NATIONAL ENERGY TECHNOLOGY LABORATORY

Overview of Application of Multiphase Flow in NETL's Energy Portfolio

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U.S. DEPARTMENT OF ENERGY

U.S. Energy Trends –
Ref: Annual Energy Outlook 2012 – Early Release

Figure 3. Electricity generation by fuel, 1990-2035 (trillion kilowatthours per year)

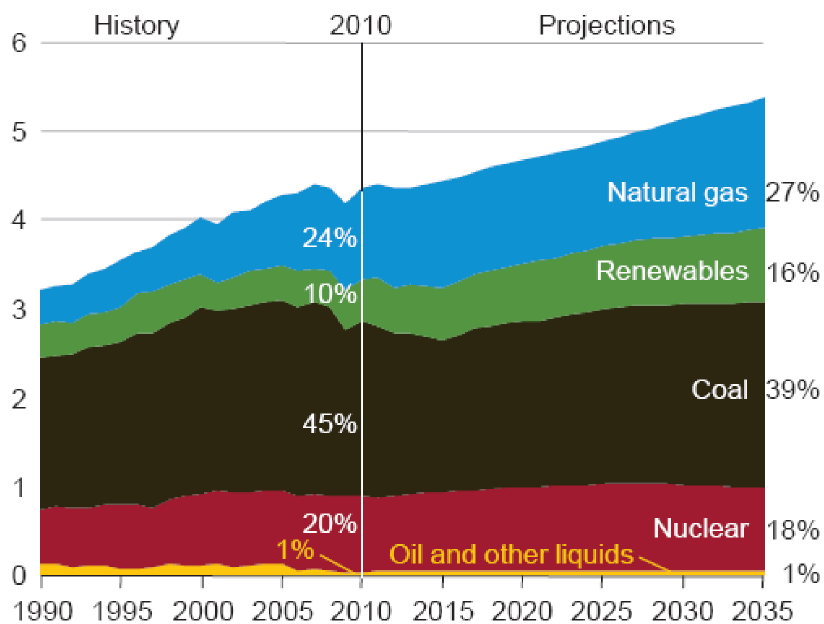
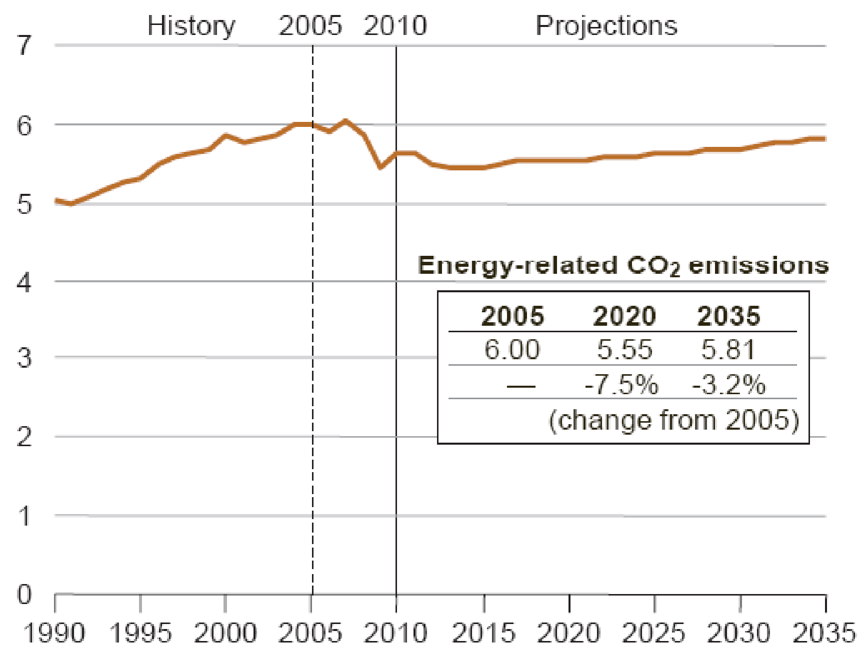


Figure 4. U.S. energy-related carbon dioxide emissions, 1990-2035 (billion metric tons)

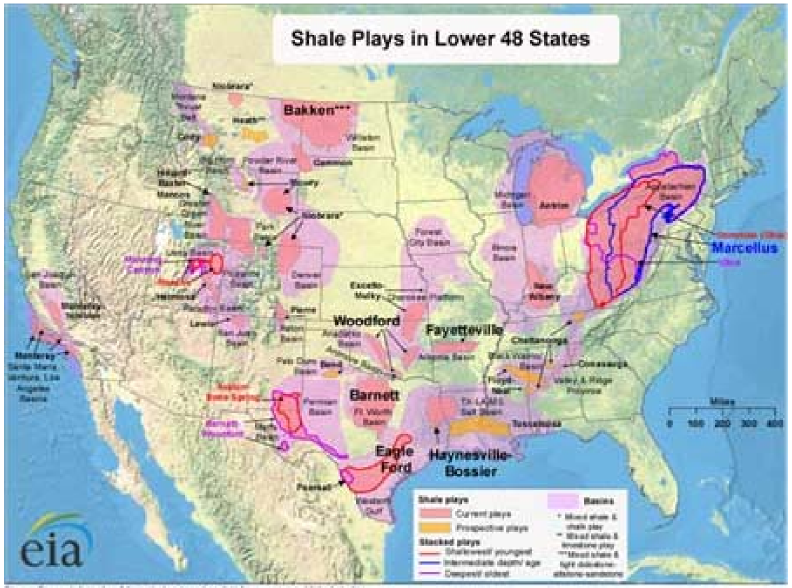


" Energy related CO2 emissions in 2035 are only 3 percent higher than in 2010 (as compared with the 10-percent increase in total energy use), and the carbon intensity of U.S. energy consumption falls from 57.4 to 53.8 kilograms per million Btu (6.3 percent decrease)" – AEO 2012 – Early Release

Implications From Future Energy Trends

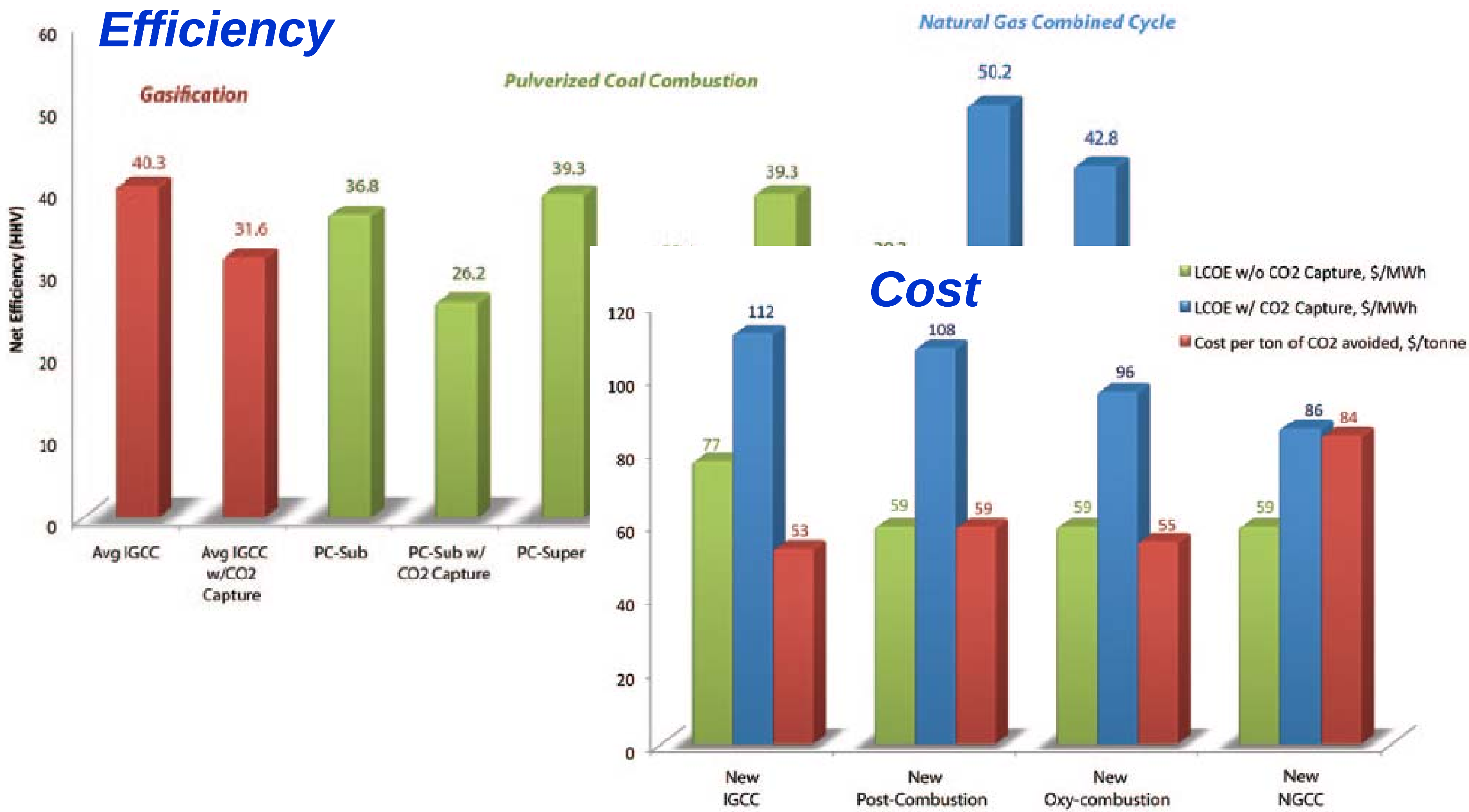
- **Coal will continue to play a significant role in electric power sector through 2035, but . . .**
- **Most of near-term growth in electric power will be fueled by natural gas**
  - NGCC efficiencies of 60-65% are currently being offered
  - Shale gas projected to meet near-term demand

How Does Multiphase Modeling Impact Future Energy Trends?



Source: Energy Information Administration based on data from various published studies
Updated: May 9, 2011

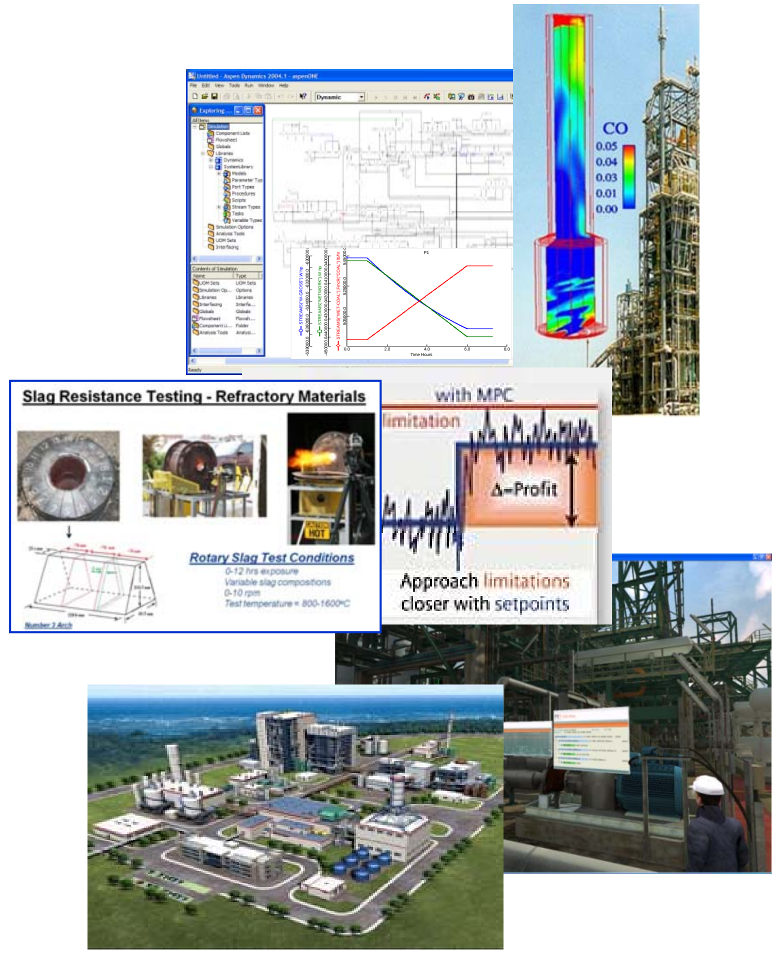
Comparison of Competing Technologies



Reference: www.netl.doe.gov Advanced Carbon Dioxide Capture R&D Program: Technology Update, May 2011

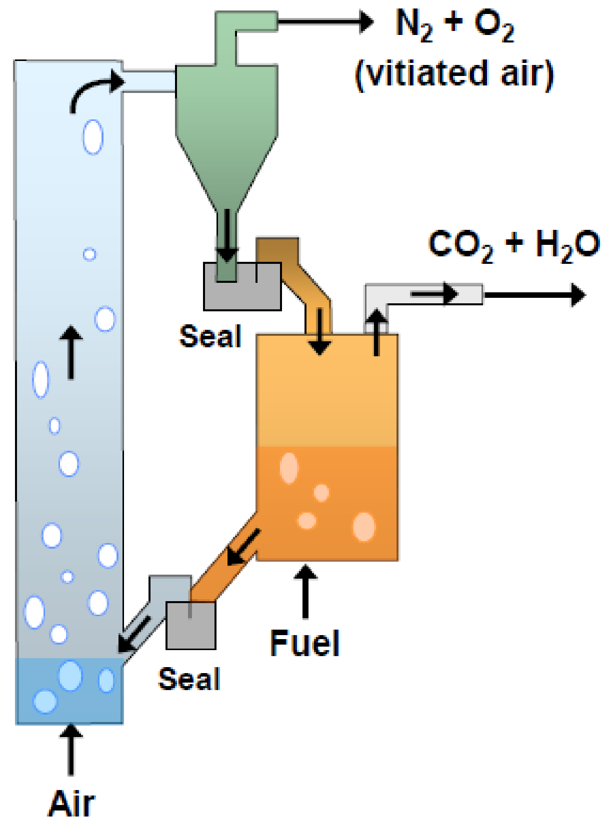
Multi-phase flow in existing and emerging energy technologies at NETL

- **Gasifiers**
  - Entrained flow
  - Feed systems
- **Sorbent systems for CO2 capture**
  - Hydrodynamics
  - Heat exchanger
- **Chemical Looping**
  - Hydrodynamics
  - Combustion efficiency
  - Solids handling and control



What Is Chemical Looping Combustion?

- **Indirect combustion process**
  - Uses solid intermediate (oxygen carrier)
  - Air and fuel do not mix directly
- **Air reactor**
  - Oxidizes solid carrier
  - Gas outlet is vitiated air
- **Fuel reactor**
  - Reduces solid carrier (oxidizes fuel)
  - Produces binary gas mixture
    - CO_2 and H_2O
    - CO_2 separated via condensation of H_2O
- **Overall heat release is same as air/fuel combustion**



Why Chemical Looping?

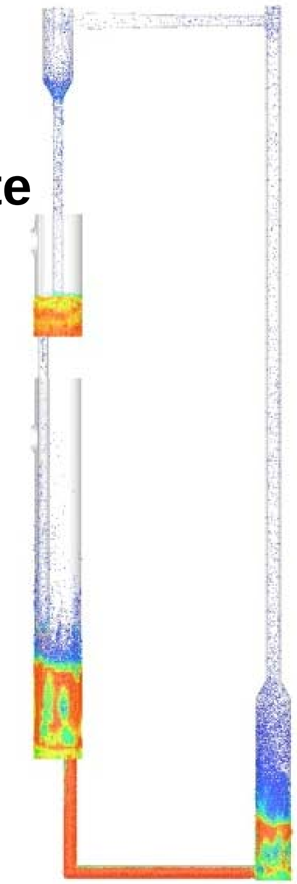
- **Early systems studies show CLC systems can exceed DOE goals**
  - Energy penalties associated with CO2 removal are small (relative to other approaches)

- **Builds on existing circulating fluidized bed technologies**

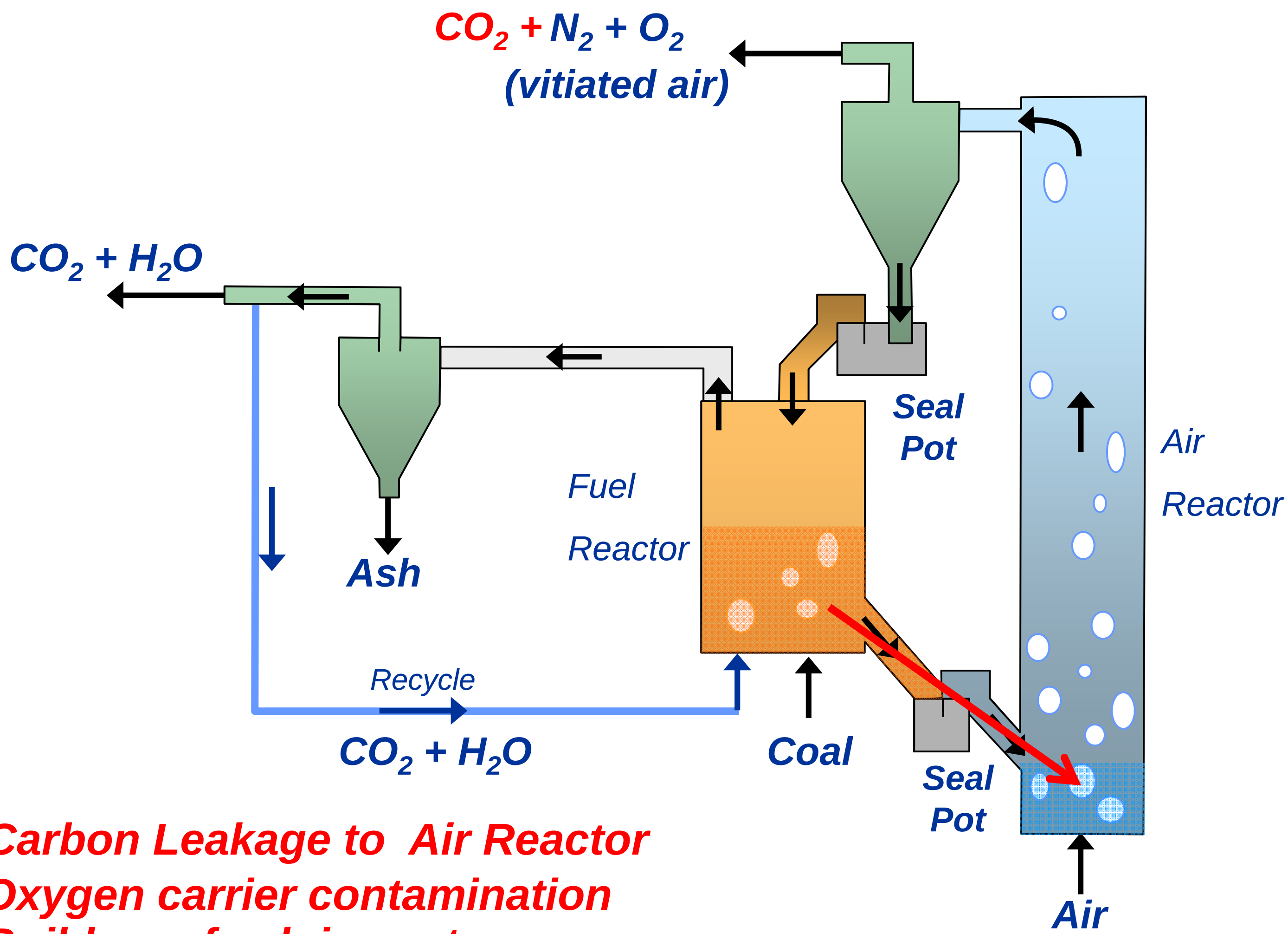
- **Potential to revolutionize the power generation market**
  - Needs technology development that does not overlook fundamental issues

Important Issues For Coal CLC

- **Separation of ash from solid oxygen carrier**
- **Accurate prediction and control of solid circulation rate**
  - Oxygen carrier-to-fuel ratio can be critical
- **Carbon conversion and leakage**
- **Heat extraction and system integration**
- **Attrition**

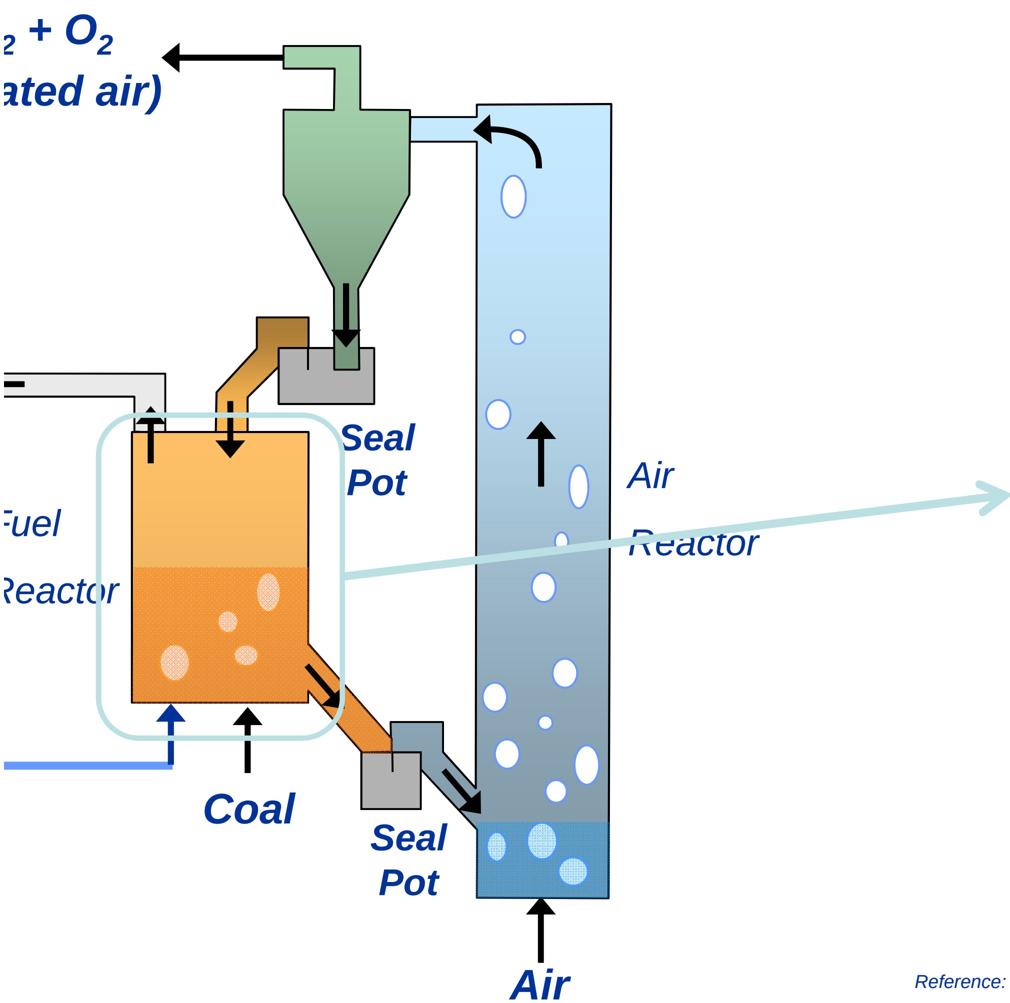


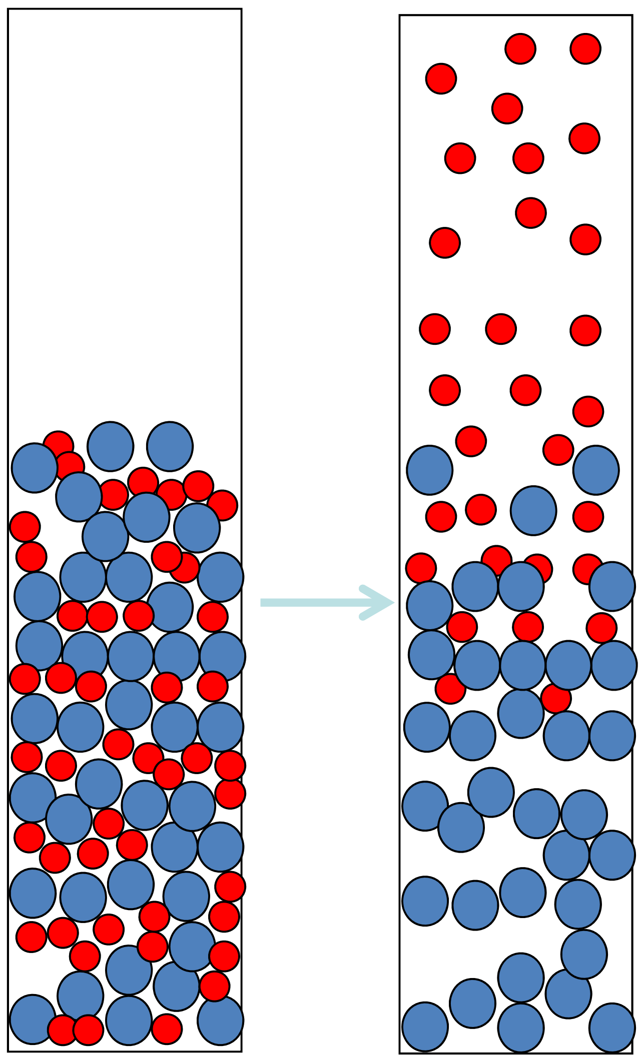
Chemical Looping Combustion Issues



Carbon Leakage to Air Reactor
Oxygen carrier contamination
Build up of ash in system

Aerodynamic Separation in Fuel Reactor

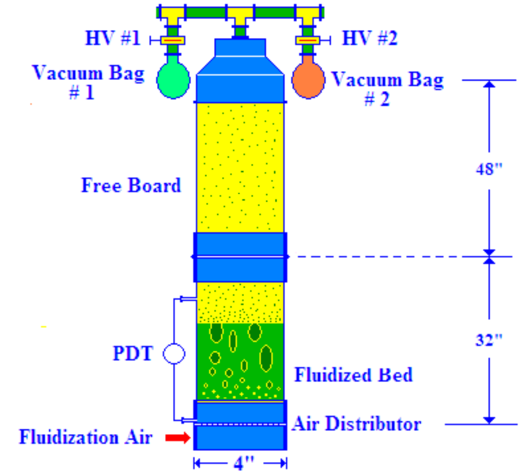


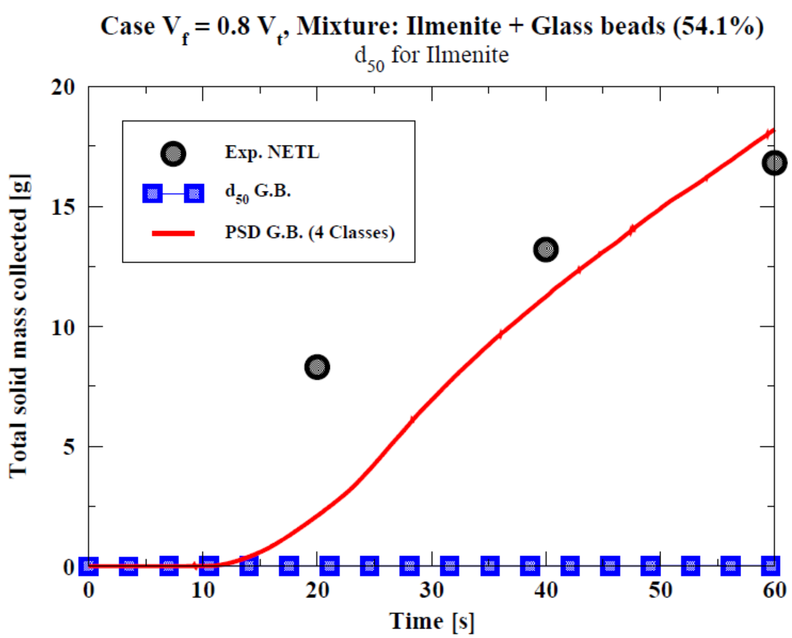


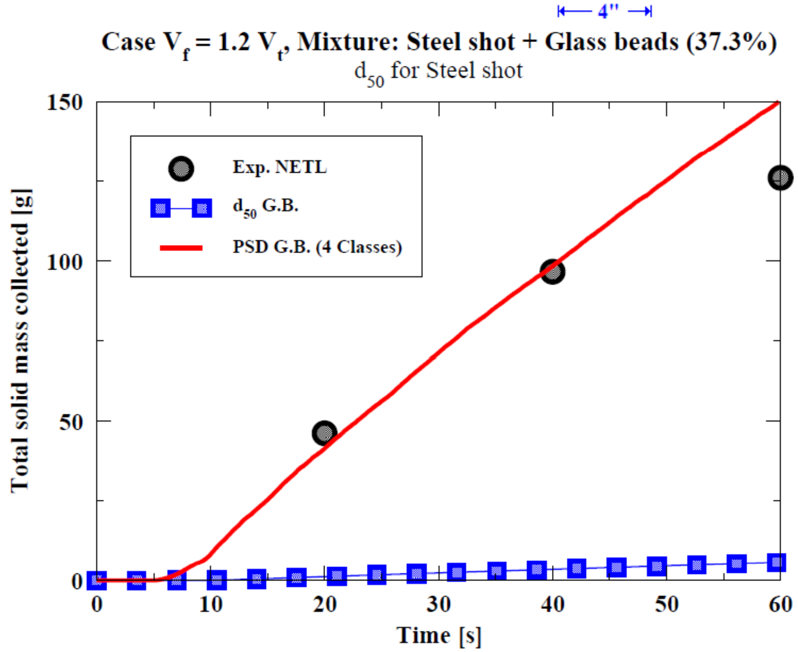
Reference: Dalton, Weber, Straub, and Mei, 2011 Clearwater Clean Coal Conference

MFIX Simulations of NETL Elutriation Experiments (see Konan and Huckaby for details)

- **CFD simulations were performed of several binary-particle experiments performed at NETL.**
  - The broad PSD of the lighter particle type poses a challenge

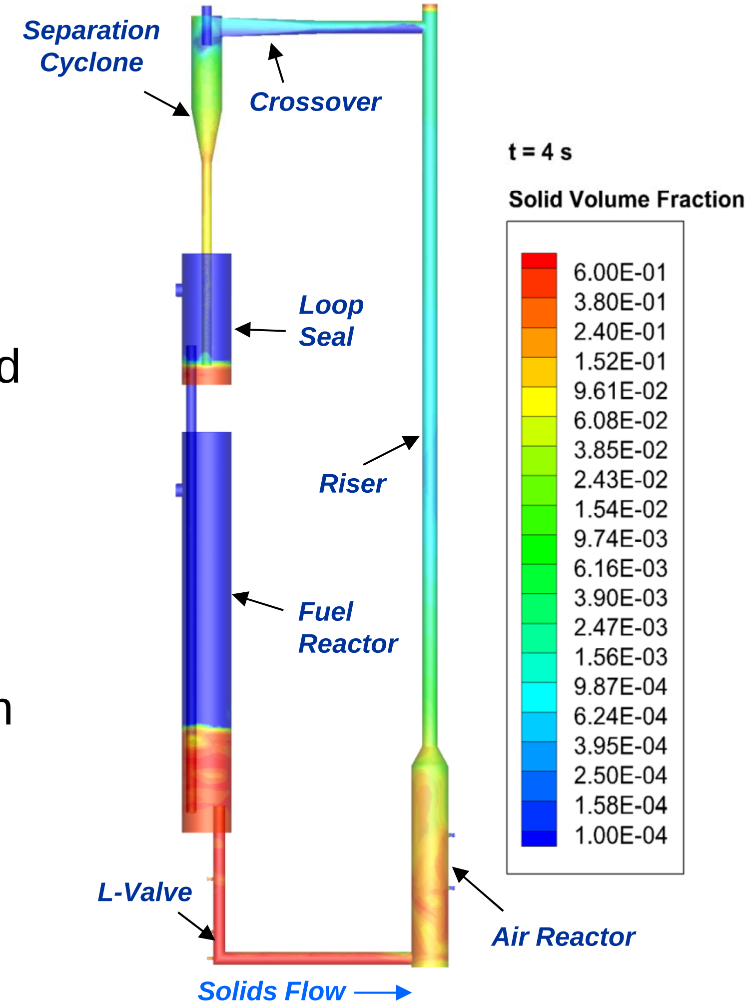






Modeling the Chemical Looping Process

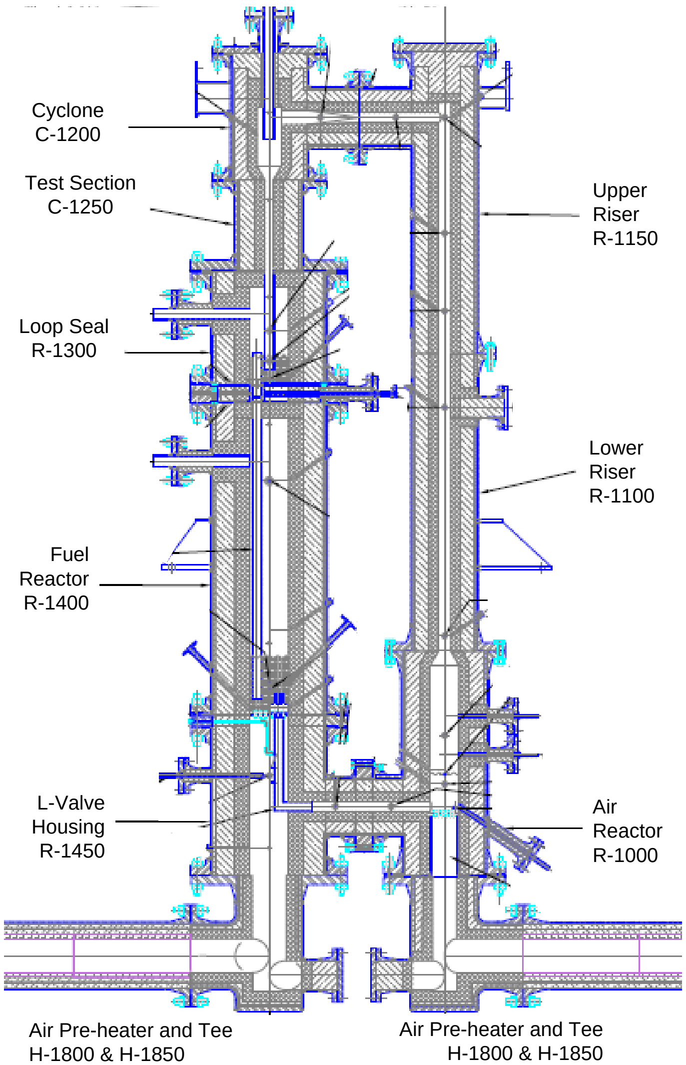
- **Fluent**
  - 2D Simulations
  - 3D Simulation
  - See Poster Liu, Huckaby, Gallagher and Carpenter for more details
- **Barracuda (3D)**
  - Non-reacting (Cold) Flow Simulations
  - Reacting (Hot) Simulations
  - See James Parker (CPFD) presentation for more details
  - Contact R. Breault, J. Weber, or D. Huckaby (NETL)



CLR whole system – 3D, front view

Reference: Breault et. al, 2012, 11th Annual Conference on Carbon Capture, Utilization & Sequestration, Paper # 274, Pittsburgh, PA

Validating the Predictions:
Small-Scale Chemical Looping Reactor (CLR)



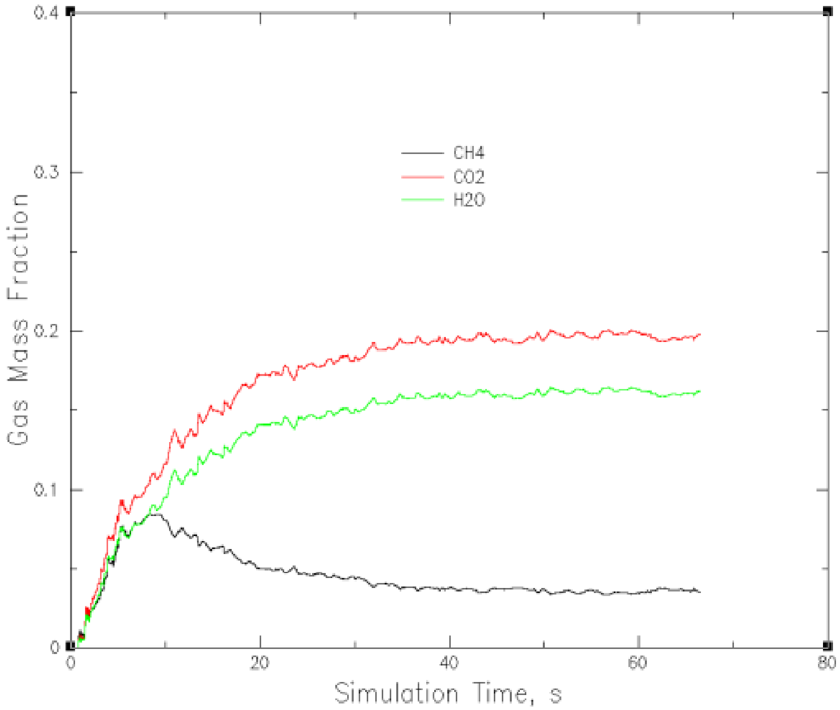
Current Status: Being Installed at NETL

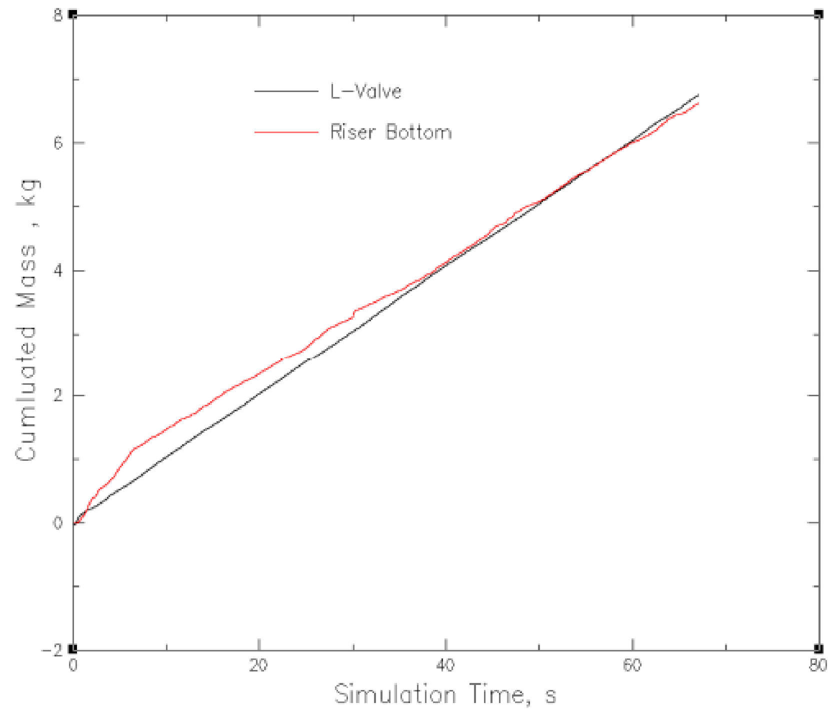
CLR Vessels Delivered to NETL

Project Structure

Air Reactor Bubble Caps

Hot (Reacting) Simulations –
Solids Circulation





Can we measure solids circulation rate in-situ at operating temperatures to calibrate these models?

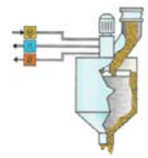
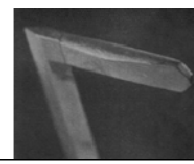
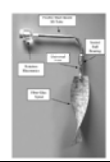
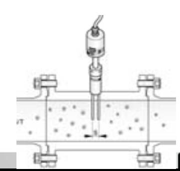
Reference: Breault et. al, 2012, 11th Annual Conference on Carbon Capture, Utilization & Sequestration, Paper # 274, Pittsburgh, PA

In-Situ Solids Circulation Rate Sensors
(Review of Test Conditions)

Application	Carrier	Temperature	Pressure
NETL Chemical Looping reactor Project	Fe Cu	788 -1004°C 704-1004°C	1.7 bar 1.7 bar
Chalmers University[1]	Fe	1000°C	1 bar
Southeast University[2]	Ni	1040°C	1 bar
Natural Gas Combined Cycle[3]	Fe	832°C	20.5 bar
Natural Gas Combined Cycle un-fired[4] Natural Gas Combined Cycle fired	Fe Fe	850°C 850°C	8 bar 16 bar
Alstom CLC[5] Alstom CL Gasification	CaS CaS	1093°C 1093°C	1 bar 1 bar
	Maximum	1093°C	20.5 bar

1. *Berguerand, N.; Lyngfelt, A. Design and Operation of a 10 kWth Chemical-Looping Combustor for Solid Fuels - Testing with South African Coal. Fuel* ***2008,*** *87, 2713-2726.*
2. *Shen, L., Wu, J. and X. Experiments on Chemical Looping Combustion of Coal with a NiO Based Oxygen Carrier. Combustion and Flame,* ***2009,*** *156, 721-728.*
3. *Lozza, Giovanni, et al. Three Reactors Chemical Looping Combustion for High Efficiency Electricity Generation with CO_2 Capture from Natural Gas. Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air, Barcelona, Spain, 2006; GT2006-90345.*
4. *Consonni, S., et al. Chemical-Looping Combustion for Combined Cycles with CO_2 Capture. Proceedings of ASME Turbo Expo 2004: Power for Land, Sea and Air, Vienna, Austria, 2004; GT2004-53503.*
5. *ALSTOM POWER INC. Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers, Phase 1 - A Preliminary System Evaluation; PPL REPORT NO. PPL-03-CT-09; Power Plant Laboratories: Windsor, CT, 2003.*

In-Situ Solids Circulation Rate Measurements

Device Type	Typical Temp(max)	Pressure Limit(max)	Measuring Technique
Contact			
Coriolis	up to 130ºC	Atmosphere	 [6]
Impact plate	up to 70ºC	5kPa	 [7]
Diverting/Curved Chute	up to 400ºC	Atmosphere	 [6]
Momentum Probe*	up to 40ºC	atmosphere	 [8]
Rotating Vane**	up to 40ºC	340 kPa	 [9]
Differential Pressure*	> 1100 ºC	> 20 MPa	
Electrostatic	120ºC	NR	 [10]

- •Food or plastic pellet handling (low erosion)
- •Mostly atmospheric pressure
- •Low temperature
- •DP is indirect, and reported with low accuracy (baseline)
- •Spiral has successful use in B22

Non-Contact Technologies

Device Type	Typical Temp(max)	Pressure Limit(max)
Non-Contact		
Optical[a,b]	1100ºC	> 20 MPa
Capacitance[c]	up to 200ºC	NR
Microwave[e]	200 ºC (1000ºC)	up to 1000 kPa
Ultrasonic	up to 300ºC	up to 1000 kPa
Electromagnetic[a]	up to 398ºC	up to 1600 kPa
Gamma / X-ray[d]	NR	NR

Windows a concern

ECVT being developed separately (Tech4Imaging)

+ Commercial device ?

Reported for solid-liquid flows

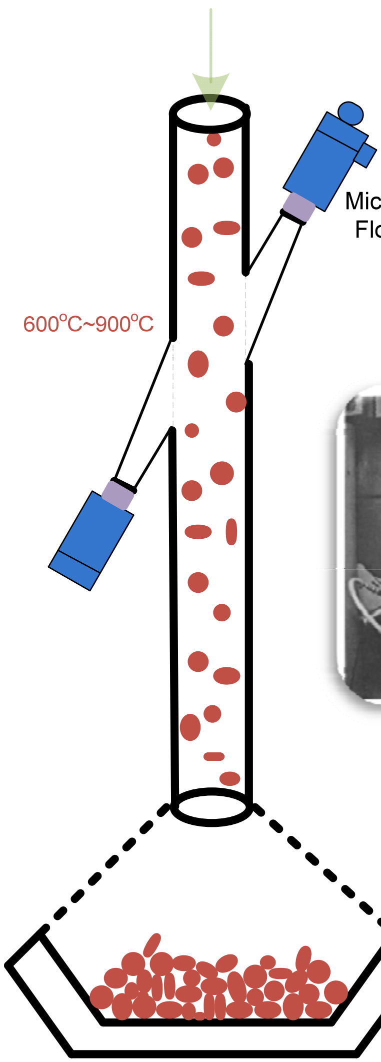
Conceptual; needs magnetic particles

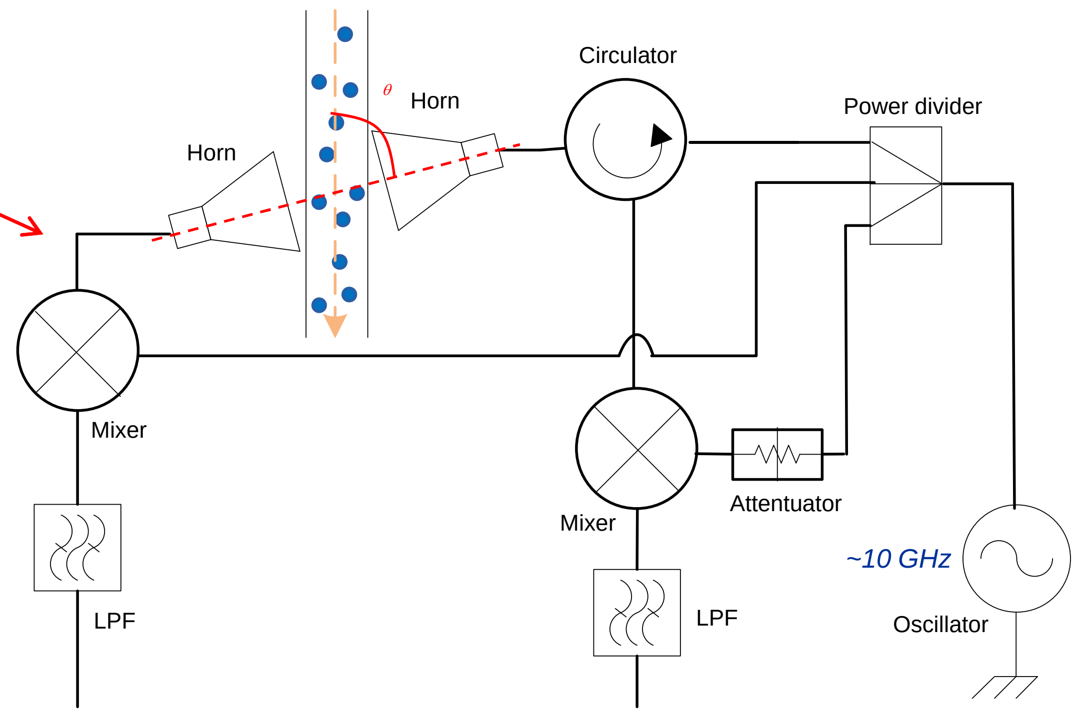
+ See through the pipe walls

a. Not a commercial product.
b. Dependent upon window materials. Specs shown for windows available. Deposition resistance not evaluated.
c. Cannot detect through metal pipe wall.
d. Device is completely external to process.
e. Normal operating temperature 200°C. 1000°C offered on custom order.

CMU Microwave Sensor Development

Principle of solid flow measurement



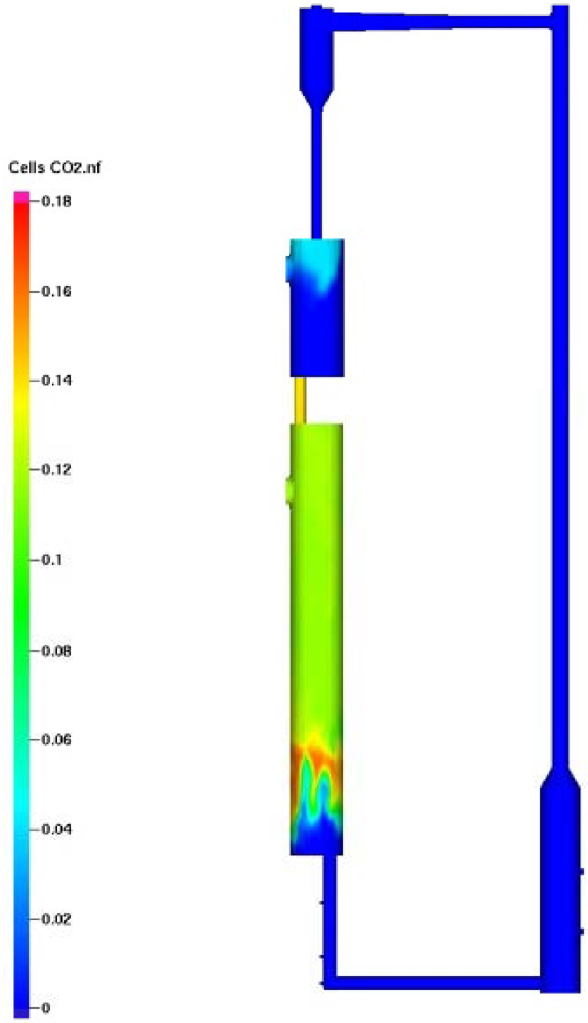


Measure scattering and doppler shift

* M.J. Millen et al, Flow Measurement and Instrumentation, 2000, p153-158

Hot (Reacting) Simulations –
Gas Composition

- **Methane enters the fuel reactor at ~24 mole % and leaves at ~8 mole %.**
- **There is no CO_2 leakage through the non-mechanical valve and into the air reactor.**
- **The air reactor at the design conditions consumes only about half the oxygen in air.**



Reference: Breault et. al, 2012, 11th Annual Conference on Carbon Capture, Utilization & Sequestration, Paper # 274, Pittsburgh, PA

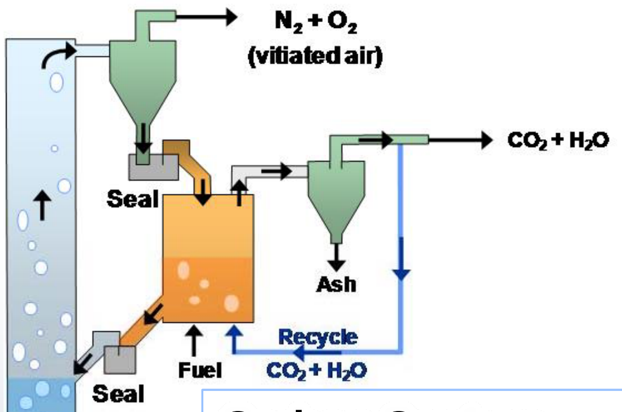
Other Options to Accelerate CLC Development?

- **Are there smaller applications (non-power generation) where CLC's make sense?**
- **Are there small CO2 sinks where CLC technology could be demonstrated?**
- **Can we calibrate CFD models and successfully predict scale-up performance?**

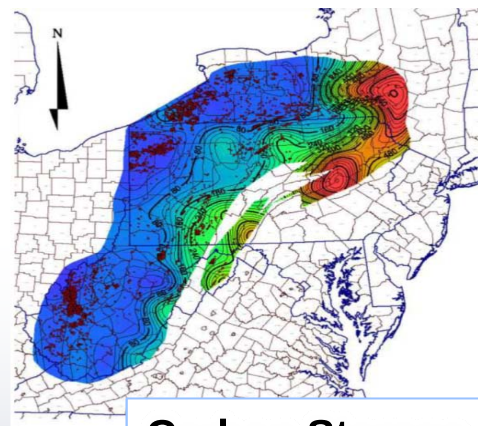
DOE/NETL's Industrial Carbon Management Initiative (ICMI)?

ICMI Research areas

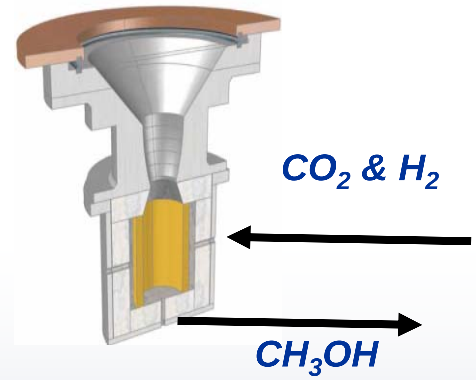
Focus is on "industrial" applications: NG or coal boilers, process heat, chemical production, others.   Technical results expected to benefit coal power as well.



Carbon Capture
Chemical Looping Combustion



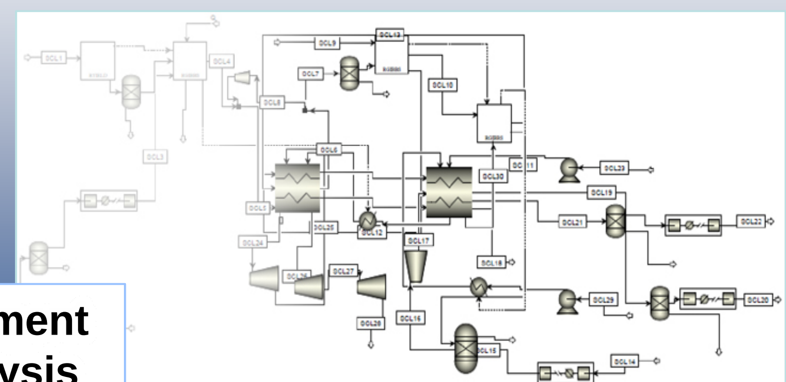
Carbon Storage
Depleted Shale Fields



Carbon Utilization
Photocatalytic Conversion

CCUS for Industrial Applications

Industrial assessment and systems analysis



Industrial CLC Screening

- Potential
- Proven
- Preferred
- In Testing
- Capture not Required

	Gas Separation/Post Combustion						Oxyfuel		Pre-Combustion				
	Chemical Solvent	Physical Solvent	Sorbent	Membrane	Carbonate Looping	Cryogenic	Oxyfuel	Chemical Looping Combustion	Chemical Solvent	Physical Solvent	Sorbent	Membrane	Chemical Looping Reforming
Refineries													
Process Heating - N4													
Steam/Utilities - N4													
Hydrogen Production													
FCC Regeneration													
Cement													
Cement Kiln - N2							N1						
Iron & Steel													
Traditional Blast Furnace - N5		N3					N3						
DRI													
Oil & Gas													
O&G Processing													
O&G Processing Steam/Utilities													
Oil Sands Steam Production - SAGD													
Oil Sands Processing - Hydrogen													
Oil Sands Processing - Steam													
Ethanol/Ethylene													
Bioethanol via fermentation - N6													
Ethylene													
Steam/Utilities													
Pulp & Paper													
Kraft Mills - N5													
Steam and Heat													
Ammonia/Fertilizer													
Hydrogen Production													

N1 Will not be suited to retrofit -- new plant only
N2 Pre-combustion not suitable due to lower radiant properties
N3 Oxyfuel with CO_2 removal via solvent
N4 Post Combustion limited due to many point sources
N5 Makes up majority of plants, ~70%
N6 CO_2 from fermentors only (no fuel) -- Produces relatively pure CO_2

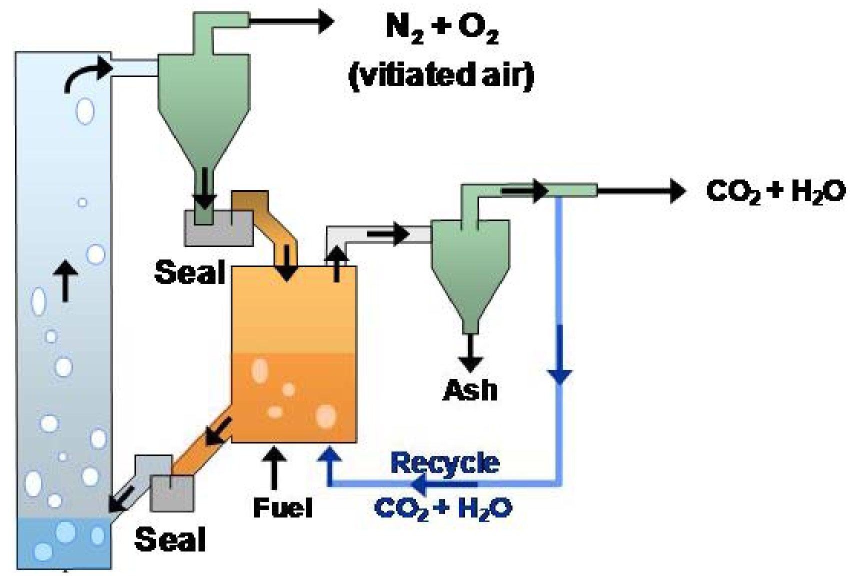
Developing and Validating the CL Technology

Industrial applications (includes NG, smaller scale)

Iterate with more information

- **Attributes:**
  - Fuel (NG, solid fuels)
  - Size
  - Cost
  - Performance
- **System issues & configuration**
  - Attrition
  - Material supply & handling
  - Heat exchanger/integration
  - Sensors and control
  - Emissions
  - Carrier cost/supply & re-use
- **Components**
  - Hydrodynamics
  - Heat transfer
  - Size/cost
- **Basic data**
  - Carrier capacity
  - Carrier reaction rate w/oxygen
  - Carrier reaction rate w/fuel
  - Carrier degradation

Power applications (coal, 100+MW scale)



ICMI research task provide the data and analysis.

These data will enable CCSI* scale-up simulation.

** Carbon Capture Simulation Initiative - www.acceleratecarboncapture.org*

Summary

- **Multiphase models are used to address areas**
  - Gasification
  - CO2 Sorbents and Sequestration
  - Chemical Looping Combustion
- **Accelerated deployment of sustainable technology options**
  - Multiphase modeling
  - Balance between “fundamental” understanding and “build a larger plant”
    - Device to measure solids circulation rate at elevated temperature
- **Introduction to Industrial Carbon Management Initiative (ICMI)**
- **Informal Working Group on Chemical Looping**
  - Monthly Web-Ex meetings
  - Universities and gov’t labs across the U.S. and Sweden

Informal Chemical Looping Working Group

(contact douglas.straub@netl.doe.gov for more info)