>Chlorine ($/ton)</th>
<th>Oxygen ($/ft^3)</th>
<th>VCM ($/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>492.5</td>
<td>212.2</td>
<td>0.001445</td>
<td>499.2</td>
</tr>
<tr>
<td>2005</td>
<td>499.4</td>
<td>214.1</td>
<td>0.001436</td>
<td>506.2</td>
</tr>
<tr>
<td>2006</td>
<td>506.2</td>
<td>216.1</td>
<td>0.001427</td>
<td>513.2</td>
</tr>
<tr>
<td>2007</td>
<td>513.1</td>
<td>218.0</td>
<td>0.001418</td>
<td>520.2</td>
</tr>
<tr>
<td>2008</td>
<td>519.9</td>
<td>219.9</td>
<td>0.001409</td>
<td>527.2</td>
</tr>
<tr>
<td>2009</td>
<td>526.7</td>
<td>221.8</td>
<td>0.001400</td>
<td>529.2</td>
</tr>
<tr>
<td>2010</td>
<td>533.6</td>
<td>223.8</td>
<td>0.001391</td>
<td>535.2</td>
</tr>
<tr>
<td>2011</td>
<td>540.4</td>
<td>225.7</td>
<td>0.001382</td>
<td>543.21</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>24.17</td>
<td>10.56</td>
<td>0.000102</td>
<td>26.15</td>
</tr>
</tbody>
</table>
NPW & ROI

\[ NPW = \sum_{k=1}^{n-1} \frac{CF_k}{(1+i)^k} + \frac{CF_n + V_s + I_w}{(1+i)^n} - TCI \]

\[ TCI = \sum_{k=1}^{n} CF_k (1+r)^{-k} + (V_s + I_w)(1+r)^{-n} \]

Where
TCI = total capital investment
CF = cash flow
i = interest rate = 0.05
V_s = savage value
I_w = working capital
## Economic Analysis

<table>
<thead>
<tr>
<th>Plant Capacity</th>
<th>4.09 billion lb/yr</th>
<th>6.44 billion lb/yr</th>
<th>10.5 billion lb/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCI</td>
<td>$47,110,000</td>
<td>$68,886,000</td>
<td>$77,154,000</td>
</tr>
<tr>
<td>NPW</td>
<td>$133,739,000</td>
<td>$284,828,000</td>
<td>$161,759,000</td>
</tr>
<tr>
<td>ROI</td>
<td>0.24</td>
<td>0.25</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Risk Analysis

Monte-Carlo simulation
- Mean and Standard Deviation
- Random Number Generation
- NPW
- Risk Measurement
- Probability

Decision: Plant Capacity

Detailed Economic Analysis
Monte Carlo

- Assume normal distribution
- Perform random walks
  \[ \text{Norminv(Rand(), Mean, Std. Dev.)} \]
- Stop the iterations when the data converges
  Approximately 1000 trials
- Reduce error compared to analytical approach
Project Risk Curves

Cumulative Probability

Net Present Worth ($10^6)

-6000 -4000 -2000 0 2000 4000 6000

Cumulative Probability

-6000 -4000 -2000 0 2000 4000 6000

Net Present Worth ($10^6)

-6000 -4000 -2000 0 2000 4000 6000

Cumulative Probability

-6000 -4000 -2000 0 2000 4000 6000

Net Present Worth ($10^6)

-6000 -4000 -2000 0 2000 4000 6000

Cumulative Probability

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Net Present Worth ($10^6)

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Cumulative Probability

-6000 -4000 -2000 0 2000 4000 6000

Net Present Worth ($10^6)

-6000 -4000 -2000 0 2000 4000 6000

Cumulative Probability

-6000 -4000 -2000 0 2000 4000 6000

Net Present Worth ($10^6)
Comments

Capacity of 4.09 billion lb/yr:
41.7% chance of negative NPW

Capacity of 6.44 billion lb/yr:
31.5% chance of negative NPW

Capacity of 10.5 billion lb/yr:
36.8% chance of negative NPW
Probability vs. Net Present Worth

Highest Probability of positive NPW

NPW ($10^6)

- 6.44 billion lb/yr
- 4.09 billion lb/yr
- 10.5 billion lb/yr
Decision

Plant Capacity of 6.44 billion lb/yr:

- Highest NPW
- Highest ROI
- Lowest risk: 31.5% of losing money
- High probability of making money
Detailed Economic Analysis

Plant Capacity: 6.44 billion lb/yr

Plant Equipment:
- Four Heat Exchangers
- Four Distillation Towers
- Seven Flash Tanks
- Three Reactors
- Adsorption System
- Incineration Unit

Total Equipment Cost: $15.3M
<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Equipment Cost</strong></td>
<td></td>
<td>$15,284,100</td>
</tr>
<tr>
<td>Equipment Installed</td>
<td>47% of TEC (P&amp;T)</td>
<td>7,183,527</td>
</tr>
<tr>
<td>Incineration Unit (install)</td>
<td>Flow Rate Correlation</td>
<td>10,500</td>
</tr>
<tr>
<td>Instrumentation &amp; Control</td>
<td>18% of TEC (P&amp;T)</td>
<td>2,751,138</td>
</tr>
<tr>
<td>Piping (installed)</td>
<td>50% of TEC (P&amp;T)</td>
<td>7,642,050</td>
</tr>
<tr>
<td>Electrical (installed)</td>
<td>11% of TEC (P&amp;T)</td>
<td>1,681,251</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>19,268,466</td>
</tr>
<tr>
<td><strong>Building Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office</td>
<td>$45/ft^2 (Brick Building) in 3000 ft^2</td>
<td>135,000</td>
</tr>
<tr>
<td>Process Building (5-Unit)</td>
<td>$15/ ft^2 (Steel Building) in 4600 ft^2/Unit</td>
<td>375,000</td>
</tr>
<tr>
<td>Service Building</td>
<td>$45/ ft^2 (Brick Building) in 2000 ft^2</td>
<td>90,000</td>
</tr>
<tr>
<td>Storage Building</td>
<td>$15/ ft^2 (Steel Building) in 4000 ft^2/Unit</td>
<td>62,500</td>
</tr>
<tr>
<td>Maintenance Unit/Shop</td>
<td>$45/ ft^2 (Brick Building) in 1500 ft^2</td>
<td>67,500</td>
</tr>
<tr>
<td>Administration/Accounting</td>
<td>$45/ ft^2 (Brick Building) in 2500 ft^2</td>
<td>112,500</td>
</tr>
<tr>
<td>Environment/Research</td>
<td>$45/ ft^2 (Brick Building) in 3000 ft^2</td>
<td>135,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>977,500</td>
</tr>
<tr>
<td><strong>Yard Improvement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Cleaning</td>
<td>$4400/acre (total of 50 acres)</td>
<td>220,000</td>
</tr>
<tr>
<td>Grading</td>
<td>$465/acre (total of 10 acres)</td>
<td>4,650</td>
</tr>
<tr>
<td>Fencing</td>
<td>$9/ft (total of 9000 ft)</td>
<td>81,000</td>
</tr>
<tr>
<td>Walkways</td>
<td>$4.50/ ft^2 (total of 5000 ft^2)</td>
<td>22,500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>328,150</td>
</tr>
<tr>
<td>Land Cost</td>
<td>$1270/acre (total of 50 acres)</td>
<td>63,500</td>
</tr>
<tr>
<td><strong>Total Direct Plant Cost</strong></td>
<td></td>
<td>35,921,716</td>
</tr>
<tr>
<td>Engineering &amp; Supervision</td>
<td>32% of TEC (P&amp;T)</td>
<td>4,890,912</td>
</tr>
<tr>
<td>Construction Expenses</td>
<td>41% of TEC (P&amp;T)</td>
<td>6,266,481</td>
</tr>
<tr>
<td>Contractor's Fee</td>
<td>21% of TEC (P&amp;T)</td>
<td>3,209,661</td>
</tr>
<tr>
<td>Contingency</td>
<td>42% of TEC (P&amp;T)</td>
<td>6,419,322</td>
</tr>
<tr>
<td><strong>Total Indirect Cost</strong></td>
<td></td>
<td>20,786,376</td>
</tr>
<tr>
<td>Fixed Capital Investment</td>
<td>Direct+Indirect</td>
<td>56,708,092</td>
</tr>
<tr>
<td>Working Capital</td>
<td>86% of TEC (P&amp;T)</td>
<td>13,144,326</td>
</tr>
<tr>
<td><strong>Total Capital Investment</strong></td>
<td>Direct+Indirect+Working Capital</td>
<td>69,852,418</td>
</tr>
<tr>
<td>Employee</td>
<td># of Employee</td>
<td>$/yr</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------</td>
<td>--------</td>
</tr>
<tr>
<td>Plant Chairman</td>
<td>1</td>
<td>$105,000</td>
</tr>
<tr>
<td>Managers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant Manager</td>
<td>1</td>
<td>$80,000</td>
</tr>
<tr>
<td>Unit Managers</td>
<td>5</td>
<td>$73,000</td>
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<tr>
<td>Operational Engineers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer Programmer</td>
<td>1</td>
<td>$62,890</td>
</tr>
<tr>
<td>Computer Engineer</td>
<td>2</td>
<td>$74,310</td>
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<tr>
<td>Chemical Engineers</td>
<td>5</td>
<td>$72,780</td>
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<tr>
<td>Process Engineers</td>
<td>5</td>
<td>$73,000</td>
</tr>
<tr>
<td>Electrical Engineers</td>
<td>3</td>
<td>$68,630</td>
</tr>
<tr>
<td>Environment Engineers</td>
<td>3</td>
<td>$62,000</td>
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<tr>
<td>Industrial Engineers</td>
<td>3</td>
<td>$61,900</td>
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<tr>
<td>Mechanical Engineers</td>
<td>2</td>
<td>$63,500</td>
</tr>
<tr>
<td>Maintenance Engineers</td>
<td>2</td>
<td>$30,000</td>
</tr>
<tr>
<td>Operator</td>
<td>30</td>
<td>$68,000</td>
</tr>
<tr>
<td>Supervisor</td>
<td>5</td>
<td>$70,000</td>
</tr>
<tr>
<td>Administration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Financial Manager</td>
<td>1</td>
<td>$60,000</td>
</tr>
<tr>
<td>Production Manager</td>
<td>1</td>
<td>$68,000</td>
</tr>
<tr>
<td>Sales Manager</td>
<td>1</td>
<td>$60,000</td>
</tr>
<tr>
<td>Accounting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Budget Analysts</td>
<td>2</td>
<td>$53,000</td>
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<tr>
<td>Financial Analysts</td>
<td>1</td>
<td>$62,000</td>
</tr>
<tr>
<td>Tax Preparers</td>
<td>2</td>
<td>$33,000</td>
</tr>
<tr>
<td>Auditor</td>
<td>2</td>
<td>$35,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Economic Summary

- Total Product Cost - $1.59 billion
- Net Profit - $26.2 million
- NPW - $265 million
- ROI - 23.7%
Environmental Impact vs. Profit
Waste Reduction Algorithm

- Evaluate effects of design changes on environment
- Reactors can not be varied
  - Exothermic reactions allow heat integration
- Variable design parameters
  - Oxygen usage
  - Furnace temperature
Impact Calculations

Impact/hr

\[ I_i = \sum M_j \times \sum x_{kj} \Psi_k \]

- \( M_j = \) mass flow rate of stream \( j \)
- \( x_{kj} = \) mass fraction of chemical \( k \) in stream \( j \)
- \( -\Psi_k = \) characteristic potential impact of chemical \( k \)
Environmental Impact vs. Profit

- Original Furnace Temperature
- Lower Furnace Temperature
- Higher Furnace Temperature

- Oxygen furnace
- Oxygen hot utility, incinerator
- All Oxygen
- Oxygen incinerator
- All Air

Graph showing the relationship between Environmental Impact (EI) in lb/Hr and Profit (in Million $) for different furnace temperatures and oxygen usage.
Sequestering CO₂ Emissions

- Enhanced oil recovery
- Brine aquifers injection
- Located beneath shale layer
- 3100 ft
- FCI is a function of CO₂ flow rate
  - 27.753 $/(kg/hr) = $11.4 million
- OC is a function of CO₂ flow rate and depth
  - 0.0000912 $/(kg/hr)(ft) = $183,000/yr
VCM Plant Emissions in the United States

Capital Investment to achieve this emission reduction = $2.5 Million
Decreased Net Profit = $1.3 Million/year
Conclusion

- Balanced Process
- Incineration and Carbon Adsorption
- 6.4 billion lbs/year
- Taft, LA
- Sequestration of CO₂