Integrated Pollutant Removal: Modeling and Experimentation

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Goals

• Removal of all pollutants from a fossil fuel flue gas stream.
• Produce liquid CO₂ suitable for sequestration
• Power Generation Thermal efficiency above 33%
• Small incremental additional cost
• Use off-the-shelf technologies
Background

• Project evolved from CO$_2$ sequestration research started in 2000
  – If we are going to sequester CO$_2$ we have to capture it economically

• Based on performance improvement principles used in power plant performance improvement program in Indonesia
Lesson Learned:
Borrow Technologies From Other Industries!

- Petrochemical industry
- Chemical industry
- Petroleum refining industry
Two Paths to CO$_2$ Capture

- Present Technology
- Application of Existing Technology in New Forms
- Development of New Technologies
- Non-Exclusive
- CO$_2$ Capture
Conclusions

• There are no breakthroughs necessary to effectively remove CO₂ from denitrified flue gas (recirculating boilers, oxyfuel, etc)
  – Technologies needed are routinely used in other industries.

• 33% thermal efficiency plants can be built using existing technology. They can capture 99% of the CO₂ and other combustion product pollutants
Integrated Pollutant Removal

IPR = FGR + Hybrid Heat Exchange

Air Separation Unit

1. Cyclone
2. Splitter
3. Fan
4. O₂
5. Recirculated Flue Gas
6. Direct Contact Heat Exchanger And Condenser
7. Compressor
8. Filter
9. Reactive Treatment
10. Water For Final Treatment
11. Indirect Heat Exchanger

Compressed Flue Gas to Next Stage and Condensation

Reaction Products

Pump

Cooling Water

Reaction Products

Recirculated Flue Gas

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Energy Recovery and Conservation as Key Components in Low Emission Power Plants

• Estimates that do not consider energy recovery are pessimistic
• Existing plants are successful because they recover energy wherever possible
• Advances in power plant technology have included energy recovery
Power Plant Design
The Approach to Integrated Pollutant Removal

- Oxygen + flue-gas as combustion “air”
- Remove all pollutants and acid gases through compression and condensation
  - Remove coarse particulates and particle bound Hg (filtration)
  - Concentrate condensables and pollutant gases
  - Condense and remove H₂O and CO₂
    - Entrain particulates with fine particle bound Hg²⁺
    - Dissolve and react SOₓ, NOₓ, Hg²⁺
  - Decrease volume flow rate through compression and condensation
    - Increase relative volume of Hg⁰
- Recover energy through heat transfer and expansion
Enabling Technologies

Integrated Pollutant Removal

- Wet Heat Exchange
- Wet Compression
- Oxy-fuel combustion
- Expander Heat Recovery
- Water Treatment
- Oxygen Supply
- Flue-gas Recirculation
CRADA With Jupiter Oxygen (Cooperative Research and Development Agreement)

- Proven proprietary oxy-fuel system for aluminum melting
- Experience in oxygen production and burner technology
- Applying oxy-fuel to power generation
- Supplements IPR need for oxy-fuel system
- Gives a new dimension to heat transfer control with flexible oxygen content
Oxygen Costs For 400 MW Coal Plant

Capital cost: $160,000,000 ($20,000/ton/hr/day)

Power Required for Operation

- 250 kWh/ton (Cryogenic) => 82.5 MW (Used in model*)
- 235 kWh/ton (Cryogenic) => 77.55 MW
- 147 kWh/ton (Ion Transport Membrane) => 48.51 MW

*330 ton/hr O₂
*153 ton/hr #6 Illinois Old Ben mine 26 coal
Three Stages Of Condensation In IPR

- **Ambient Pressure**
  - **H₂O Condensation**
    - Acidic H₂O

- **< 1000 psi**
  - **Moderate Pressure**
    - H₂O/CO₂ Condensation
      - CO₂ Compression
      - H₂O/CO₂ Compression

- **> 1000 psi**
  - **High Pressure**
    - CO₂ Condensation
      - N₂ / O₂
Mass Flow Reduction

Recirculating Combustion Products From Boiler

2,077 ton/hr

1,609.5 ton/hr

Return to Oxygenation and Boiler

Bleed Stream 394.5 ton/hr

Cooling 73 ton/hr

First condensation 13.5 ton/hr

15 psia H₂O

Second condensation 277.5 ton/hr

180 psia H₂O

Third condensation 59.6 ton/hr

1,200 psia CO₂

Fourth condensation 18.05 ton/hr

2,500 psia CO₂

Fifth condensation 25.85 ton/hr

381 ton/hr

103.5 ton/hr

43.9 ton/hr

381 ton/hr

15 psia 180 psia 1,200 psia 2,500 psia 5,000 psia

H₂O H₂O CO₂ CO₂ CO₂

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Volumetric Flow Rate (ft$^3$/s)

Pressure (psia)

- 15 15
- 180
- 1200
- 2500
- 5000

Values:
- 3378.5
- 2945.94
- 150.09
- 6.53
- 1.49
- 0.5
Progressive Composition of Exhaust

Conventional Boiler

Furnace Exhaust

Post Condensation 1

Post Condensation 2

Post Condensation 3

Post Condensation 4

Final Exhaust

- O2
- N2
- CO2
- SO2
- H2O
# Flow Conditions (Conventional)

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Recirculating</th>
<th>Final Exhaust</th>
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<tbody>
<tr>
<td>Flow (lb/hr)</td>
<td>3,642,100</td>
<td>4,154,248</td>
<td>51,700</td>
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Ratio of conventional exhaust mass to condensed exhaust ≈ 70/1

Ratio of high-pressure exhaust volume ≈ 31,000/1

Example Benefit: Elemental mercury at high volumetric concentration in final bleed stream, suitable for removal by conventional methods.
IPR Technical Approach

- Heat Transfer
- Solution Chemistry
- Thermodynamics

- Computer Model Equilibrium
- Economic Analysis
- Laboratory Dynamic Steady State Column Characterization
- Bench-Scale Demonstration Compression Characterization PM/Hg fate
- Materials
Parametric computer model of wet flue-gas heat exchanger
IPR Technical Approach

Heat Transfer | Solution Chemistry | Thermodynamics

Computer Model Equilibrium

Laboratory Dynamic Steady State Column Characterization

Bench-Scale Demonstration Compression Characterization PM/Hg fate

Economic Analysis

Materials

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Laboratory Column Model
Hurdles To Effective Implementation

1. Hybrid heat exchange
2. Two phase compression
3. Wastewater treatment
4. Corrosion
5. Leakage
6. Heat recovery
7. Advanced combustion designs
8. Detailed design and optimization
9. Cost of $O_2$ (capital, operational, energy)
IPR Technical Approach

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- Bench-Scale Demonstration Compression Characterization
  PM/Hg fate

- Materials
FY 2002 On-site Review
August 20-21, 2002

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Bench-scale System Model

Based on Model BNCH12

Example with no recirculation and CO₂ primary air

Diversion Stack

Cooling water

Cooled Combustion Vessel

Oxygen

Carbon Dioxide

Coal

Cyclone/Baghouse

Chemical injection

Wet Heat Exchanger

Cooling Water

500 lb/hr

Cool gas

Filter

Compressor

500 lb/hr

500 lb/hr

Cooling water

2,000 psia

91% CO₂, 1.5% N₂, 7% O₂, 0.5% H₂O

Liquid CO₂ out

80 lb/hr

HP Regulator

Accumulator

LP Regulator

Pressure measurement

Gas analysis

Flow measurement

O₂ measurement

SO₂ measurement

Temperature measurement

91 lb/hr

21 lb/hr

2,000 psia

Gas analysis

Temperature measurement

Pressure measurement

SO₂ measurement

Flow measurement

O₂ measurement

Temperature measurement

91 lb/hr

21 lb/hr

2,000 psia

Gas analysis

Temperature measurement

Pressure measurement

SO₂ measurement

Flow measurement

O₂ measurement

Temperature measurement

Junk Yard Wars Approach

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Demonstration System

- Challenge from Jupiter 8/5/04
- Acceptance of challenge 8/22/04
  - Incremental approach
  - Off the shelf equipment
  - Primary air recirculation (oxy-fuel)
  - No applied heat recovery
- Beginning of detailed design 8/15/04
- Beginning of construction 8/30/04
- Successful operation 11/3/04
Results

• > 99% of SO₂ removed
• All flue gas condensable at 1,500 psia
• Hg capture volume reduced as predicted
• All particulates removed from system
Thank you for your attention