Future Combustion Technologies:
Chemical Looping Combustion
Direct Power Extraction
Pressure gain combustion

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Industrial boilers: smaller size enables early application of low-cost carbon capture. Smaller CO₂ volume can be used in EOR, future enhanced gas recovery, or converted to niche chemicals with renewable/waste energy.

**ICMI Research Areas**

- **Chemical looping:** Eliminates the need for air separation in oxy-fuel systems.
- **CO₂ Conversion:** Making CO₂ a feedstock with renewable/waste energy.
- **Chemical Looping:** Low-cost CO₂ Capture for coal or NG boilers.
- **CO₂ and Shale Formations:** Defining the potential for storage.
- **And Enhanced Natural Gas Recovery**

**Comparison of CO₂ capture costs**

Chemical looping eliminates the need for air separation in oxy-fuel systems.

<table>
<thead>
<tr>
<th>Cost of CO₂ Removed ($/tonne)</th>
<th>Relative to Supercritical PC without capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td></td>
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<tr>
<td>40</td>
<td></td>
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<tr>
<td>30</td>
<td></td>
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<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
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<td>0</td>
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</table>

- **Post-Combustion**
- **Oxycombustion**

- **A – Supercritical PC w/Current Amine**
- **B – Ultrasupercritical PC w/Current Amine**
- **C – USC PC w/Amine + Adv. Compress**
- **D – USC PC w/Advanced CO₂ Sorbent + Adv. Comp.**
- **E – USC PC + Adv. CO₂ Membrane + Adv. Comp.**
- **H – Advanced Oxycombustion Power Cycles**
Project Objectives

- Develop simulation models that will be powerful tools to accelerate technology deployment
  - Minimize deployment cost and risk
  - Identify gaps for further targeted research
- Experimental data to calibrate simulation models
  - Design, install, and operate chemical looping reactor (CLR) facility
  - Develop sensors and diagnostics
  - Develop kinetic database and improved carriers
- Conduct techno-economic analysis to project costs and benefits of deploying technology developed in this initiative

Supports DOE’s goal of beginning widespread, affordable deployment of Carbon Capture and Storage (CCS) technologies within 8 to 10 years
Technical Approach

**Combined Experimental/Modeling**

- Integrated Reacting Unit
- Combined Experimental/Modeling
- Fuel Conversion
  - CO₂ leakage
- Solids Circulation Rates
- Process Design
  - Inputs/Outputs
  - Cold - Flow Circulating Experiment
  - Oxygen carrier development and testing
- Attrition Resistance
  - Attrition Test
  - ASTM D5757
Cold-flow hydrodynamics for chemical looping

- Minimum Fluidization
- L Valve Tests
- Provides information for Hot Flow

\[ y = 0.6907x + 1.4692 \quad R^2 = 0.8826 \]

\[ y = 0.0286x + 32.963 \quad R^2 = 0.8215 \]
Solid Circulation Rate Measurements

- Three Techniques:
  - Solids Cut-Off
  - Microwave
  - $\Delta P$ Crossover

Measured solids flow rates (cold flow) are being used to validate model predictions.

Microwave sensor will be considered for hot reactive test.
Chemical Looping Reactor – status

50 kWth, 1000 °C, electrically heated input flows, refractory insulated, currently near atmospheric pressure operation

- Rig operational with excellent temperature control.
- Balky solids flow so far – carrier transport being improved.
- Batch mode testing data (next slide).

Deposits on fuel reactor distributor plate.

L-valve

Red arrows- solids flow
Batch CLR Reactions (5% CH4/N2; 8” bed)

Batch mode: Expected temp. drops (not circulating)
Attrition Testing

• The ASTM 5757D standard has been identified and utilized for testing of materials.

• Post and Pre-analysis of shape and particle size distribution is carried out via SEM and QICPIC.

• Hematite has shown a stronger attrition resistance than FCC catalyst in the unreacted state.

• The system has also been utilized to optimize the attrition resistance of other oxygen carrier materials.
CLC Techno-economic overview

Natural Gas Steam Generator Capacity
• 27,500 lb/hr (~10 MW Thermal) and 275,000 lb/hr (~100 MW Thermal)
• 600 psi with 100°F of superheat steam

Application: Steam Conditions, Availability Requirement, Constraints (e.g. emissions)

CLC Process Concept (e.g. fluid beds, circulating beds, moving beds; solids circulation)

CLC Process Flow Schematic / Process Simulation

M&E Balances

Process Design (equipment sizing, pressure drops, heat losses, external resources)

Equipment Costs

Operating Costs

Steam Cost

The reference CLC case:
• Circulating fluid bed reactors
• Literature iron oxide carrier kinetics

Reactor models completed based on literature carrier kinetics
Cost estimated: completed based on cost correlations

Aspen simulation
## Reference Plant Cost of Steam

<table>
<thead>
<tr>
<th></th>
<th>$ /1000 lb steam</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed operating cost</td>
<td>0.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Variable operating cost</td>
<td>2.5</td>
<td>14.3</td>
</tr>
<tr>
<td>water</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>electricity</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>oxygen carrier</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Capital Recovery</td>
<td>2.3</td>
<td>13.3</td>
</tr>
<tr>
<td>Fuel</td>
<td>12.3</td>
<td>69.6</td>
</tr>
<tr>
<td>Total cost of steam</td>
<td>17.7</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Note: The total cost of steam is calculated as the sum of all individual costs.
# Perspective on Parameter Importance

assumes changes in parameters are within operating range

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Vessel Height</th>
<th>Vessel Diameter</th>
<th>Circ. Rate</th>
<th>Boiler Eff.</th>
<th>Auxiliary Power</th>
<th>CO₂ Capture</th>
<th>Equip. Cost</th>
<th>Cost of Steam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Reactivity (literature)</td>
<td>Large + = -</td>
<td></td>
<td></td>
<td>Small + = -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrier Loss (0 %) and Price ($0/lb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Small + = -</td>
<td></td>
<td>Medium + = +</td>
<td></td>
</tr>
<tr>
<td>Carrier Size (0.28mm) and Density (203 lb/ft³)</td>
<td>Small + = -</td>
<td></td>
<td>Small + = -</td>
<td>Small + = -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrier Conversion (from reducer 47%; from oxidizer 95%)</td>
<td>Medium + = +</td>
<td>Large + = -</td>
<td>Small + = +</td>
<td>Small + = -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor Temperature (1700 F)</td>
<td>Small + = -</td>
<td>Small + = +</td>
<td>Small + = -</td>
<td>Small + = -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor Velocities (reducer outlet 33.6 fps; oxidizer outlet 29.4 fps)</td>
<td>Large + = +</td>
<td>Large + = -</td>
<td>Small + = +</td>
<td>Small + = -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas Conversion (97.5%)</td>
<td>Medium + = +</td>
<td></td>
<td>Small + = -</td>
<td>Small + = -</td>
<td>Large + = +</td>
<td>Small + = +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxidizer XS O₂ (3.6mol % in off-gas)</td>
<td>Small + = -</td>
<td>Small + = +</td>
<td>Small + = -</td>
<td>Small + = -</td>
<td></td>
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</table>
Making Oxy-fuel an \textbf{Advantage}  
\textit{Oxy-fuel combustion produces CO}_2 \textit{concentrated flue gas – at a cost.}

- Producing pure oxygen requires a lot of energy!
- If one could find a way to make significant extra power \textit{because of the available oxygen, oxy-fuel would be an advantage.}
- Oxy-fuel already provides an advantage for process industries that benefit from high temperatures (e.g., glass making, steel).
- Oxy-fuel already provides advantages in propulsion (rocket engines)
- How can you make oxy-fuel an advantage for power generation?

Steel production

Space propulsion

Power generation
“Direct Power Extraction” - making oxy-fuel combustion an advantage

• **Description:** Extracts power using magnetohydrodynamics (MHD)
  – Higher efficiency because it *uses* temperatures only possible with oxy-fuel.
  – Provides “capture-ready” feature of oxy-fuel; uses steam “bottoming” cycle.
  – Could be retrofit to coal steam plants (natural gas) – later converted back to coal

• **What is the R&D**
  – Develop durable electrodes, current control, and optimal hydrodynamics.
  – Validate simulation tools and predict optimal generator configurations.
  – Identify and test new approaches for power extraction.

• **Benefits**
  – May allow retrofit of power plants with higher efficiency *and* carbon capture.
  – Potential spin-offs to other industries/applications:
    • Electrically conductive ceramics, arc prevention/control (material processing)
    • Advanced propulsion and power (with DOD, NASA)
Direct Power Extraction (via MHD)

- **Magnetohydrodynamic (MHD) Power Generator:**
  Use a strong magnet and convert kinetic energy of conductive gases directly to electric power.

- **Higher thermal efficiency via higher temperatures**
  - Need to use in combined cycle
  - Synergy w/ oxy-fuel for CCUS

- **MHD cycle: turns efficiency disadvantage (oxygen production) to efficiency advantage (power production)!**

_A USSR built MHD Generator From Petrick and Shumyatsky (1978)_

![Plot from Okuno et. al. 2007](image)

*MHD generator concept proven in 1980s w/ grid transferred power in both U.S. and USSR*
R&D Approach – Past & Present

- **Legacy effort (pre 1992) largely proof-of-concept.**
  - Expensive large-scale demonstrations.
  - Coal power generation only (in U.S.).
  - Did not consider CO₂ control.
  - Primitive simulation tools, magnets versus now.

- **Present effort: targeted on key technical issues, not demonstration**
  - Validated simulation to assess scale performance.
  - Lab experiments on key challenge issues – build on legacy effort.
  - New approaches to power extraction, generator geometry.
  - New magnet technology, materials, and simulation.
  - Identify “spin-off” technologies and synergies.
    (Organize with gov’t agencies Industry, etc.)

What is the advantage of pressure-gain combustion?

Michael Idelchik, Vice President of Advanced Technologies at GE Research…Research…Sept 2009 interview on Pulse Detonation for Technology Review published by MIT.

“An existing turbine burns at constant pressure. With detonation, pressure is rising, and the total energy available for the turbine increases. We see the potential of 30 percent fuel-efficiency improvement. Of course realization, including all the hardware around this process, would reduce this.

I think it (efficiency gains) will be anywhere from 5 percent to 10 percent. That's percentage points--say from 59 to 60 percent efficient to 65 percent efficient. We have other technology that will get us close [to that] but no other technology that can get so much at once. It's very revolutionary technology.

The first application will definitely be land-based--it will be power generation at a natural-gas power plant. “

“If we can turn 5% pressure loss in a turbine into 5% pressure gain, it has the same impact as doubling the compression ratio” – Dr. Sam Mason, Rolls-Royce (2008)*

* Quotation courtesy Fred Schauer AFRL
Technical challenges & approaches

- Fuel Injection
- Fuel/Air Mixing
- Backflow due to detonation
- DDT / Initiation

- Detonation wave directionality
- NOx Emissions

- Maintain Pgain
- Quasi-steady flow

- Unsteady heat transfer
- Cooling flow

NETL combustor rig planned for component test

Simulation of wave propagation
(I. Celik, NETL-RUA, WVU)

Fundamentals of detonation physics with natural gas
(D. Santavicca, NETL-RUA, Penn State)
Summary

• Advanced combustion approaches may enable efficient carbon dioxide management:
  – Chemical looping: inherent CO2 separation.
  – Pressure-gain combustion: step change in generation efficiency for IGCC, NGCC could offset capture penalty.

• Today’s presentation:
  – NETL-ORD Chemical Looping studies: development and validation in progress.
  – Overview of initial studies on direct power extraction.
  – Potential for pressure-gain combustion: experiments coming.
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