Design and Evaluation of New Flue Gas Cleanup Processes to Meet New EPA Regulations

IPRO 496-304a
Spring 2003
Team Members

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  - Dimitre Kolev
  - Jotvinge Vaicekauskaite
  - Tristan Wilson
  - Ali Zenfour
Overview

- Introduction
- Project Validity
- Problem Definition
- Base Case Scenario
- Operation Descriptions
- Economic Analysis
- Process Selection
- Conclusions/Suggestions
Objectives

- Design the most cost efficient cleaning process for flue gas that removes $\text{SO}_x$, $\text{NO}_x$, Particulate Matter:
  - that meets current and future EPA standards
  - that is viable in the long run
  - based on existing and new technologies
  - which study its effects on cost of electricity by comparing and analyzing costs of burning IL vs. WY coal
Introduction – Pollution Control

- **Clean Air Act (1990) – The EPA institutes new, more vigorous environmental regulations on power plant emissions**

- **By 2010**
  - 6,400 fewer premature deaths
  - $40B health benefits reduction

- **By 2020**
  - 12,000 fewer premature deaths
  - $93B health benefits reduction
# Clean Air Act (1990)

**[lb/mmBtu]**

<table>
<thead>
<tr>
<th></th>
<th>SOX</th>
<th>NOX</th>
<th>HG</th>
<th>P.M.</th>
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<td>1.2</td>
<td>0.7</td>
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<td>2000</td>
<td>0.6</td>
<td>0.4</td>
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<tr>
<td>2020</td>
<td>-70%</td>
<td>-70%</td>
<td>-80%</td>
<td>-70%</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>2000</td>
<td>0.3</td>
<td>0.1</td>
<td>-80%</td>
<td>0.02</td>
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<tr>
<td>2020</td>
<td>-70%</td>
<td>-70%</td>
<td>-80%</td>
<td>-70%</td>
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Base Plant

- Mid-sized coal burning power plant (400MWe)

- Burning Illinois No. 6 coal

- Particulate matter removal only current unit operation (Electrostatic Precipitator (ESP) or Baghouse)

- Unit operations to remove $\text{SO}_x$ and $\text{NO}_x$ later.
Base Plant Diagram

Coal Combustor

10% Excess Air
Coal

Flue Gas

Heat Exchanger

Flue Gas

T = X\degree F

Heat to Create Steam

Various Unit Operations (SO\textsubscript{2}, NO\textsubscript{x}, Hg, and Particulate Reduction)

Stack

Out to Atmosphere

T = 100\degree F
Coal Statistics

- **Illinois No. 6 (wt%)**
  - C: 67.37
  - H₂: 4.20
  - N₂: 1.16
  - S: 3.25
  - O₂: 6.02
  - Ash: 10.00
  - Moisture: 8.00

- **Wyoming PRB (wt %)**
  - C: 49.88
  - H₂: 3.40
  - N₂: 1.62
  - S: 0.48
  - O₂: 9.82
  - Ash: 6.40
  - Moisture: 28.40
## Coal Combustion

### Reactions

- \( \text{C} \) \(_{(s)} \) + \( \text{O}_2 \) \(_{(g)} \) \( \rightarrow \) \( \text{CO}_2 \) \(_{(g)} \)  
  \[ \Delta H_{\text{rxn}} = -393.509 \text{ kJ/mol} \]

- \( \text{S} \) \(_{(s)} \) + \( \text{O}_2 \) \(_{(g)} \) \( \rightarrow \) \( \text{SO}_2 \) \(_{(g)} \)  
  \[ \Delta H_{\text{rxn}} = -296.830 \text{ kJ/mol} \]

- \( 0.5\text{H}_2 \) \(_{(g)} \) + \( \text{O}_2 \) \(_{(g)} \) \( \rightarrow \) \( \text{H}_2\text{O} \) \(_{(g)} \)  
  \[ \Delta H_{\text{rxn}} = -241.818 \text{ kJ/mol} \]

- \( 0.5\text{N}_2 \) \(_{(g)} \) + \( 0.5\text{O}_2 \) \(_{(g)} \) \( \rightarrow \) \( \text{NO} \) \(_{(g)} \)  
  \[ \Delta H_{\text{rxn}} = 90.250 \text{ kJ/mol} \]

- \( 0.5\text{N}_2 \) \(_{(g)} \) + \( \text{O}_2 \) \(_{(g)} \) \( \rightarrow \) \( \text{NO}_2 \) \(_{(g)} \)  
  \[ \Delta H_{\text{rxn}} = 33.180 \text{ kJ/mol} \]

- 100% conversion of carbon, sulfur, and hydrogen assumed
Coal Combustion Calculations

### Coal Combustion Calculations

<table>
<thead>
<tr>
<th>Coal Compound</th>
<th>Wt%</th>
<th>g</th>
<th>M.W.</th>
<th>moles</th>
<th>mole%</th>
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<tr>
<td>H2O(g)</td>
<td>8.00</td>
<td>7.61E+10</td>
<td>18</td>
<td>4.23E+09</td>
<td>4.77</td>
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<tr>
<td>C(s)</td>
<td>67.37</td>
<td>6.41E+11</td>
<td>12</td>
<td>5.34E+10</td>
<td>60.22</td>
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<tr>
<td>H2(g)</td>
<td>4.20</td>
<td>4.00E+10</td>
<td>2</td>
<td>2.00E+10</td>
<td>22.52</td>
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<tr>
<td>N2(g)</td>
<td>1.16</td>
<td>1.10E+10</td>
<td>28</td>
<td>3.94E+08</td>
<td>0.44</td>
</tr>
<tr>
<td>S(s)</td>
<td>3.25</td>
<td>3.09E+10</td>
<td>32</td>
<td>9.66E+08</td>
<td>1.09</td>
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<tr>
<td>O2(g)</td>
<td>6.02</td>
<td>5.73E+10</td>
<td>32</td>
<td>1.79E+09</td>
<td>2.02</td>
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<tr>
<td>C(s,ash)</td>
<td>10.00</td>
<td>9.51E+10</td>
<td>12</td>
<td>7.93E+09</td>
<td>8.94</td>
</tr>
<tr>
<td><strong>Sum:</strong></td>
<td>100.00</td>
<td>9.51E+11</td>
<td></td>
<td>8.87E+10</td>
<td>100.00</td>
</tr>
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</table>

### Flue Gas

<table>
<thead>
<tr>
<th>Flue Gas Compound</th>
<th>Wt%</th>
<th>g</th>
<th>M.W.</th>
<th>moles</th>
<th>mole%</th>
<th>lb/mmBtu</th>
<th>Heating Value (Btu/mol)</th>
<th>Heating Value (Btu)</th>
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<tbody>
<tr>
<td>CO2(g)</td>
<td>23.61</td>
<td>2.35E+12</td>
<td>44</td>
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<tr>
<td>SO2(g)</td>
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<td>6.18E+10</td>
<td>64</td>
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<td>0.29</td>
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<td>H2O(g)</td>
<td>4.38</td>
<td>4.36E+11</td>
<td>18</td>
<td>2.42E+10</td>
<td>7.29</td>
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<td>NO(g)</td>
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<td>0.01</td>
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<td>-2.62E+09</td>
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<td>NO2(g)</td>
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<td>N2(g)</td>
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<td>0.00E+00</td>
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<td>O2(g)</td>
<td>0.17</td>
<td>1.65E+10</td>
<td>32</td>
<td>5.16E+08</td>
<td>0.16</td>
<td>X</td>
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<td>0.00E+00</td>
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<tr>
<td><strong>Sum:</strong></td>
<td>100.00</td>
<td>9.96E+12</td>
<td></td>
<td>3.32E+11</td>
<td>100.00</td>
<td>5.94</td>
<td>767.04</td>
<td>2.58E+13</td>
</tr>
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</table>
Heat Value Calculations

- \(\frac{400\text{MWe}}{0.35} = 2.7\times10^{10}\text{MJ/yr}\)
- \(2.7\times10^{10}\text{MJ/yr} \times \frac{1\text{Btu}}{0.001054\text{MJ}} = 2.58\times10^{13}\text{Btu/yr}\)
- \(2.58\times10^{13}\text{Btu/yr} \times \frac{1\text{lb coal}}{12,280\text{Btu}} = 2.1\times10^9\text{lb coal/yr}\)
- \(2.1\times10^9\text{lb coal/yr} = 158.9\text{ton coal/hr}\)
Coal Selection Dilemma

- Due to the higher sulfur content, flue gas from Illinois coal must be desulfurized before being released to the atmosphere.
- Under current regulations, Wyoming PRB coal must only undergo a particulate removal process, thereby making it more economical to use.
- New regulations, in addition to the Clean Air Act, would require the same cleaning operations ($SO_x$, $NO_x$, P.M.) for both forms of coal in an attempt to make Illinois coal more competitive.
Selective Catalytic Reduction (SCR)

- Selective Catalytic Reduction
  - \(2\text{NH}_3(l) + 3\text{NO}_2(g) \rightarrow 2.5\text{N}_2(g) + 3\text{H}_2\text{O}(g)\)
  - \(4\text{NH}_3(g) + 3\text{NO}_2(g) \rightarrow 3.5\text{N}_2(g) + 6\text{H}_2\text{O}(g)\)

- Ammonia injected into flue gas before passing through a honeycomb catalyst vessel at 700°F

- Reaction is pushed to completion to prevent ammonia slip.
Wet Scrubbing

- A limestone slurry reacts with sulfur dioxide at 300°F to create calcium sulfate, which is trapped in the slurry stream and removed

- \( \text{CaCO}_3(aq) + \text{SO}_2(g) + 0.5\text{O}_2(g) \rightarrow \text{CaSO}_4(aq) + \text{CO}_2(g) \)
Dry Scrubbing

- A saturated calcium hydroxide solution is passed through atomizers so that the droplets evaporate into the flue gas. The calcium hydroxide reacts with the sulfur dioxide and creates calcium sulfate again.

\[
\text{Ca(OH)}_2(aq) + \text{SO}_2(g) + 0.5\text{O}_2(g) \rightarrow \text{CaSO}_4(aq) + \text{H}_2\text{O}_2(g)
\]

- The solid particles are caught in the P.M. removal system as opposed to in the slurry.
Vessel Design

- $V = \text{Reaction}
  \quad \text{Vessel} = [m^3]$

- $Q = \text{Flue Gas Flow}
  \quad \text{Rate} = [m^3/s]$

- $\theta = \text{Residence}
  \quad \text{Time} = [s]$

$$V = Q \cdot \theta$$
Baghouse Filter

- Gas passed through fabric bag network
- Particulates collect on fabric surface
- Periodically, particles knocked off bags into hoppers to maintain efficiency and low pressure drop
Baghouse Design

- $A = \text{total Baghouse area} \ [\text{ft}^2]$

- $Q = \text{flue gas flow rate} \ [\text{ft}^3/\text{min}]$

- $F_m = \text{filtration velocity} \ [\text{ft/minute}] = 2.2$

$$A = \frac{Q}{V_F}$$
Electrostatic Precipitator (ESP)

- Uses electric forces to remove particulates
- Ionized particles are attracted to oppositely charged collection plates.
- Particles are dislodged from plates using the rapper
ESP Design

Design Equation:

\[
\frac{[\ln(1 - \eta)]^{1/k}}{Q} = -\frac{Aw}{Q}
\]

- \( A = \text{total plate area} \)
- \( w = \text{precipitation rate parameter} \)
- \( Q = \text{flow rate} \)
- \( \eta = \text{efficiency} \)
- \( k = \text{efficiency constant} \)

Project values:

A = 1.2 \times 10^6 \text{ ft}^2
w = 0.33 \text{ ft/sec}
Q = 1.03 \times 10^6 \text{ ft}^3/\text{min}
\eta = 0.999
k = 0.6
Vessel Costing

- Total volume found from previous equations
- Maximum volume from cost correlation graph used to find theoretical number of vessels, each of which has an individual cost
- Summing the individual costs gives total cost for the total volume
- Costs then inflated to 2003 values
Baghouse and ESP costs dependent on total area and found through empirical equations.

In addition, total cost has associated costs based on percentages of the bare module cost.

All values inflated to 2003 values.
### Calculated Values

<table>
<thead>
<tr>
<th>Illinois No. 6</th>
<th>S.C.R.</th>
<th>W.S.</th>
<th>D.S.</th>
<th>B.F.</th>
<th>E.S.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPITAL</td>
<td>2.43E+07</td>
<td>5.41E+07</td>
<td>4.41E+07</td>
<td>2.68E+07</td>
<td>1.81E+07</td>
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<tr>
<td>OPERATING</td>
<td>3.41E+06</td>
<td>9.74E+06</td>
<td>9.70E+06</td>
<td>2.47E+06</td>
<td>1.99E+06</td>
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<tr>
<td>ANNUALIZED</td>
<td>6.11E+06</td>
<td>1.57E+07</td>
<td>1.46E+07</td>
<td>5.44E+06</td>
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<td>Cents/kW-h</td>
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### IECM Values

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<td>OPERATING</td>
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<td>2.27E+06</td>
<td>2.08E+06</td>
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<td>5.52E+06</td>
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<tr>
<td>ANNUALIZED</td>
<td>0.210</td>
<td>0.702</td>
<td>0.592</td>
<td>0.169</td>
<td>0.147</td>
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System of Choice: SCR, Dry Scrubbing, ESP

Average Difference (Calculations vs. IECM): 9%
## Cost Comparison Two

### Illinois No. 6

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### Wyoming PRB

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<th>B.F.</th>
<th>E.S.P.</th>
</tr>
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<tbody>
<tr>
<td><strong>ANNUALIZED</strong></td>
<td>6.47E+06</td>
<td>1.39E+07</td>
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<td>4.24E+06</td>
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<td><strong>Cents/kW-h</strong></td>
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System of Choice: SCR, Dry Scrubbing, ESP
Final Analysis

- Illinois Current Cost \((SO_x, \text{ P.M.})\): 0.739 cents/kW-h
- Wyoming Current Cost \((\text{P.M.})\): 0.124 cents/kW-h \(\text{Diff.:} 0.615\)
- Illinois New Cost \((\text{NO}_x, \text{ SO}_x, \text{ P.M.})\): 0.949 cents/kW-h
- Wyoming New Cost \((\text{NO}_x, \text{ SO}_x, \text{ P.M.})\): 0.713 cents/kW-h \(\text{Diff.:} 0.236\)
- IL: $326.48/ton \text{ SO}_x \text{ removed}
- WY: $189.16/ton \text{ SO}_x \text{ removed}