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

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NETL Office of Research and Development

2013 NETL CO_2 Capture Technology Meeting
July 8 – 11, Pittsburgh PA

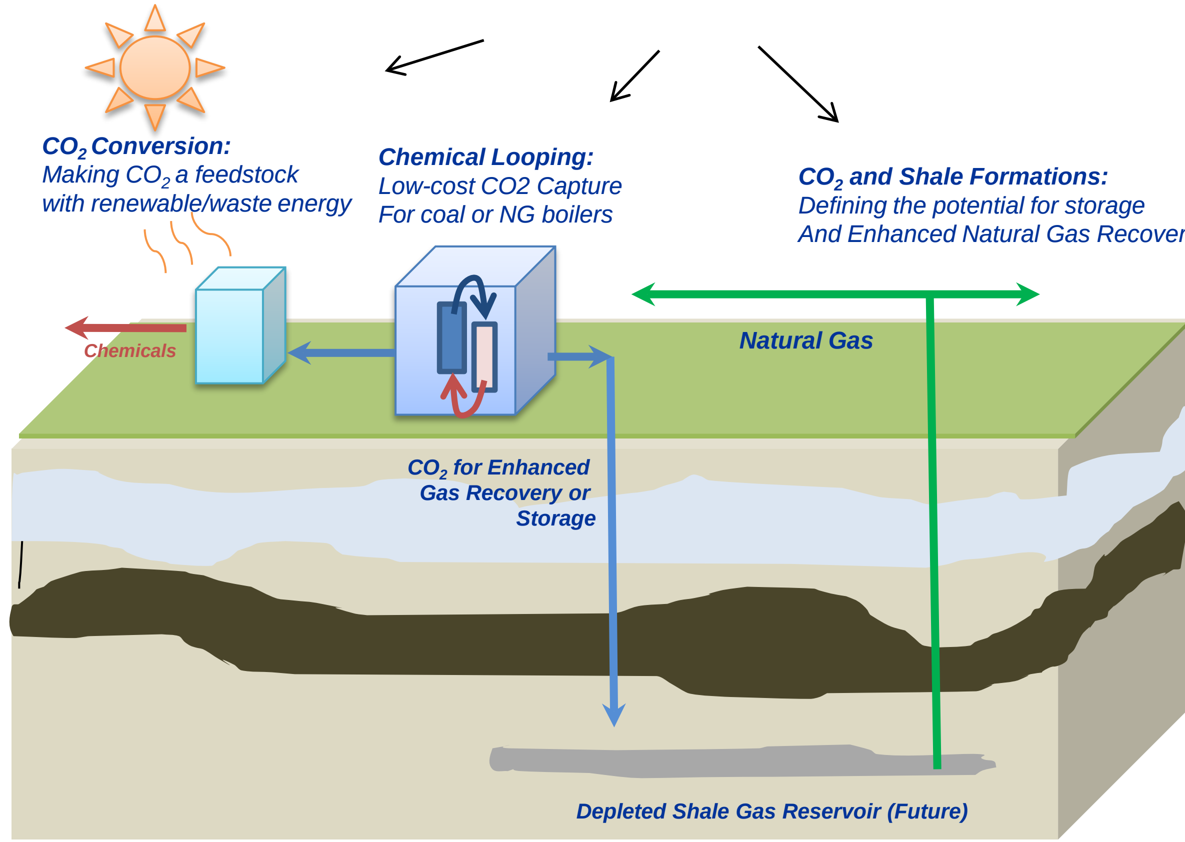
Industrial Carbon Management Initiative

Innovative Options for Future Power

Industrial boilers: smaller size enables early application of low-cost carbon capture.

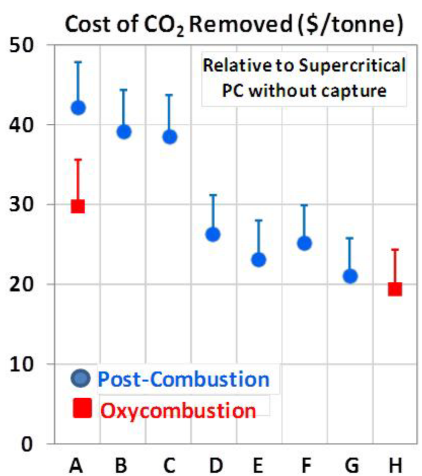
Smaller CO_2 volume can be used in EOR, *future* enhanced gas recovery, or converted to niche chemicals with renewable/waste energy.

ICMI Research Areas



Comparison of CO2 capture costs

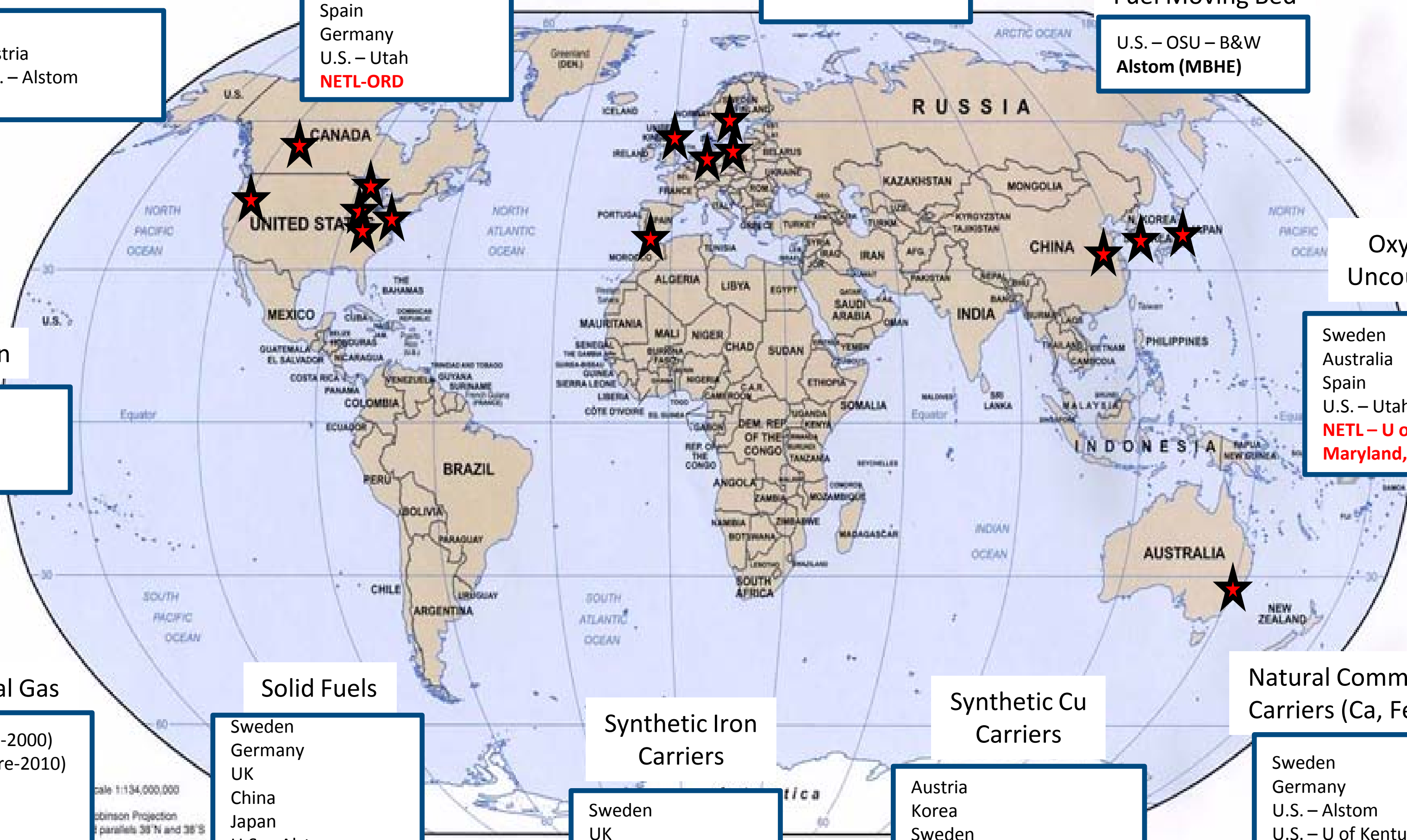
Chemical looping eliminates the need for air separation in oxy-fuel systems.



ICMI will quantify capture cost for Industrial applications

A – Supercritical PC w/Current Amine
B – Ultrasupercritical PC w/Current Amine
C – USC PC w/Amine + Adv. Compress
D – USC PC w/Advanced CO_2 Sorbent + Adv. Comp.
E – USC PC + Adv. CO_2 Membrane + Adv. Comp.
F – Adv. USC PC + Adv. Sorbent + Adv. Comp.
G – Adv. USC PC + Adv. Membrane + Adv. Comp.
H – Advanced Oxycombustion Power Cycles

CLC – Worldwide Interest



Multiple CFBs
- Austria
- U.S. – Alstom

Air CFB/ Fuel BFBR
- Korea
- Sweden
- Spain
- Germany
- U.S. – Utah
- **NETL-ORD**

Air CFB/ Fuel Spouted FBR
- China

Fuel Moving Bed
- U.S. – OSU – B&W
- **Alstom (MBHE)**

Oxygen Uncoupling
- Sweden
- Australia
- Spain
- U.S. – Utah
- **NETL – U of Pitt, Maryland, CMU**

Attrition
- Canada
- UK
- **NETL-ORD**

Natural Gas
- Japan (pre-2000)
- Sweden(pre-2010)
- Korea
- Spain
- Austria
- **NETL-ORD**

Solid Fuels
- Sweden
- Germany
- UK
- China
- Japan
- U.S. – Alstom
- U.S. – OSU-B&W
- U.S. – U of Kentucky
- U.S. – Utah
- NETL-ORD

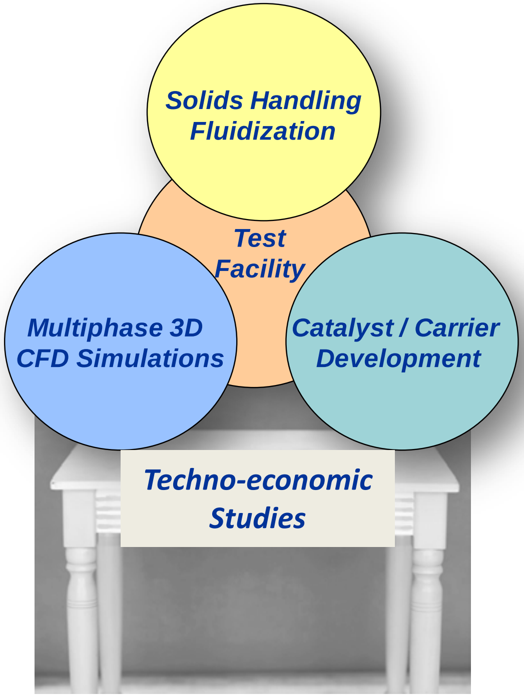
Synthetic Iron Carriers
- Sweden
- UK
- China
- U.S. – OSU-B&W
- **NETL-ORD**

Synthetic Cu Carriers
- Austria
- Korea
- Sweden
- Spain
- U.S. – Utah
- **NETL-ORD**

Natural Commodity Carriers (Ca, Fe, Cu)
- Sweden
- Germany
- U.S. – Alstom
- U.S. – U of Kentucky
- U.S. – Utah
- **NETL-ORD**

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**

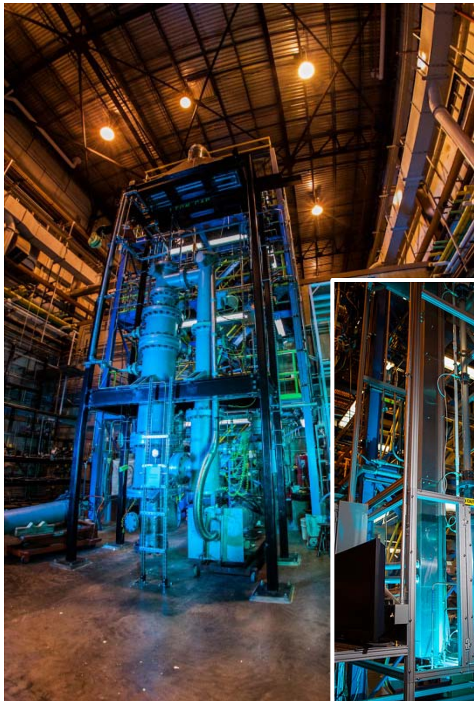


Supports DOE's goal of beginning widespread, affordable deployment of Carbon Capture and Storage (CCS) technologies within 8 to 10 years

Technical Approach

Combined Experimental/Modeling

Integrated Reacting Unit



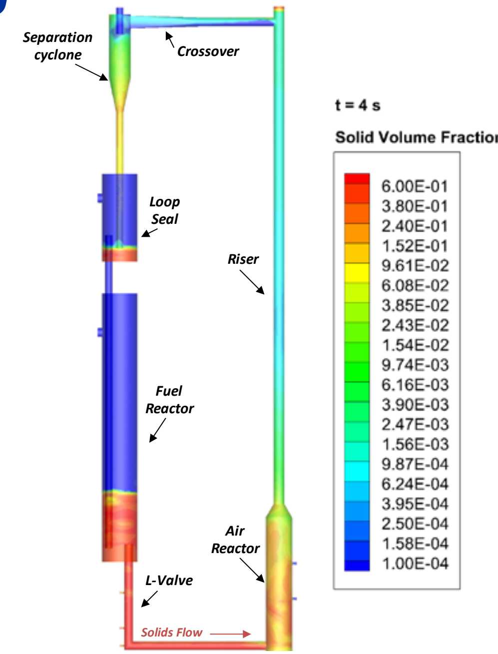
Cold - Flow Circulating Experiment

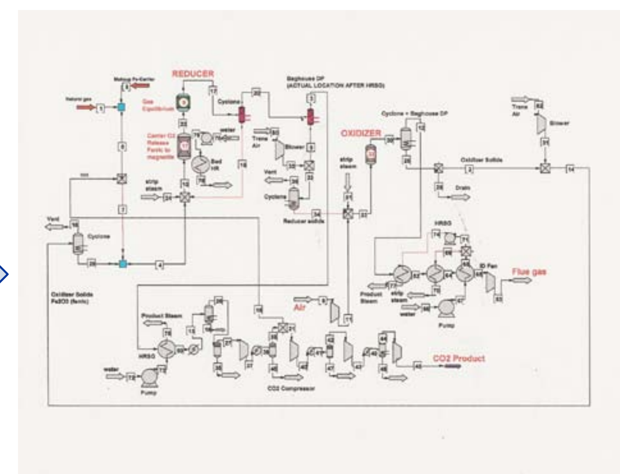
Fuel Conversion
CO_2 leakage

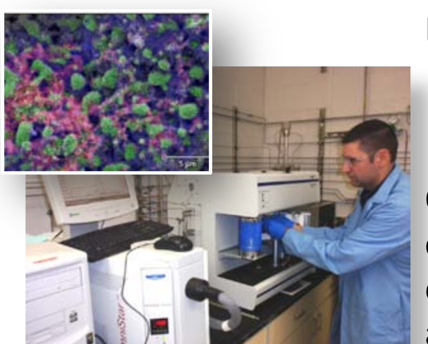
Solids Circulation Rates

Process Design Inputs/Outputs

Attrition Resistance







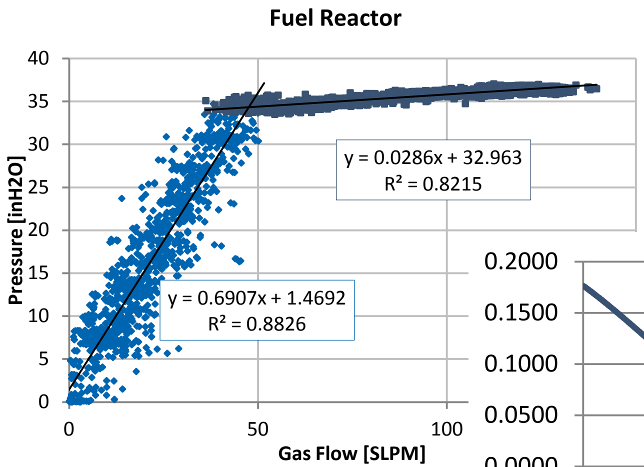
Oxygen carrier development and testing

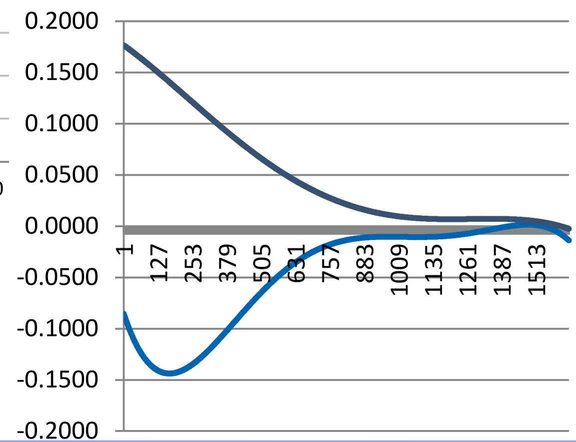
Attrition Resistance

Attrition Test
ASTM D5757

Cold-flow hydrodynamics for chemical looping

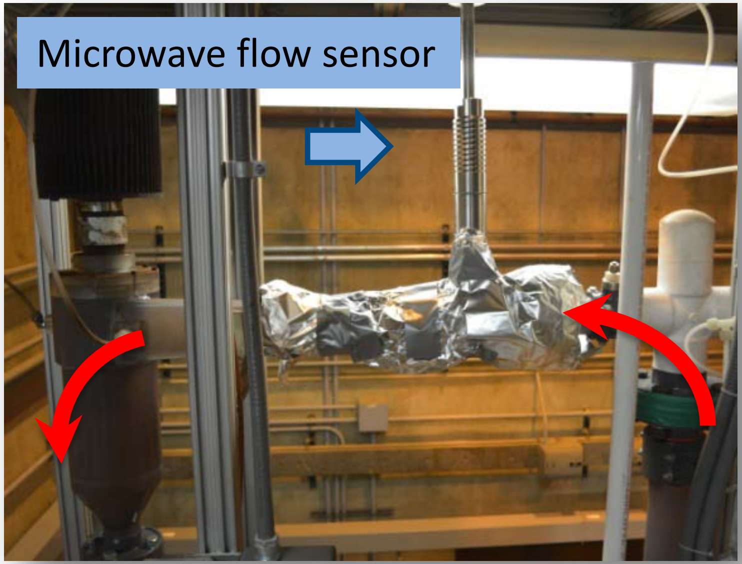
- Minimum Fluidization
- L Valve Tests
- Provides information for Hot Flow



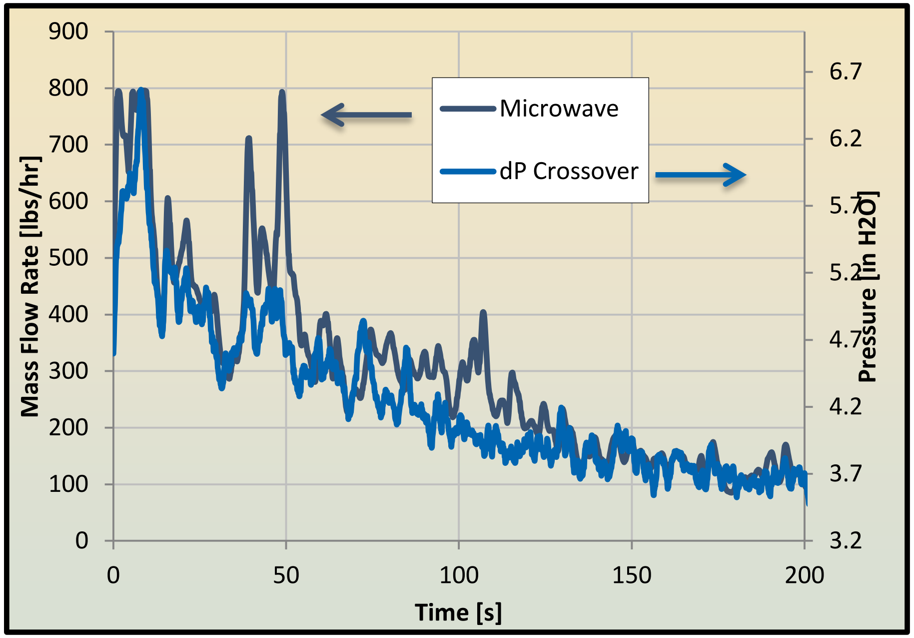


Solid Circulation Rate Measurements

- **Three Techniques:**
  - Solids Cut-Off
  - Microwave
  - ΔP Crossover



Red arrows-
solid circulation air to fuel reactor crossover



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

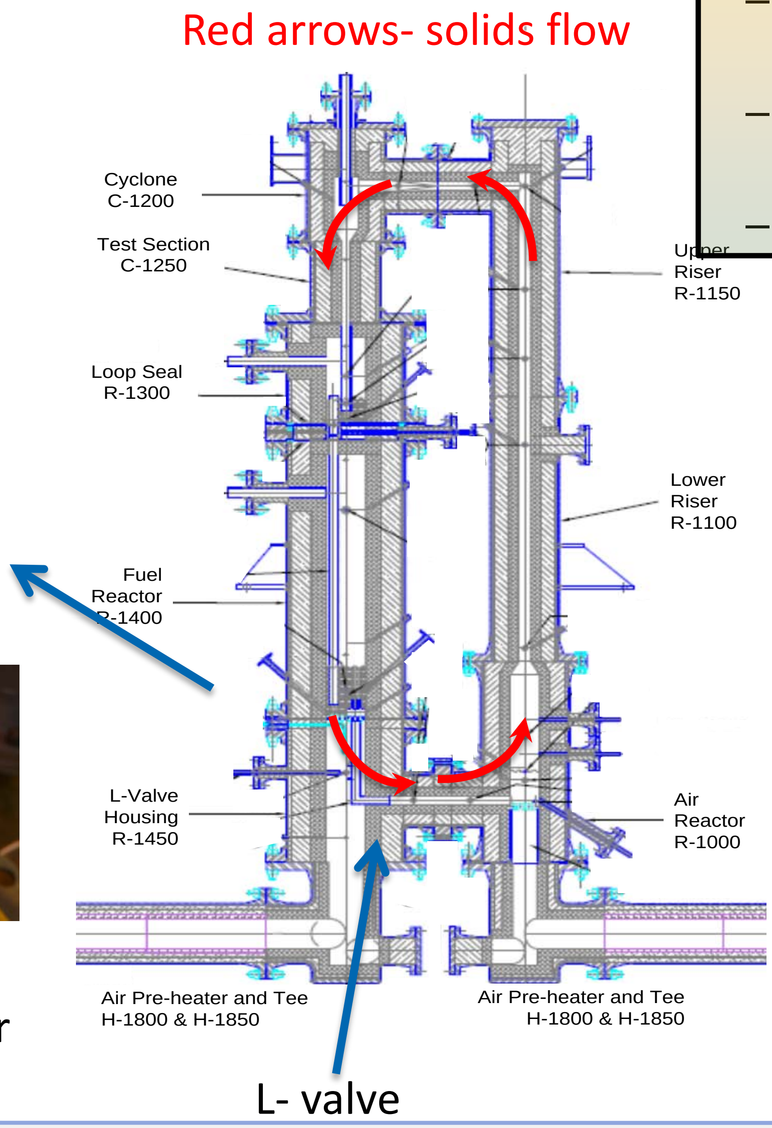
Microwave sensor will be considered for hot reactive test.

Chemical Looping Reactor – status

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

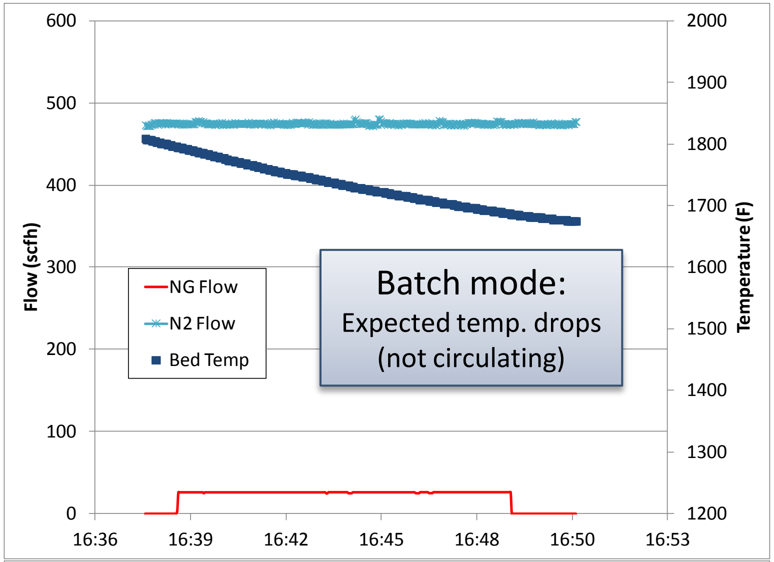
- Rig operational with excellent temperature control.
- Balky solids flow so far – carrier transport being improved.
- Batch mode testing data (next slide).

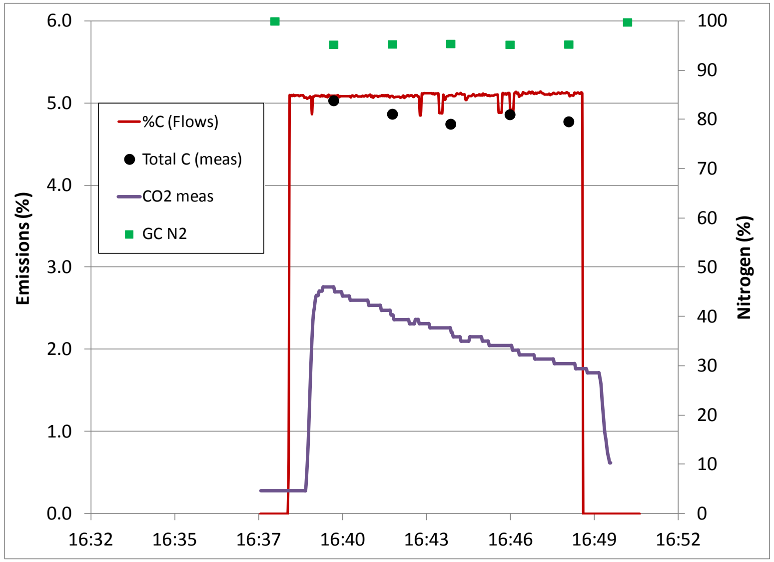
Deposits on fuel reactor distributor plate.

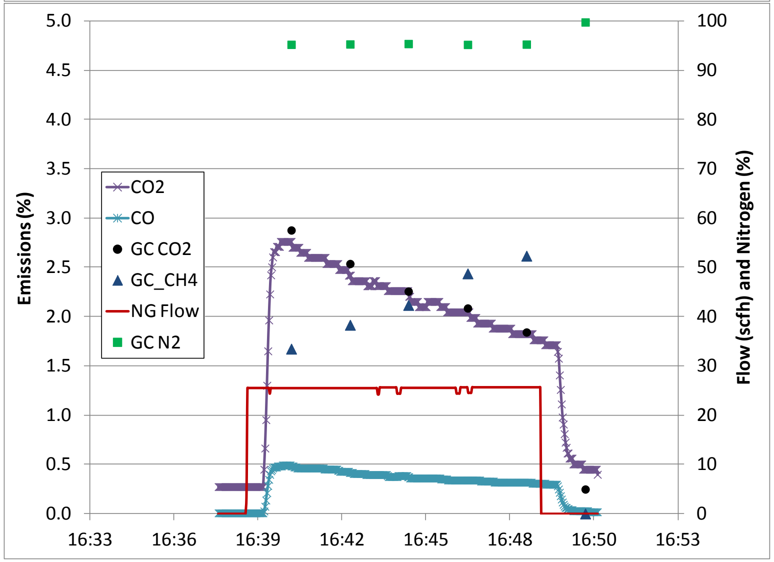


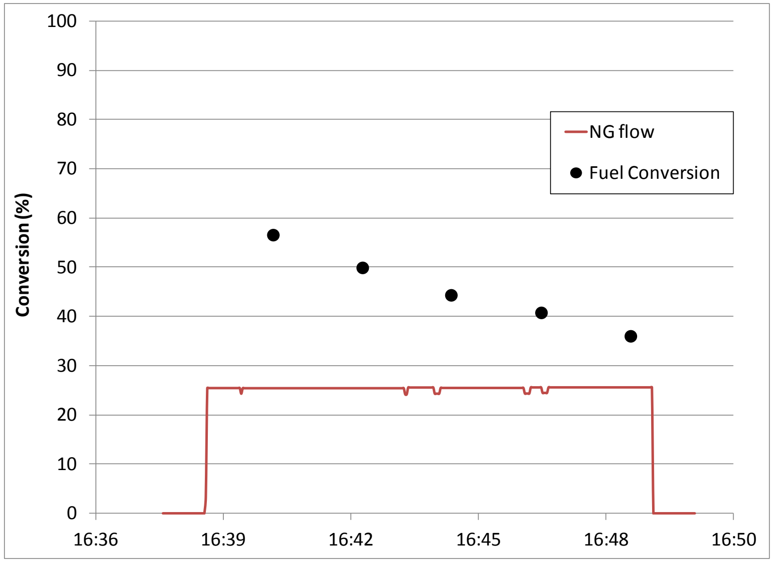
NETL

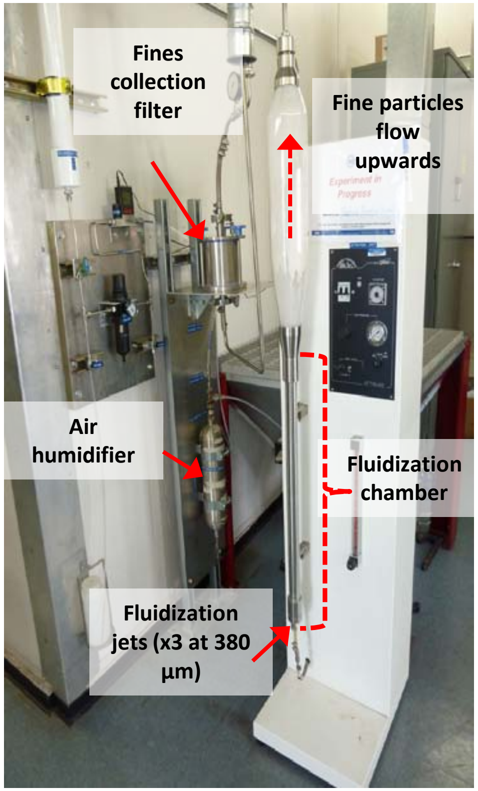
Batch CLR Reactions (5% CH4/N2; 8" bed)





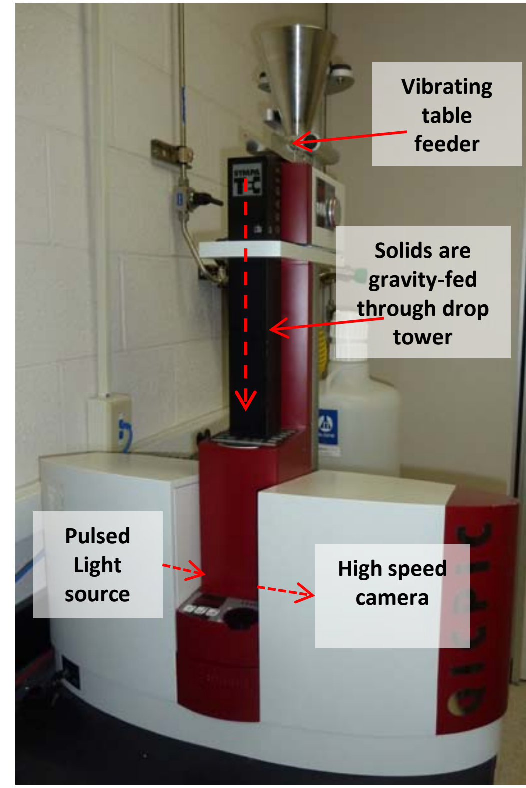


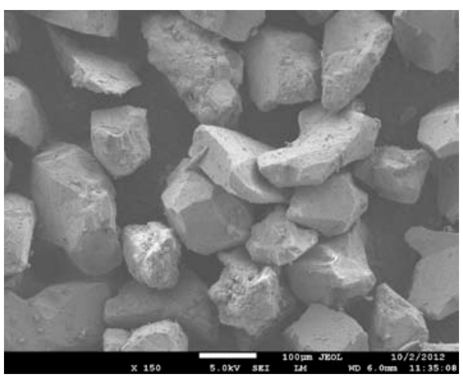




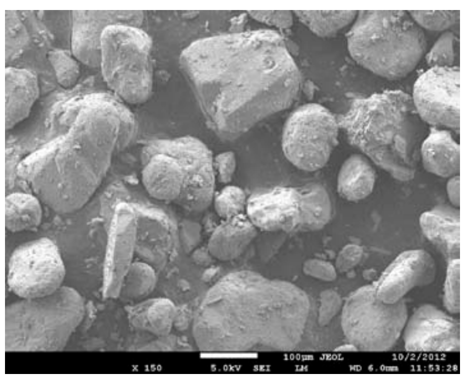
Attrition Testing

- 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.



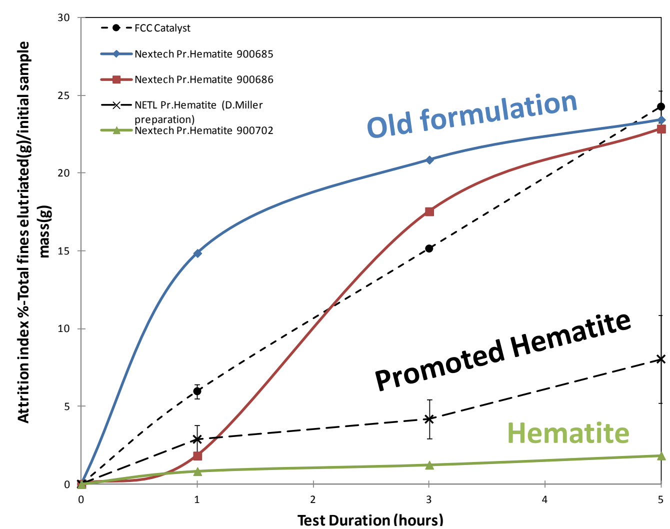


Pre-Attrition



Post-Attrition

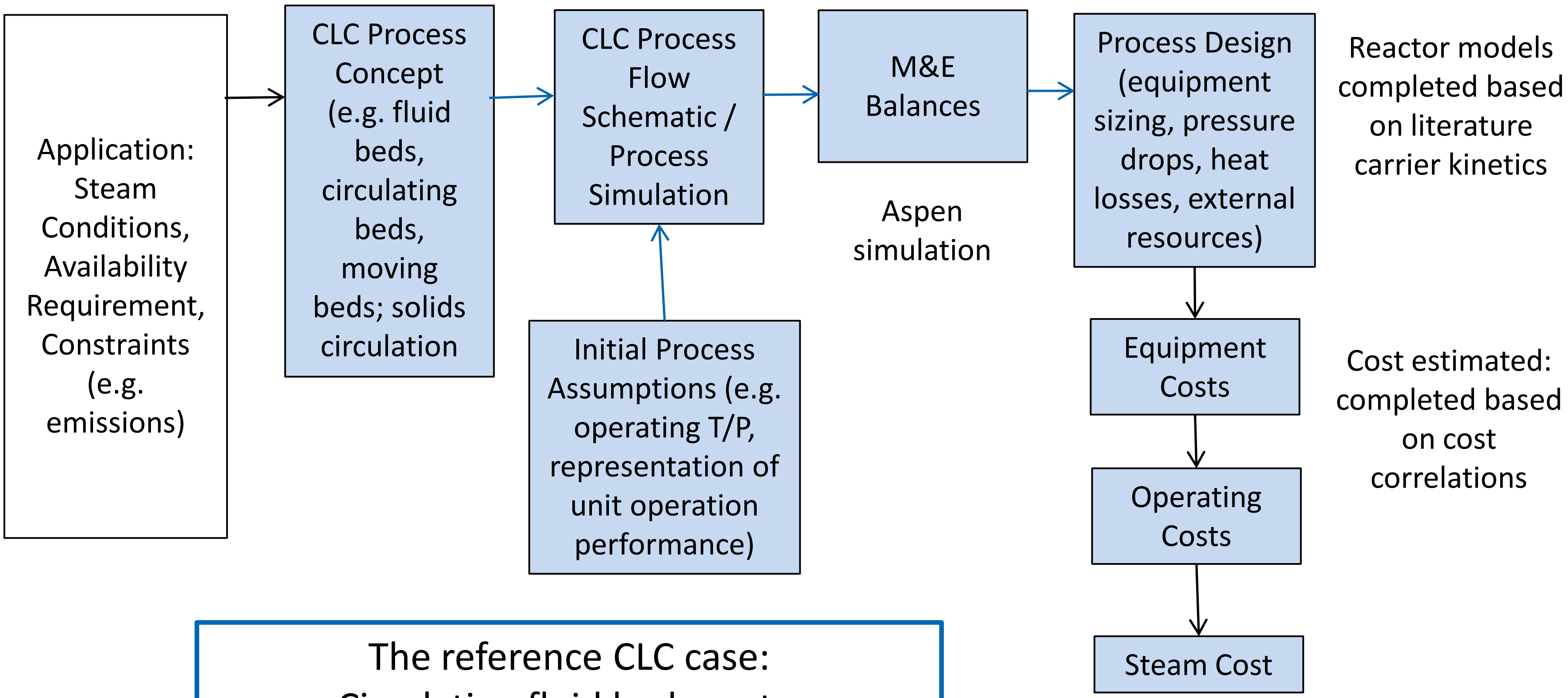
Particle abrasion, evidence of fine particles after attrition testing



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



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

Reference Plant Cost of Steam

	$ /1000 lb steam	%
Fixed operating cost	0.5	2.8
Variable operating cost	2.5	14.3
water	0.3	
electricity	2.3	
oxygen carrier	0	
Capital Recovery	2.3	13.3
Fuel	12.3	69.6
Total cost of steam	17.7	100.0

Perspective on Parameter Importance

assumes changes in parameters are within operating range

	Vessel Height	Vessel Diameter	Circ. Rate	Boiler Eff.	Auxiliary Power	CO_2 Capture	Equip. Cost	Cost of Steam
Carrier Reactivity (literature)	Large + = -				Small + = -		Small + = -	Small + = -
Carrier Loss (0 %) and **Price** ($0/lb)								Medium + = +
Carrier Size (0.28mm) and **Density** (203 lb/ft^3)	Small + = -				Small + = -		Small + = -	Small + = -
Carrier Conversion (from reducer 47%; from oxidizer 95%)	Medium + = +		Large + = -		Small + = +		Small + = +	Small + = +
Reactor Temperature (1700 F)	Small + = -	Small + = +			Small + = -		Small + = -	Small + =-
Reactor Velocities (reducer outlet 33.6 fps; oxidizer outlet 29.4 fps)	Large + = +	Large + = -			Small + = +		Small + = +	Small + = +
Natural Gas Conversion (97.5%)	Medium + = +			Small + = +	Small + = +	Large + = +	Small + = +	Small + = +
Oxidizer XS O_2 (3.6mol % in off-gas)	Small + = -	Small + = +		Small + = -	Small + = +		Small + = +	Small + = +

Making Oxy-fuel an *Advantage*

Oxy-fuel combustion produces CO_2 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 *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?**

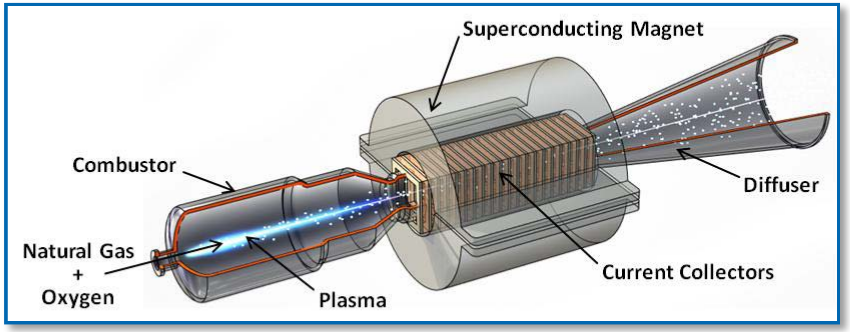
Steel production

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



MHD generator concept

High-temperature oxy-fuel combustion (with conductivity seed) accelerates through magnetic field to produce current. Hot exhaust used in conventional steam boiler.

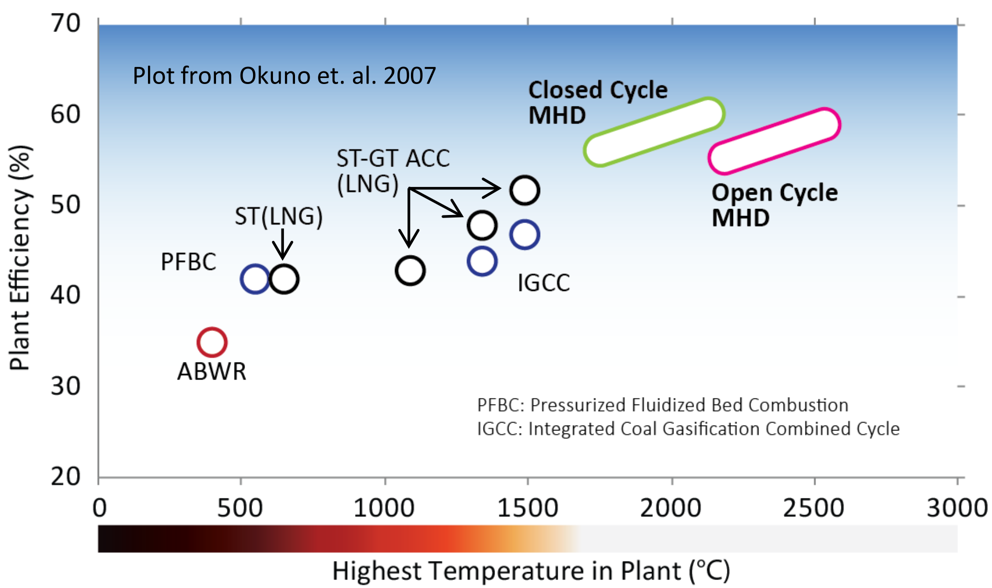
- **What is the R&D**
  - Develop durable electrodes, current control, and optimal hydrodynamics.
  - Validate simulation tools and predict optimal generator configurations.
  - Identify and test new approaches for power extraction.
- **Benefits**
  - May allow retrofit of power plants with higher efficiency 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)

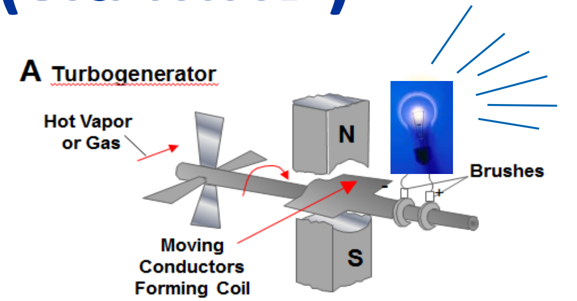
Direct Power Extraction (via MHD)

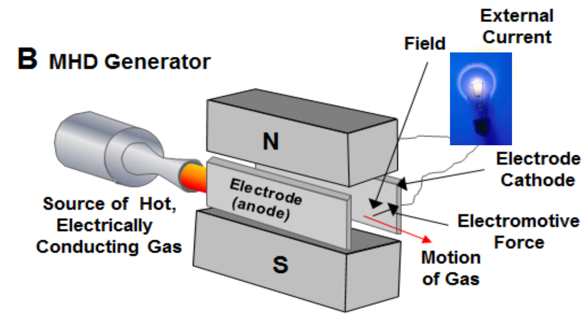
- **Magnetohydrodynamic (MHD) Power Generator:**
  Use a strong magnet and convert kinetic energy of conductive gases directly to electric power

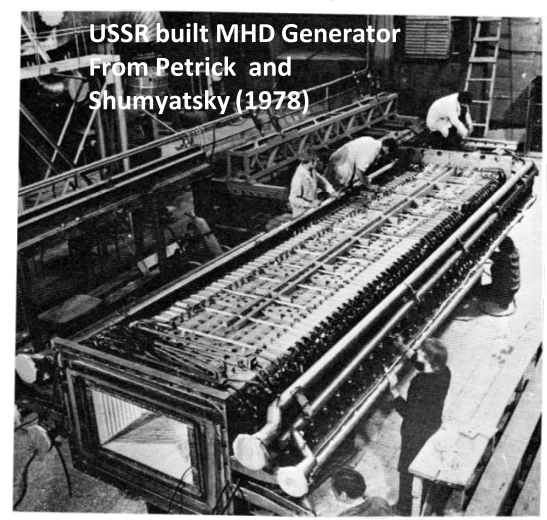
- **Higher thermal efficiency via higher temperatures**
  - Need to use in combined cycle
  - Synergy w/ oxy-fuel for CCUS

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





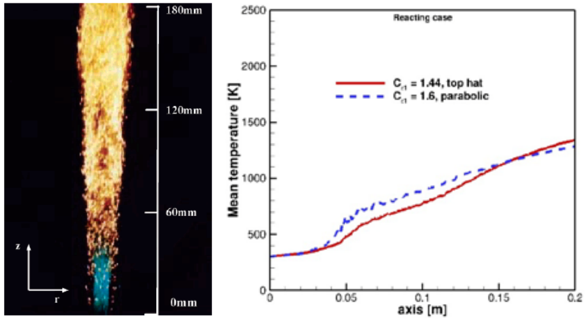




MHD generator concept proven in 1980s w/ grid transferred power in both U.S. and USSR

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 CO_2 control.
  - Primitive simulation tools, magnets versus now.

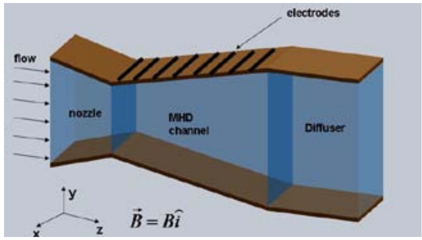


LES simulation for MHD flame conditions
(D. Haworth, NETL-RUA, Penn State.)

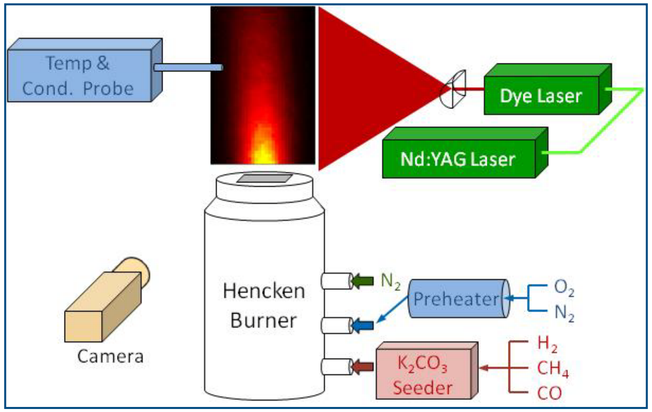
- **Present effort: targeted on key technical issues, not demonstration**
  - Validated simulation to assess scale performance.
  - Lab experiments on key challenge issues – build on legacy effort.
  - New approaches to power extraction, generator geometry.
  - New magnet technology, materials, and simulation.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

  (Organize with gov’t agencies
  Industry, etc.)

Woodside et. Al (2012). Direct Power Extraction with Oxy-Combustion: An Overview of Magnetohydrodynamic Research Activities at the NETL-RUA, 2012 International Pittsburgh Coal Conference, Pittsburgh, PA, USA, October 15 - 18, 2012.



Simulation of MHD tube
(I. Celik, NETL-RUA, WVU)



Measure of conductivity – NETL labs

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.

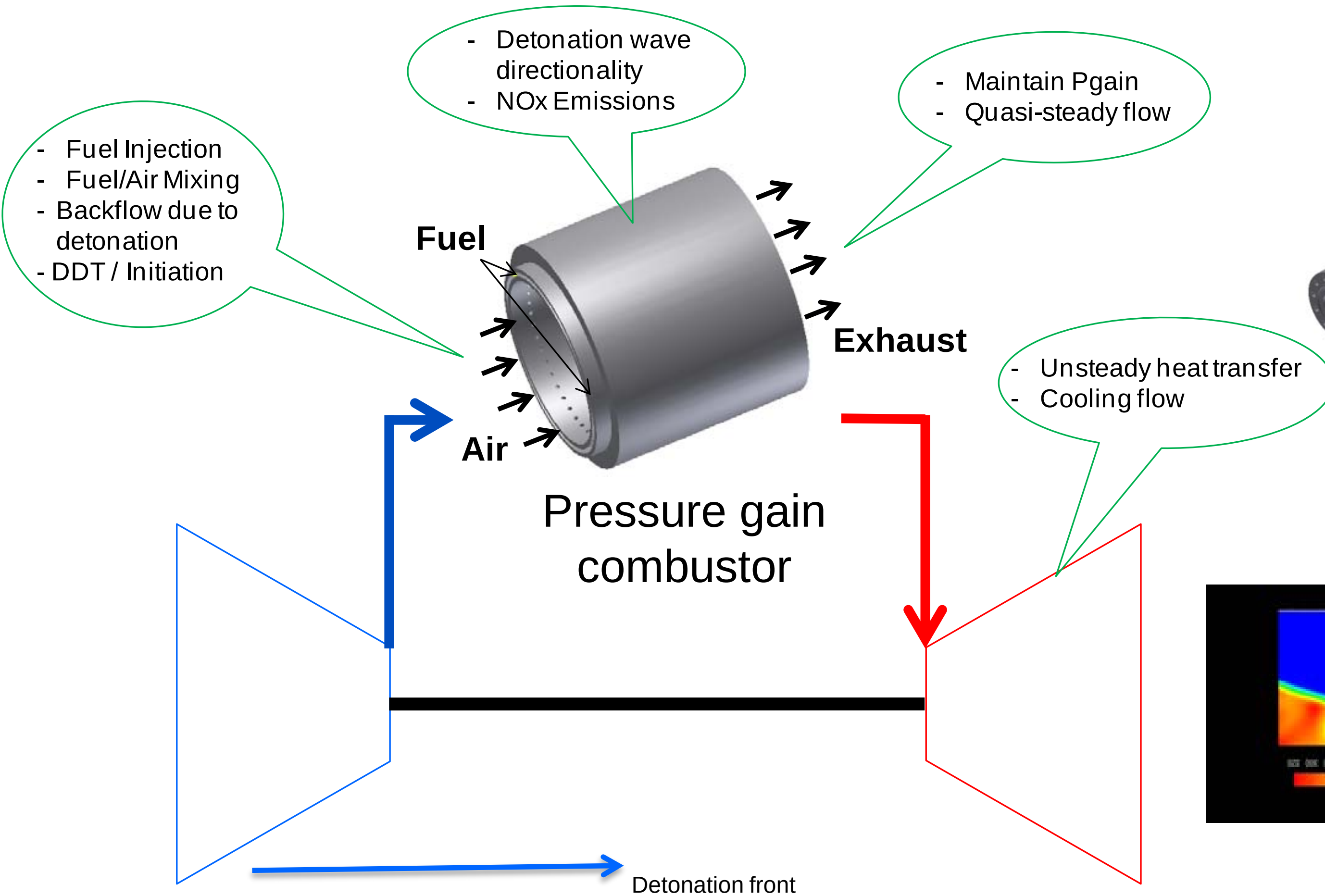
I think it (efficiency gains) will be anywhere from 5 percent to 10 percent. That's percentage points--say from ***59 to 60 percent efficient to 65 percent efficient***. We have other technology that will get us close [to that] but **no other technology that can get so much at once.** It's very revolutionary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

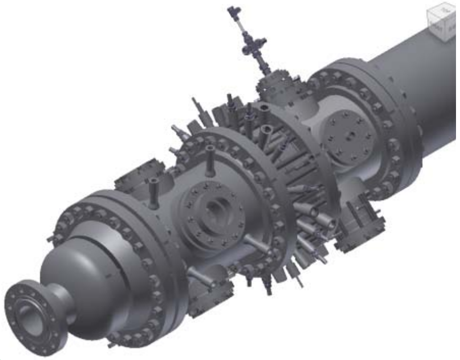
The first application will definitely be land-based--it will be power generation at a natural-gas power plant. "

"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)*****

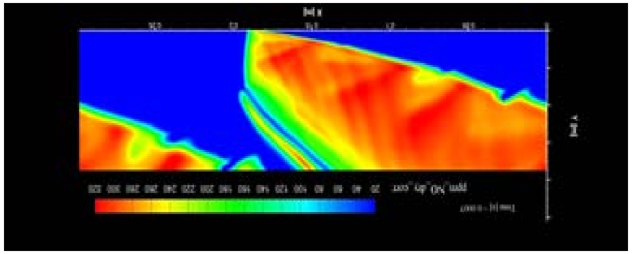
** Quotation courtesy Fred Schauer AFRL*

Technical challenges & approaches

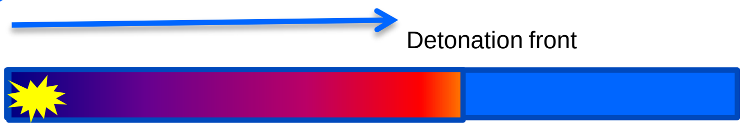




NETL combustor rig planned for component test



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.
  - Direct Power Extraction: making oxy-fuel an efficiency advantage.
  - 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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