NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Overview

Industrial Carbon Management Initiative (ICMI)

2011 NETL CO_2 Capture Technology Meeting

August 22 – 26, Pittsburgh PA

Geo. A. Richards, Focus Area Leader, Energy System Dynamics
NETL Office of Research and Development

Acknowledgements:
…too many names to list…

U.S. DEPARTMENT OF ENERGY

What Is ICMI About?

- **Focus is on "industrial" applications:**
  - Boilers, process heat, chemical production, others.
  - Technical results expected to benefit coal power as well.
- **Chemical Looping (CL) as a capture technology.**
- **Depleted shale-gas reservoirs for CO_2 sequestration.**
- **Basic research in catalytic and photo-catalytic materials for conversion of CO_2 to chemicals using light or waste heat.**
- **Most promising industrial applications will be identified and techno-economic analysis will be performed to assess the cost and benefit of ICMI-developed technology.**

Industrial Carbon Management Initiative

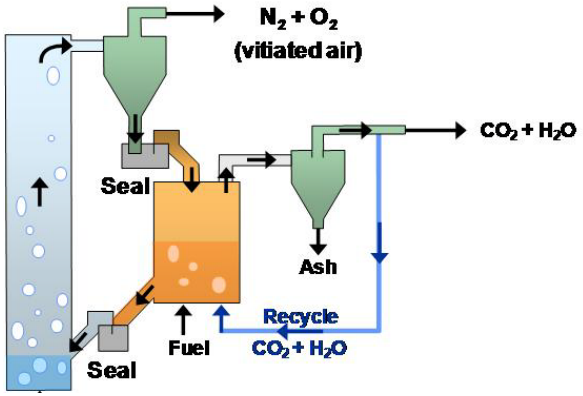
ICMI

Who Is Performing the Research?

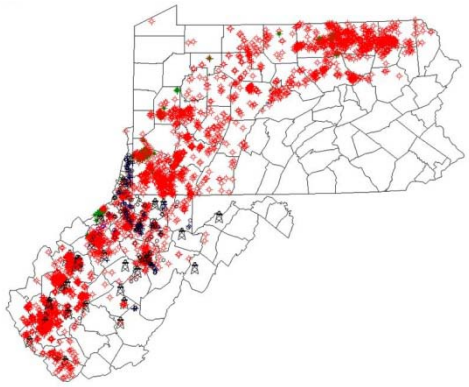
- **NETL's Strategic Center for Coal (SCC) provides funding and acts as a Technical Monitor for the project.**
- **NETL's Office of Research and Development (ORD) provides overall technical leadership and performs a portion of the research.**
- **URS was awarded under an existing contract to provide technical and administrative support (3 years, ARRA Funding).**
- **The Regional University Alliance (NETL-RUA) is participating thru URS.**

NETL Carnegie Mellon University University of Pittsburgh
PENNSTATE. VirginiaTech Invent the Future WestVirginiaUniversity. URS

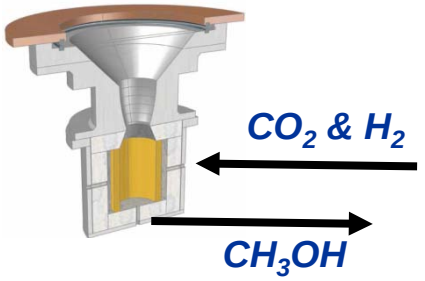
ICMI's Main Research Activities



CL Process diagram



2011 Marcellus Shale Wells



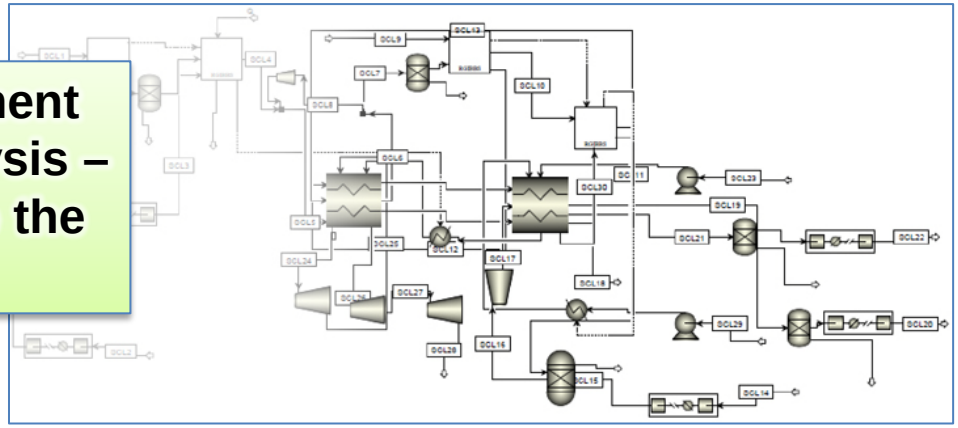
Low-Temperature Reactor

Capture - chemical looping technology evaluation.

Storage – shale gas reservoir sequestration.

Re-use – Photoactive and thermal CO2 conversion.

Industrial assessment and systems analysis – identify & evaluate the application



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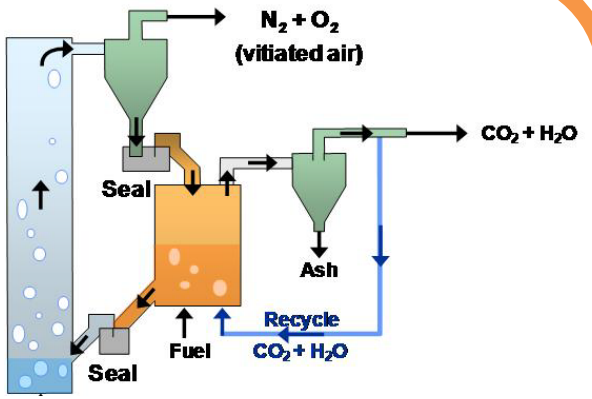

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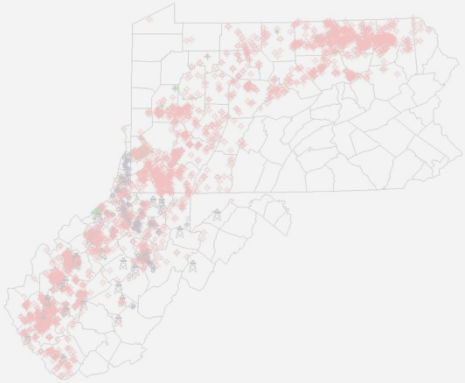
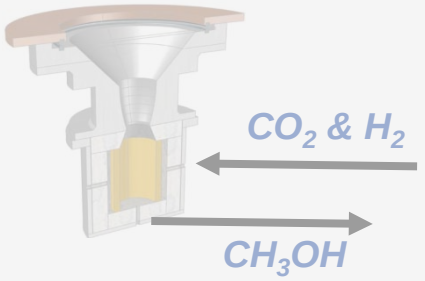


2011 Marcellus Shale Wells

Storage – shale gas reservoir sequestration.



Low-Temperature Reactor

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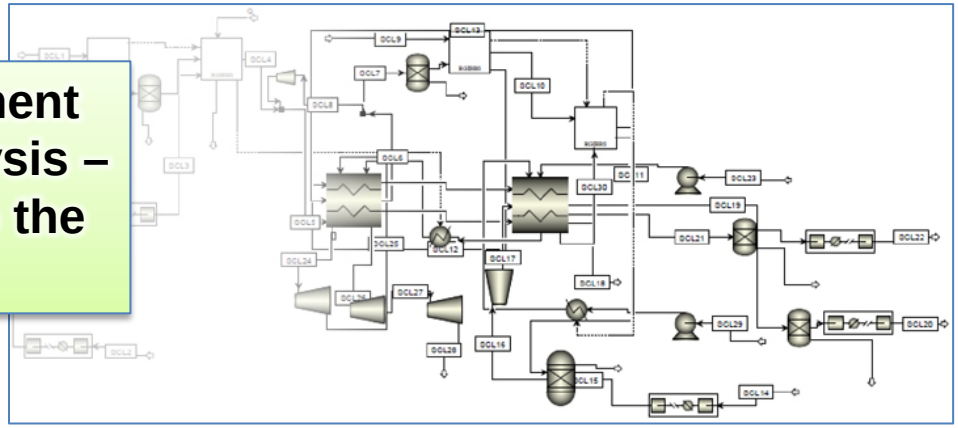
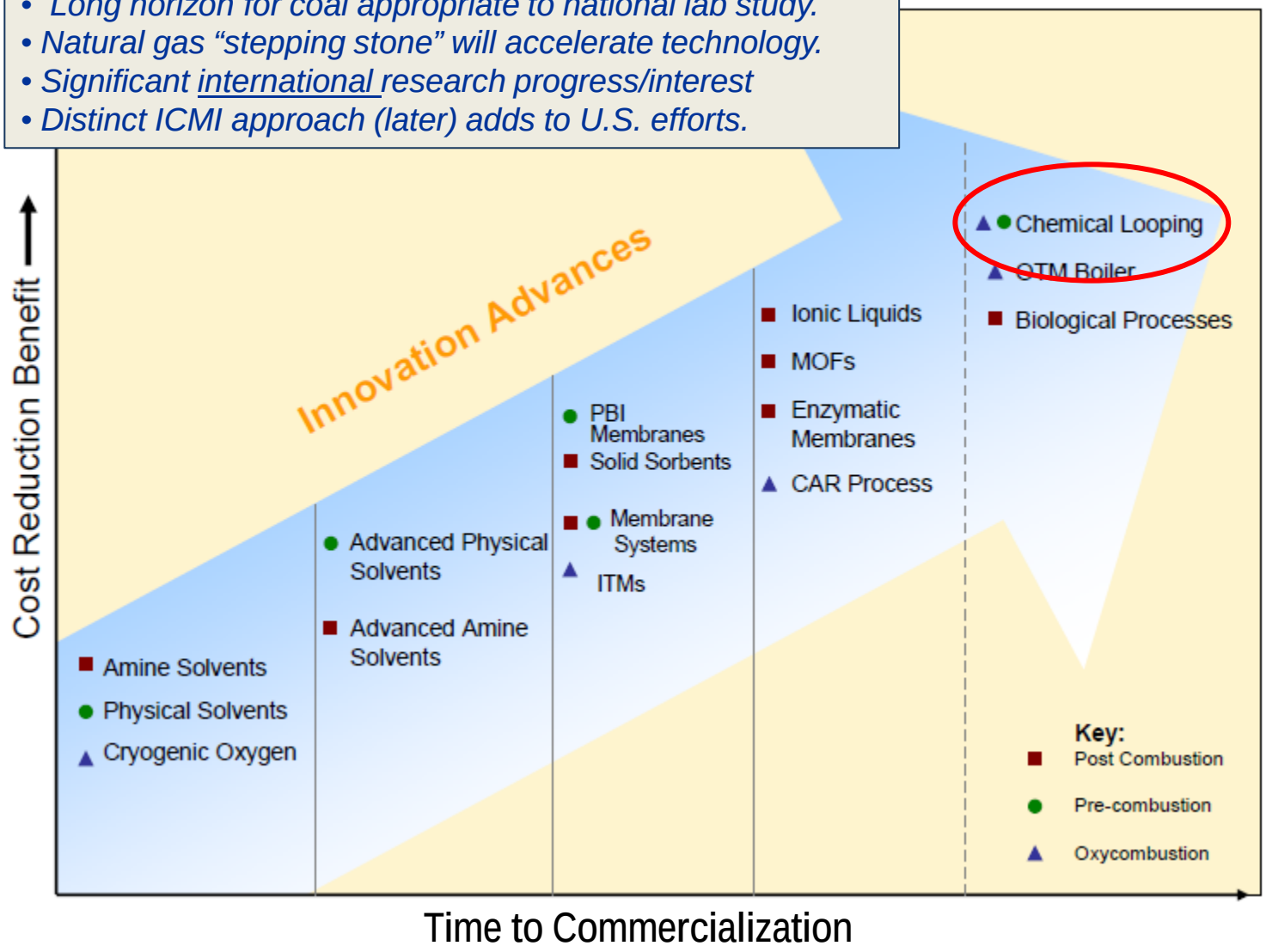


Why Chemical Looping?

- *Long horizon for coal appropriate to national lab study.*
- *Natural gas "stepping stone" will accelerate technology.*
- *Significant international research progress/interest*
- *Distinct ICMI approach (later) adds to U.S. efforts.*



Interesting Comments About CLC

(1) "The CO_2 Capture Project (CCP) sponsored by Eni, Statoil Hydro, Shell, Suncor, BP, Chevron, Petrobas, Conoco Phillips found that: *'CLC has the potential to become the preferred option" for steam boilers and process heaters…'"*

(2) Report by ENhanced CAPture of CO_2 (ENCAP), Ekstrom et al., 2009:

	CLC Bit. Rel to 445 MWe CFB Ref.	IGCC Bit. Rel. to 600 MWe w/o capt.	Oxyfuel Bit. Rel. to 600 MW PF
Energy Penalty	4%	20%	20%
CO_2 avoided $/ton	8 to 16	23 to 49	17 to 37

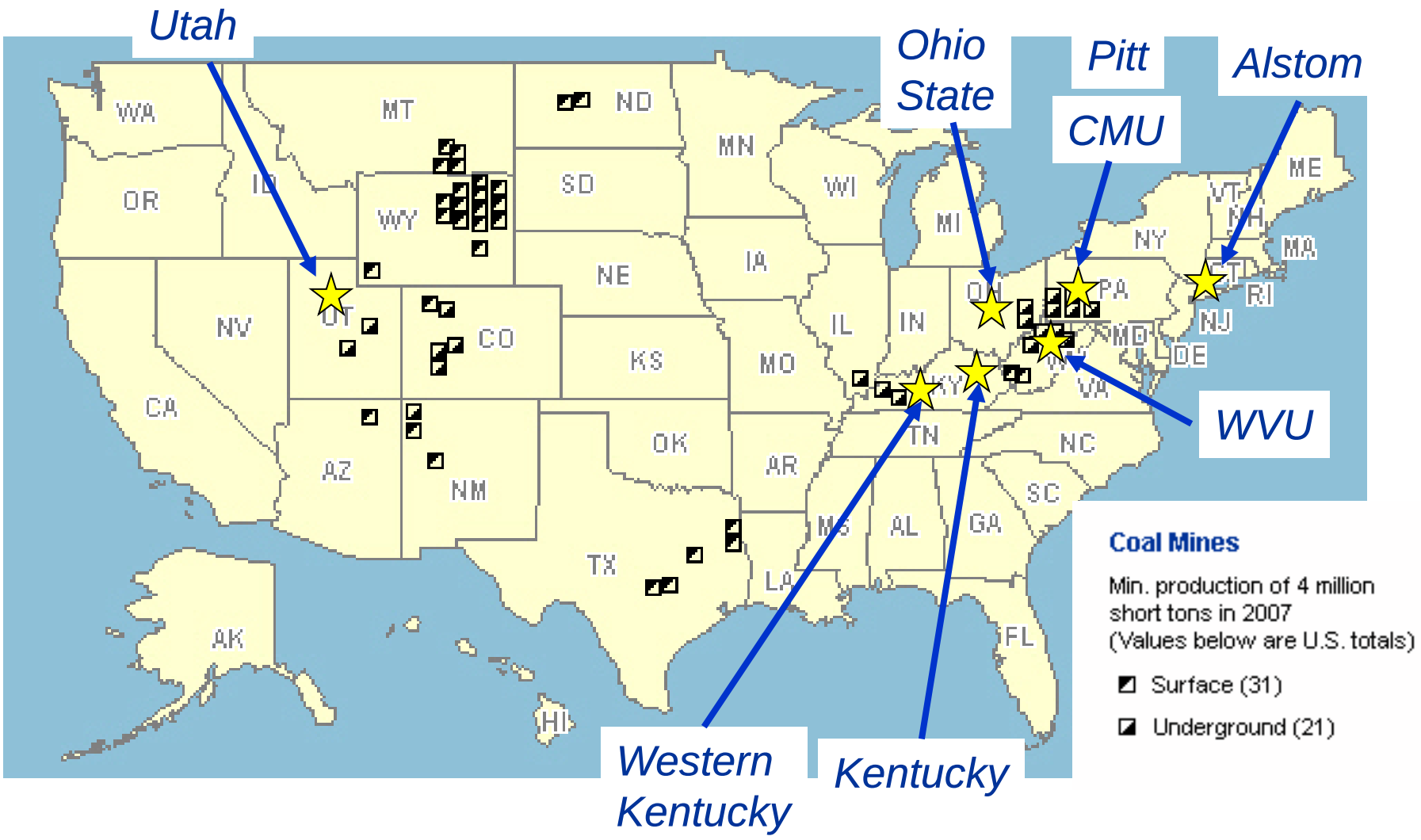
Both items above: directly from Henrik Leion and Adel Sarofim, Chemical-Looping Tutorial , The 36th International Technical Conference on Clean Coal & Fuel Systems, June 5-9, 2011.

(3) "The technology represents a step change in power generation….the merits of high efficiency with coal-base fuel and inherent carbon capture – although a series of technical barriers remain…." Peter Childs, Gas Turbine World, May-June 2011 pp 24 - 27

What Are Other Countries Doing?

- **Chalmers University, Sweden**
  - Metal carriers, gaseous and solid fuels
- **Southeast University, China**
  - Nickel and iron carriers, direct coal combustion
  - Recent (2010) publications in pressurized CLC
- **University of Cambridge, UK**
  - Copper and iron carriers with lignite coal (batch reactor)
- **Instituto de Carboquímica (CSIC), Spain**
  - Natural gas only, copper carriers
- **Vienna University of Technology, Austria**
  - Natural gas only, two entrained reactors give better gas-solid contact
- **Korea Institute of Energy Research (KIER)**
- **Japan Coal Energy Center (JCOAL)**

What's Happening Domestically?



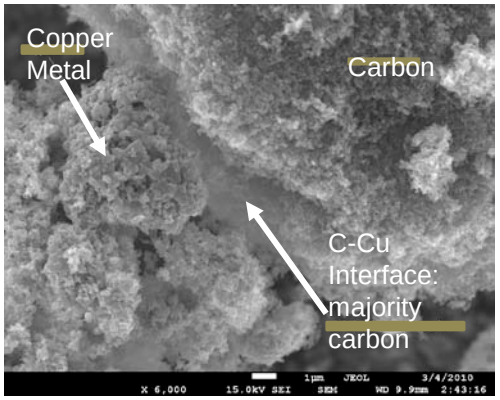
Industrial Chemical Looping (natural gas and coal)

Technical Approach:

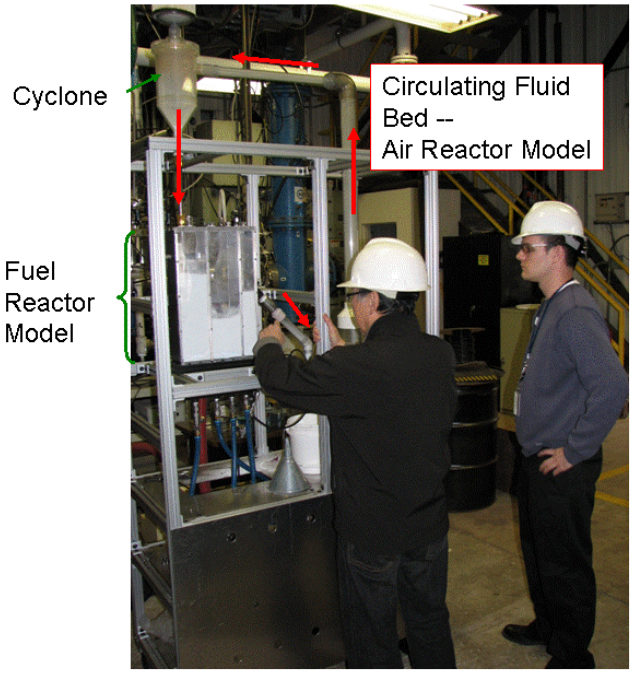
- **Research on oxygen carriers, hydrodynamics, process design for:**
  - Industrial applications (heat, steam)
  - Power
- ***Not a single design*, but data to enable design choices explored with numeric simulations.**
- **Complements specific developments by others.**
- **Assess process economics, performance.**
- **Information to NETL leadership on potential.**
- **Partnerships for continued *commercial* development.**

NETL on-site Research on Chemical Looping

- **Evaluating carrier behavior & options**
  - Physics of solid-fuel & MeO reaction.
  - Evaluation of metal “commodity” carriers from waste or natural sources.
- **Leverages NETL capability in multi-phase flow:**
  - Cold Flow Facility
    - Investigating **ash, coal, carrier separation** and handling.
    - Validate model predictions.
  - Hot Flow Facility
    - Address reaction performance
    - Detailed design in progress.
  - Reactor simulations.
    - Accelerate understanding & scale-up



C/CuO Interface Regions

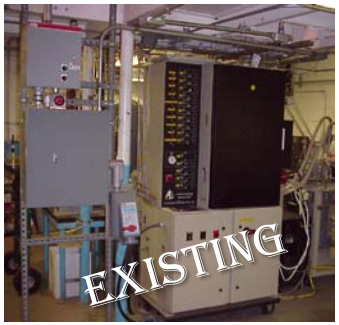


Simulation and Experimental Facilities

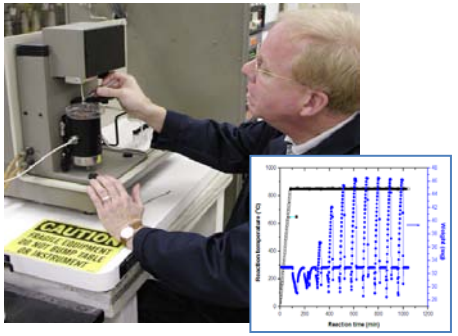
Existing Clusters

Attrition Tests

Fluid Bed Reactors



Existing TGA Lab



NETL O2 carrier - cyclic studies in progress

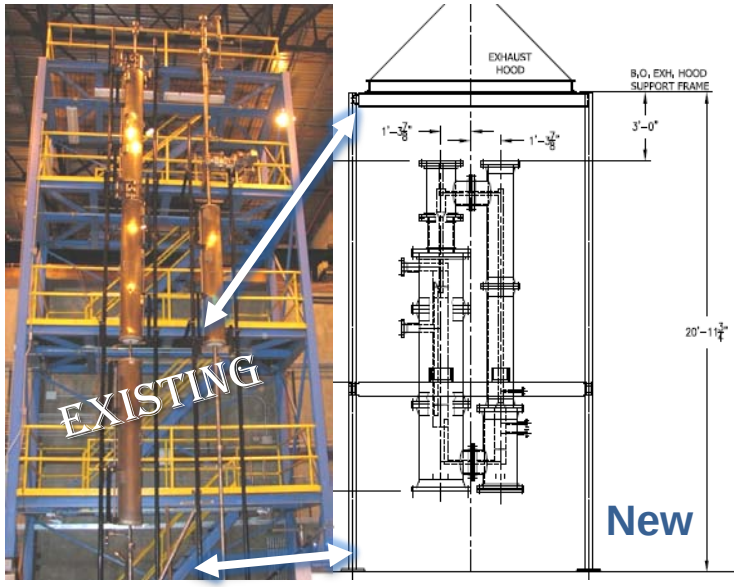
Candidate SBEUC Systems

Portable Modular System

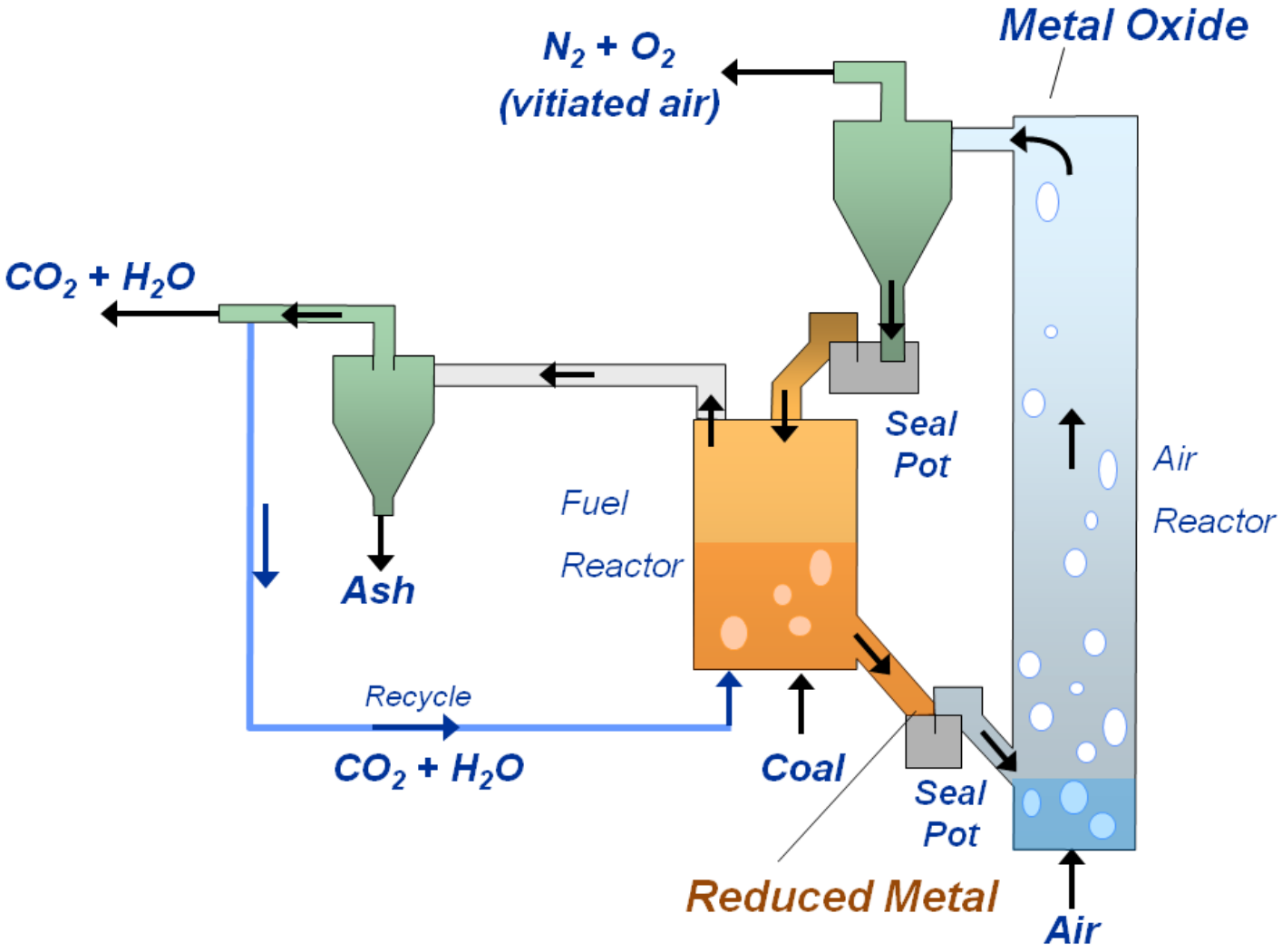
Performance Optimized System

Cold Flow with ECVTs

Integrated Chemical Looping Reactor



Issues with coal CLC?



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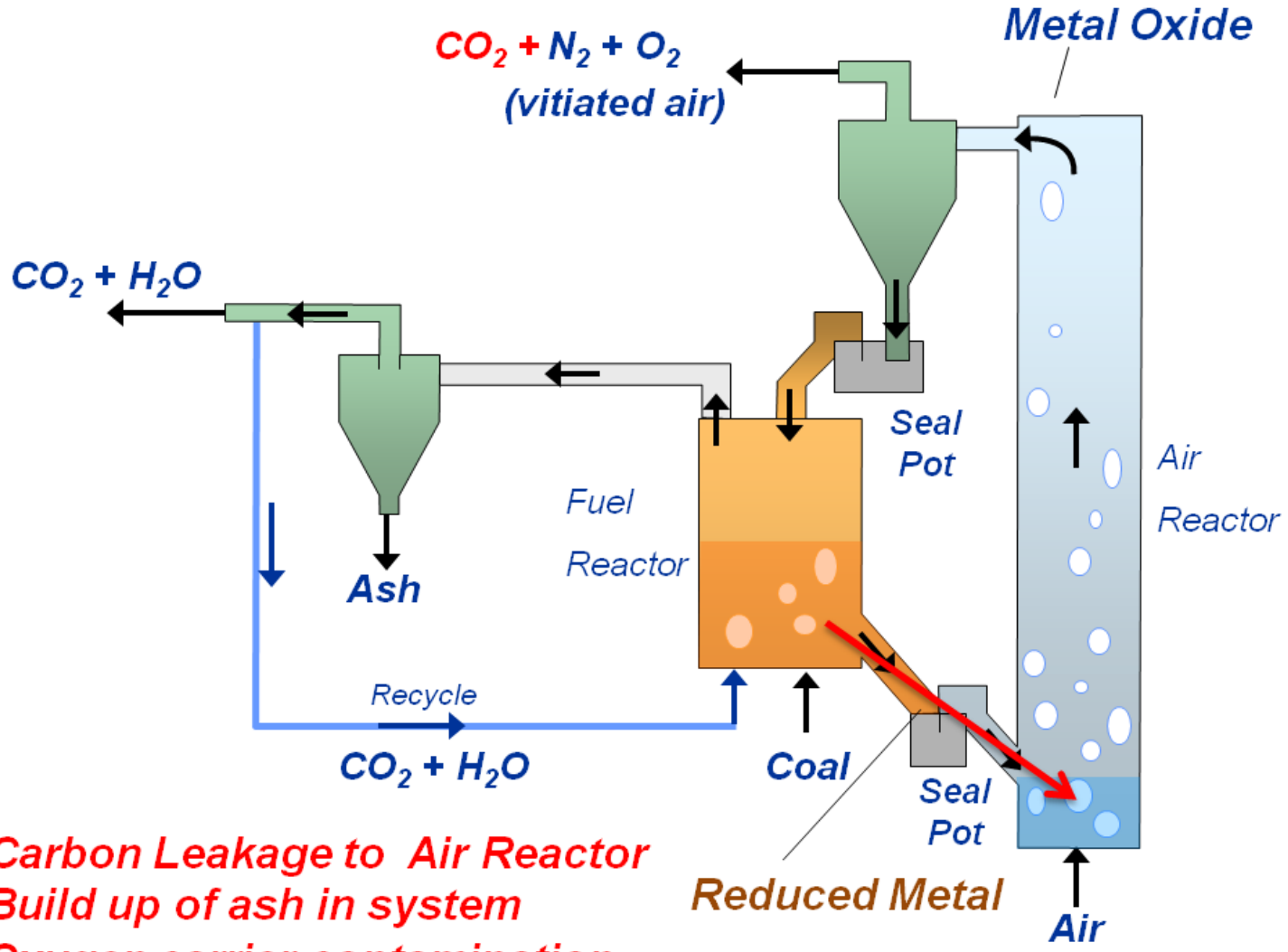
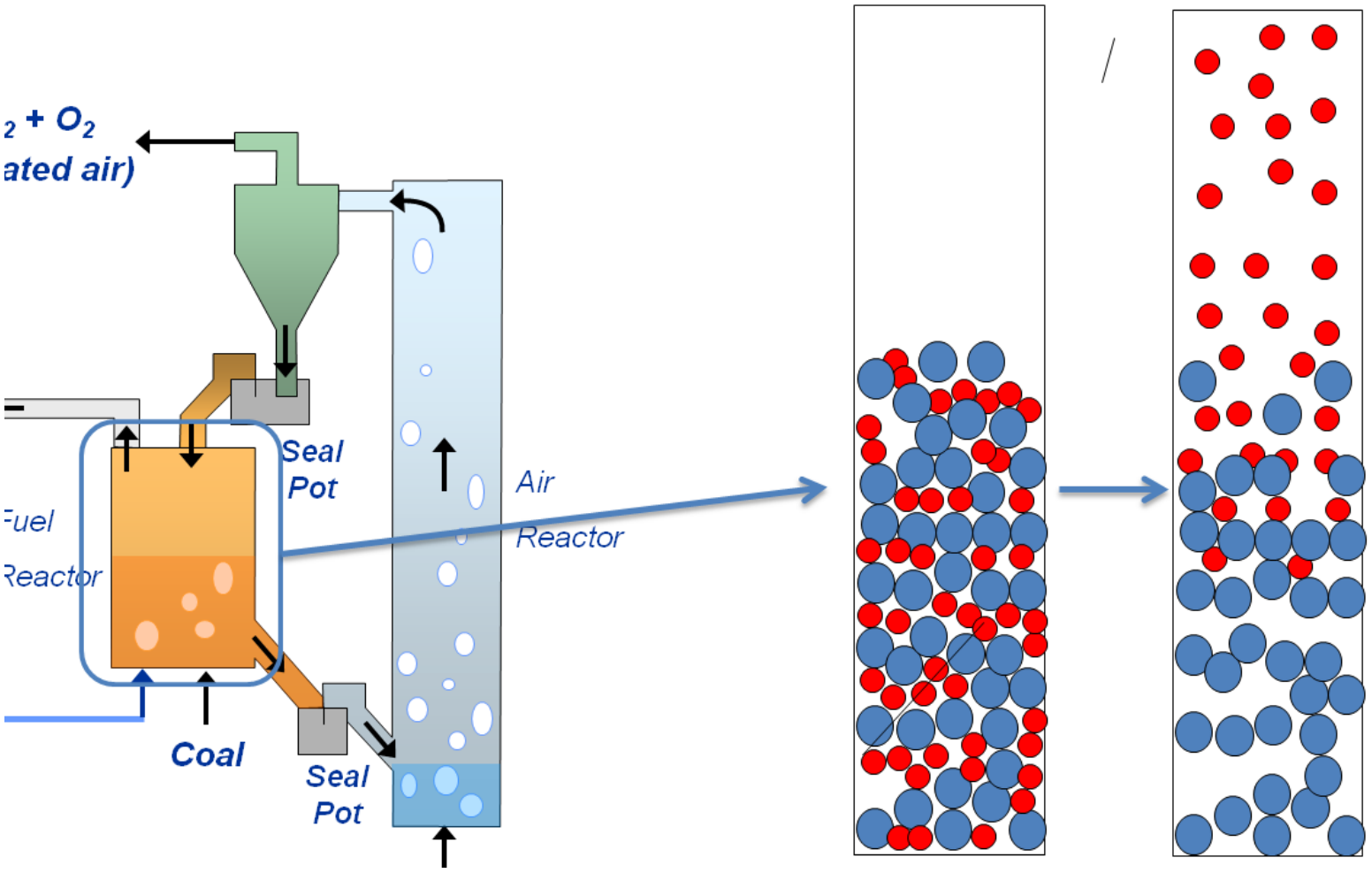
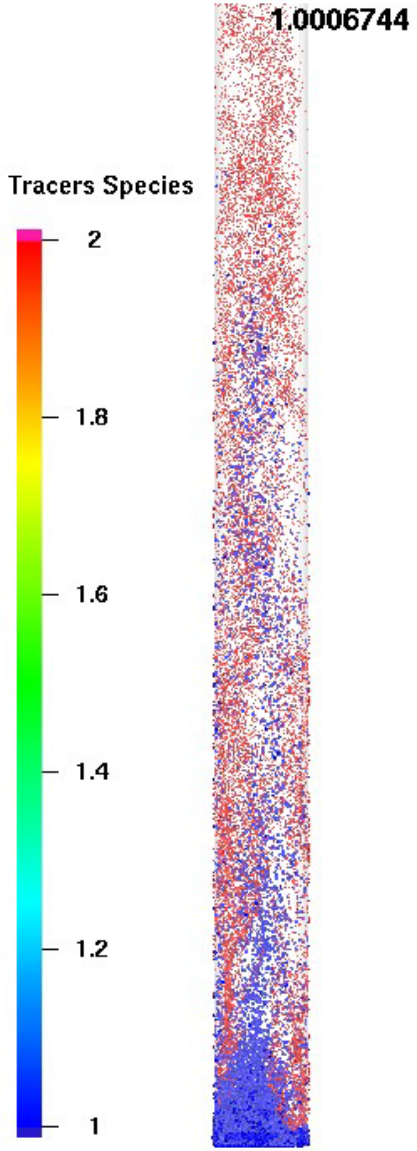


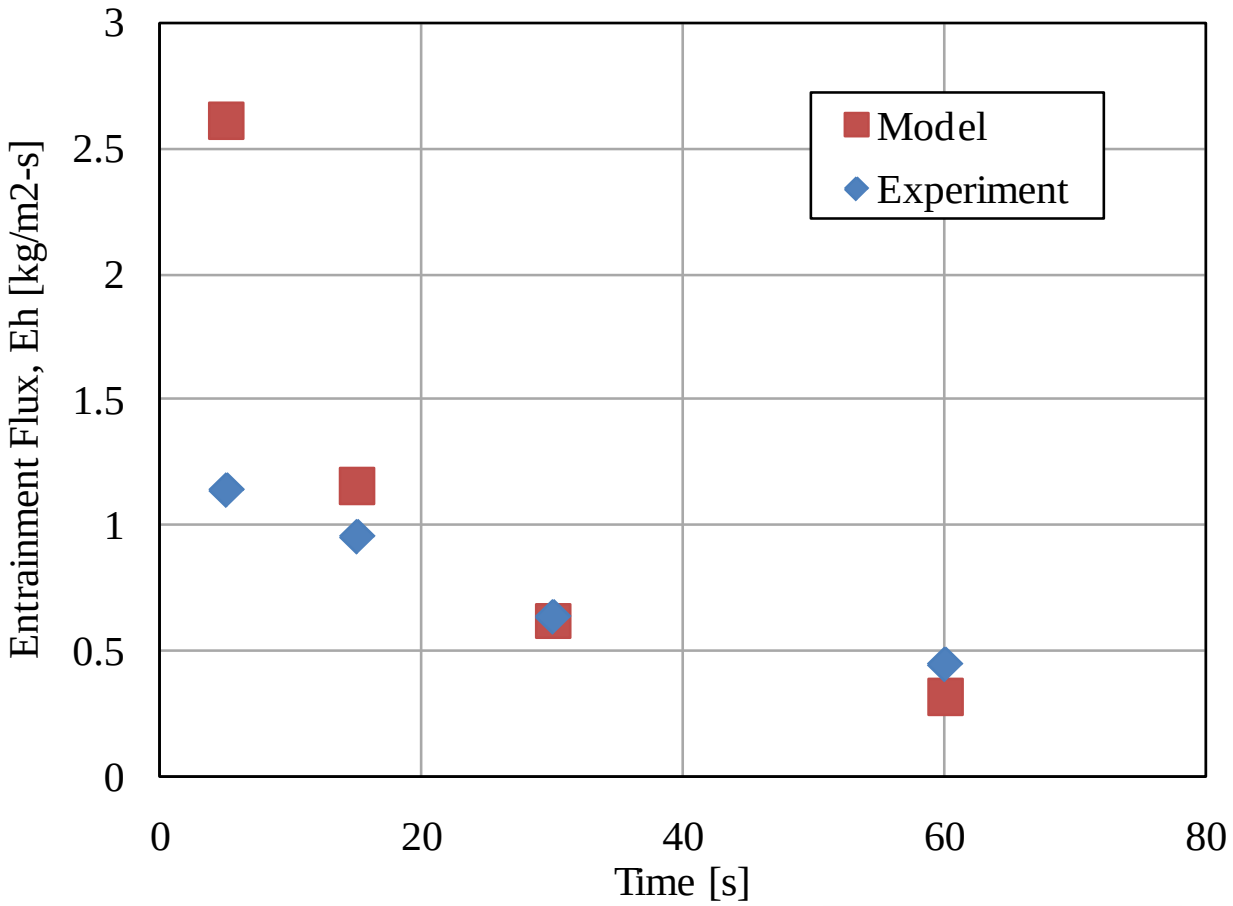
Carbon Leakage to Air Reactor
Build up of ash in system
Oxygen carrier contamination

Solution: Aerodynamic Separation



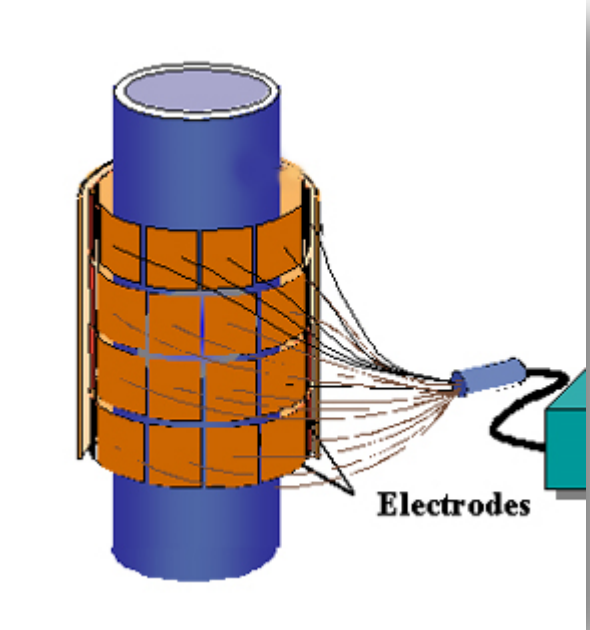
How does CFD Compare?

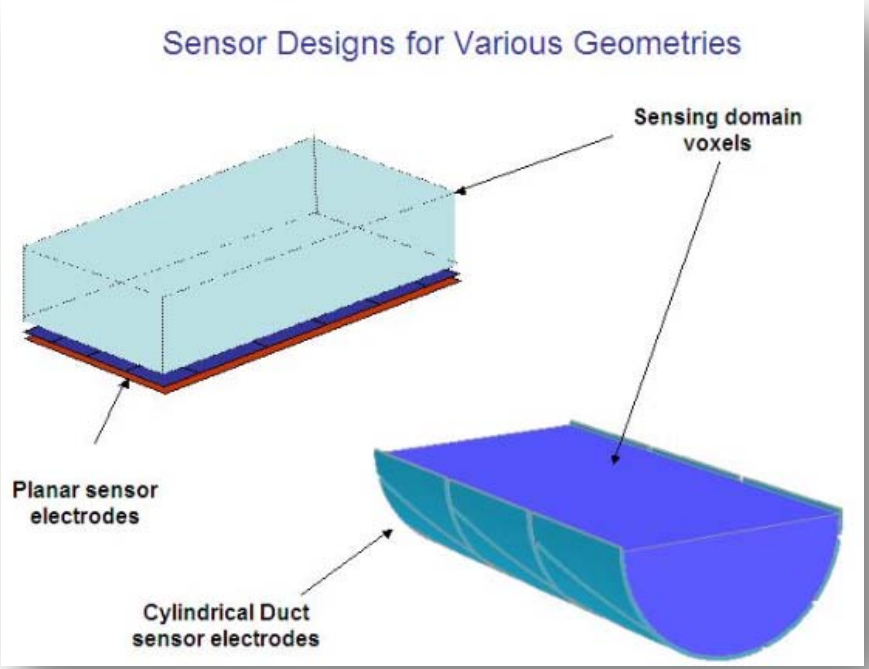




- **CPFD's Barracuda**
- **43k cells**
- **CuO/Acrylic 1.5*Ut**

ECVT Sensor Overview
(From Tech4 Imaging)

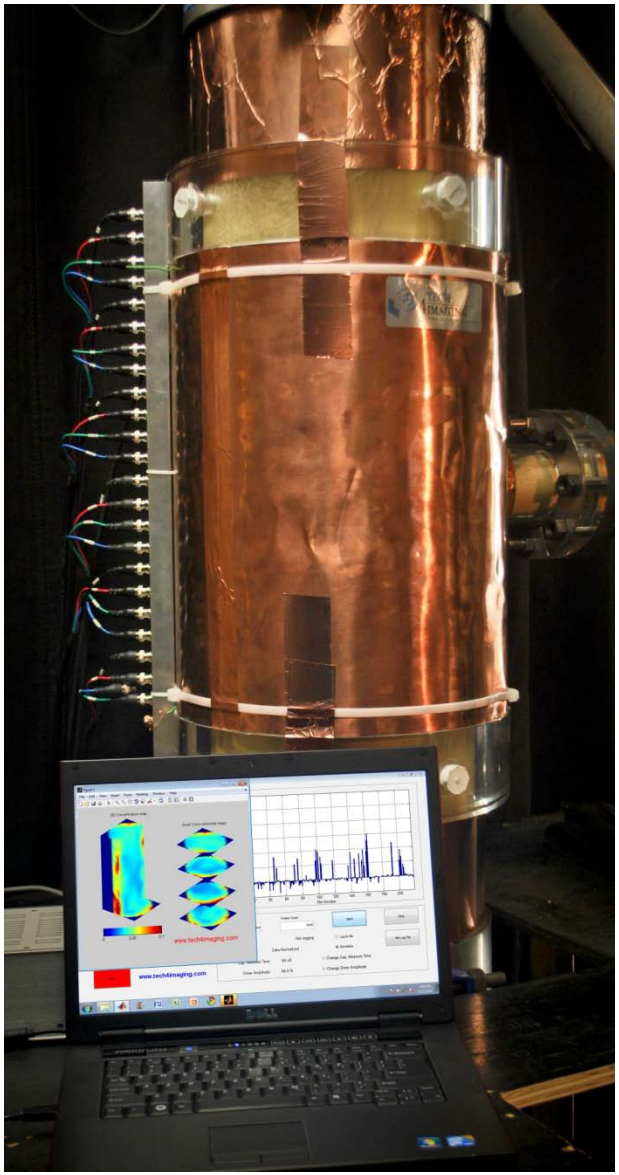




Data Collection → Reconstruction → Post Processing

1 Frame ~1s

4in ECVT sensor on CLC Demo Unit



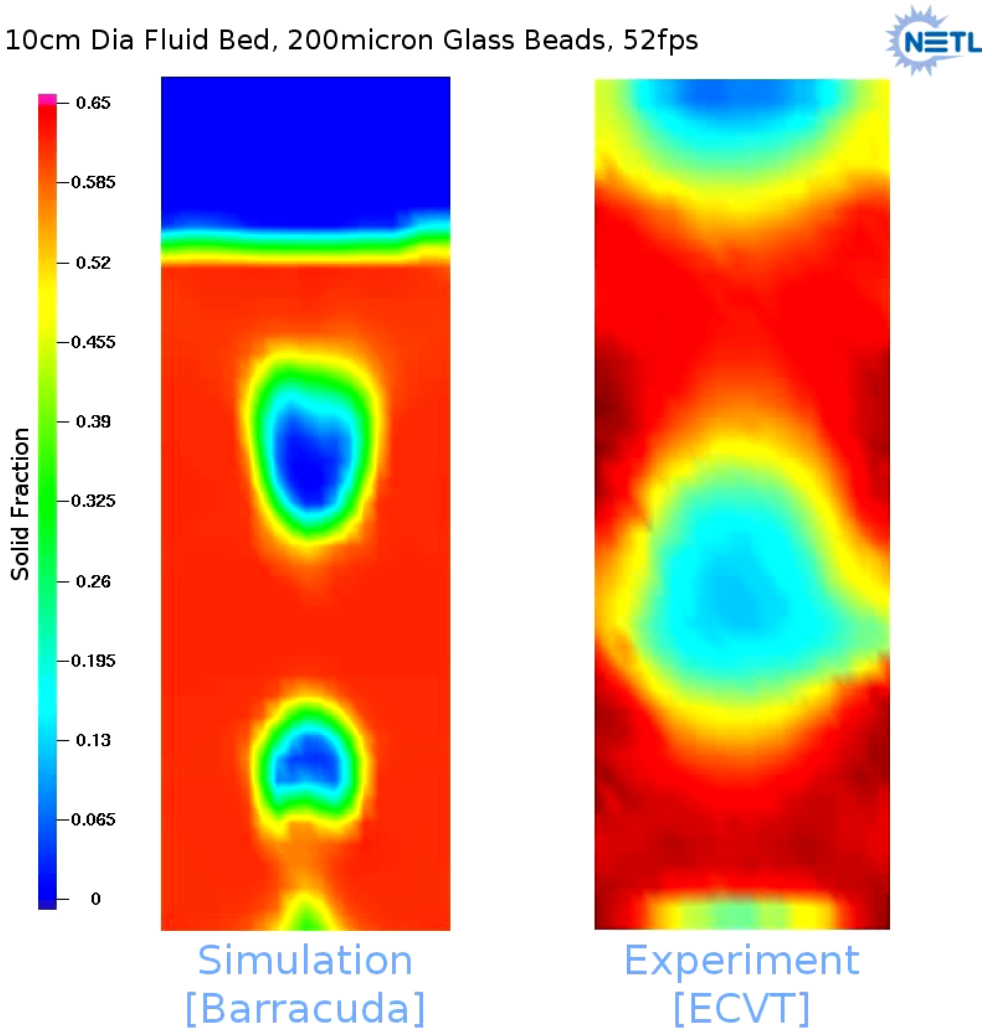
12in ECVT sensor on CFB

CFD and Measurements in the CL reactor

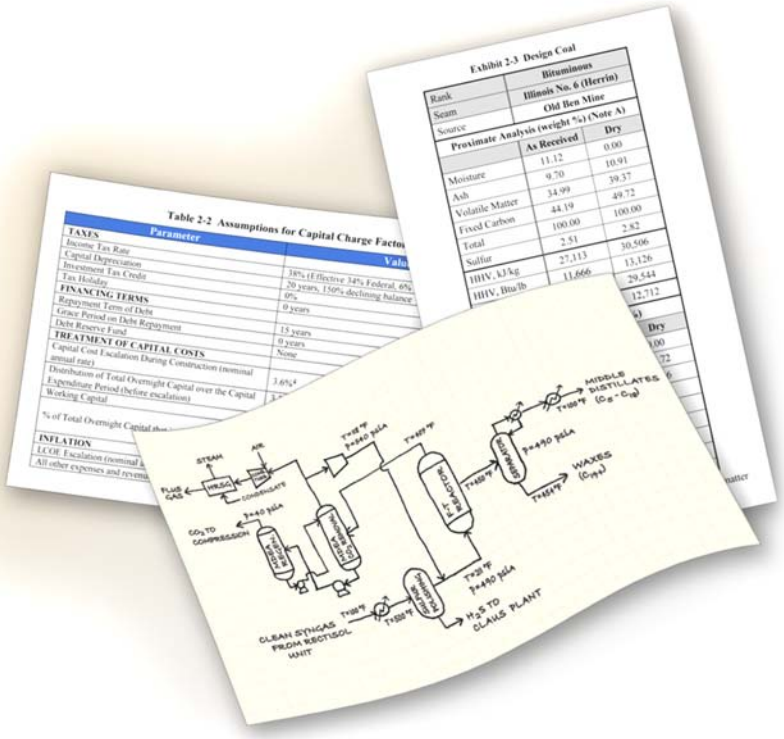
Fast model useful to explore design options.

Large bubbles may limit conversion.

Quantitative measurement of bubble dynamics – unique validation data & important insight for chem looping reactors.

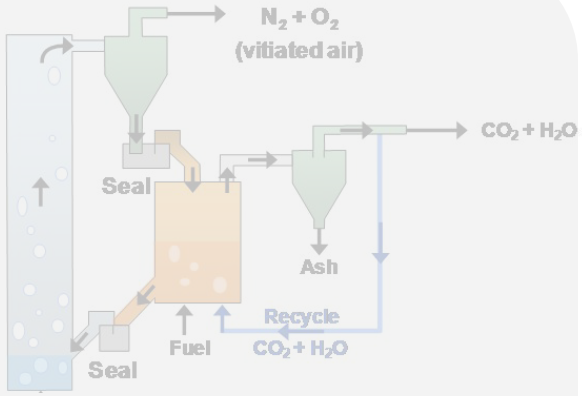


Technical and Economic Analysis

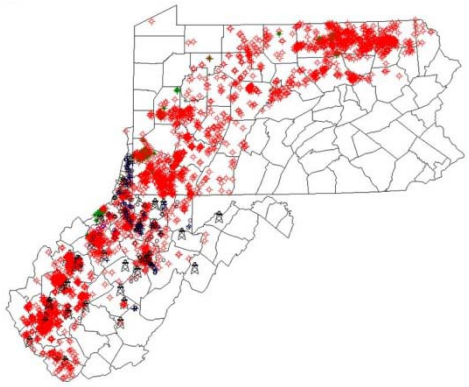


- **Identify Industrial CCS Applications.**
- **Develop Design Basis & Modeling Tools.**
  - **Use research results for key chemical looping parameters in model**
  - **Build on NETL past studies, models and protocols**
- **Perform Techno-Economic Analysis.**
- **Estimate Benefits.**

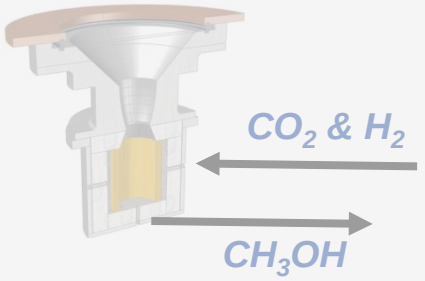
ICMI's Main Research Activities



CL Process diagram



2011 Marcellus Shale Wells



Low-Temperature Reactor

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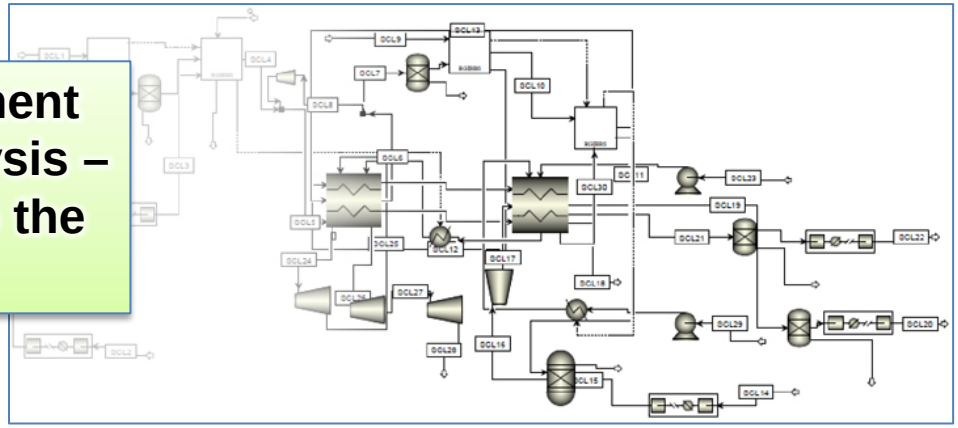
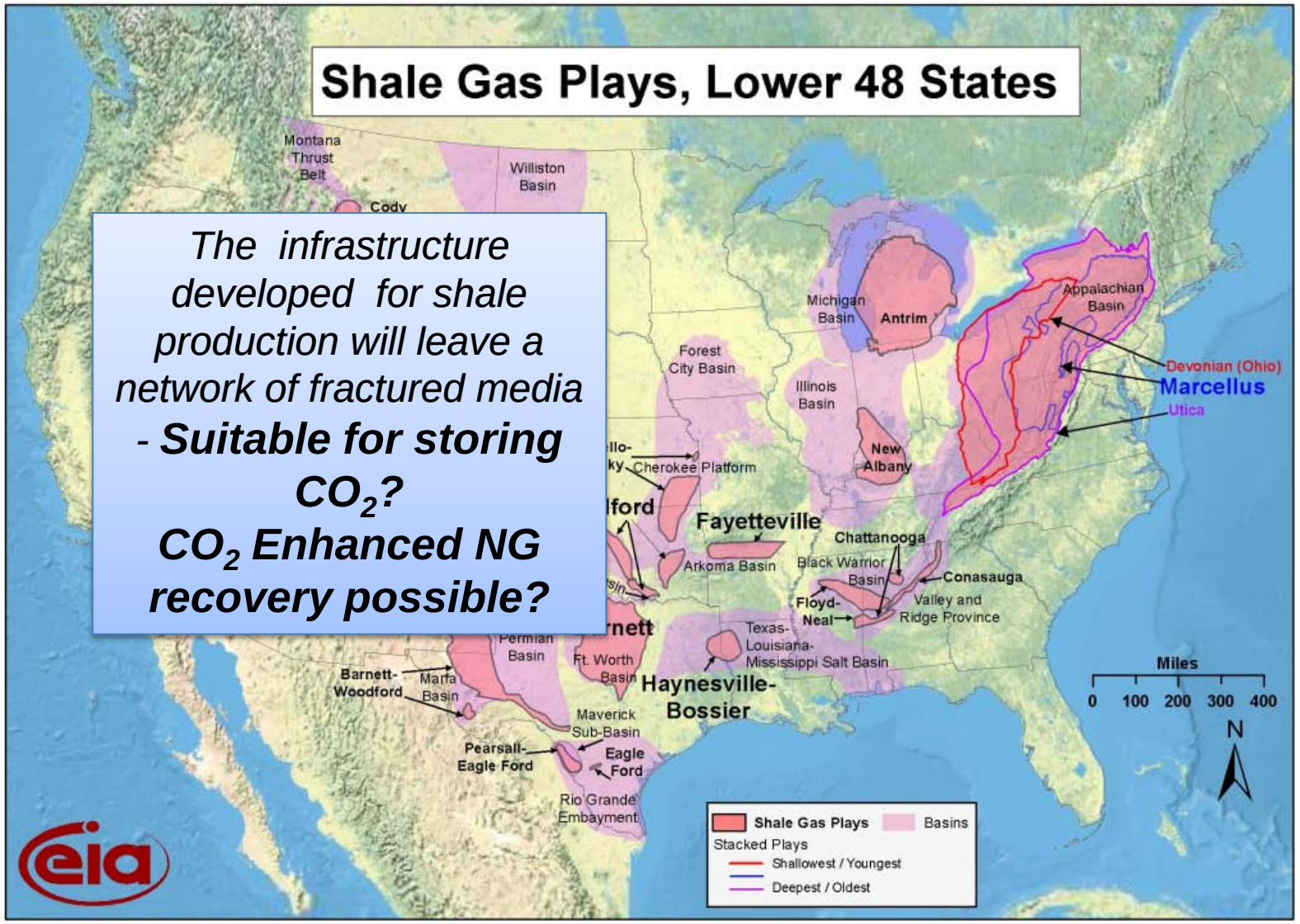
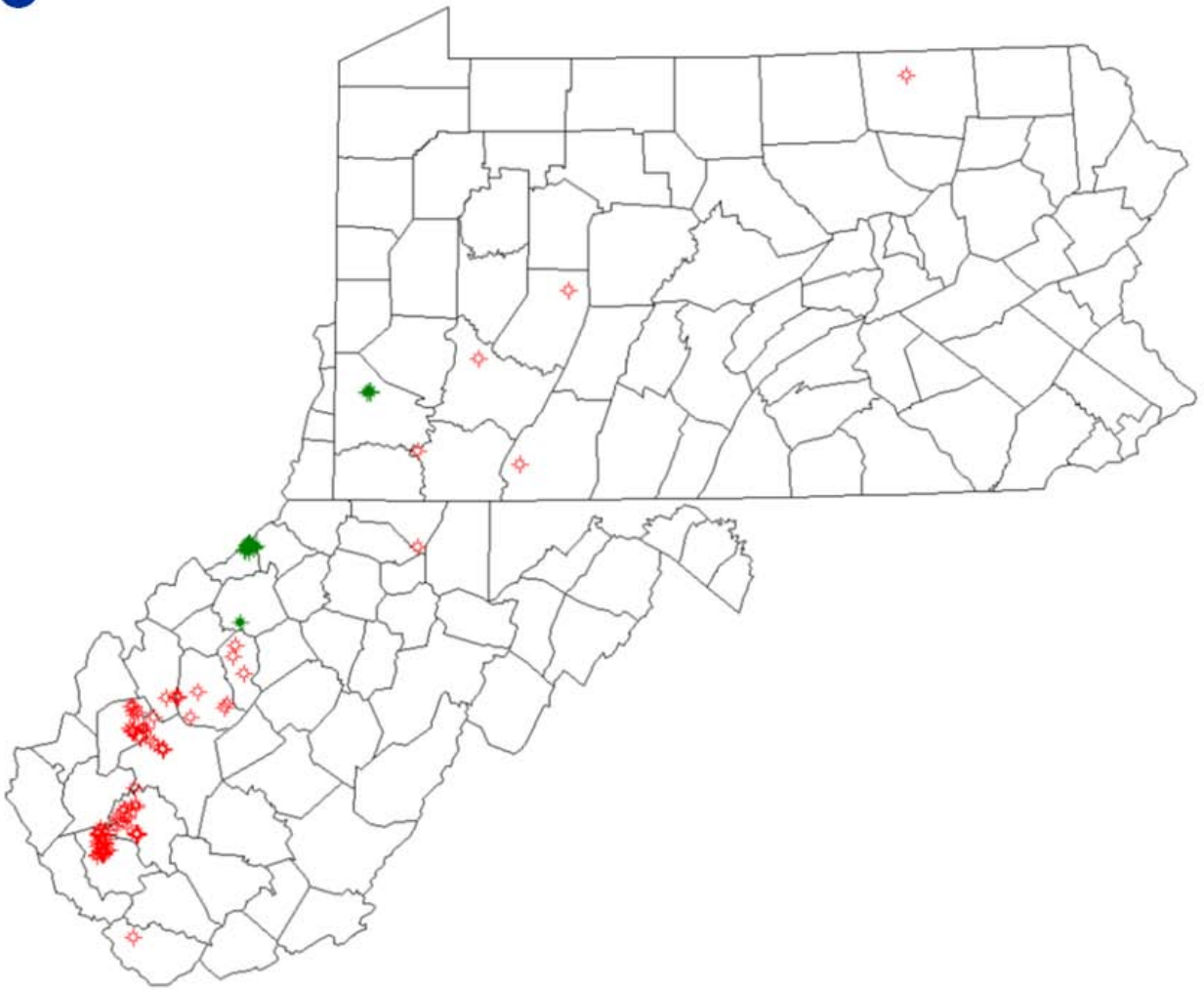




Source: Energy Information Administration based on data from various published studies.
Updated: March 10, 2010

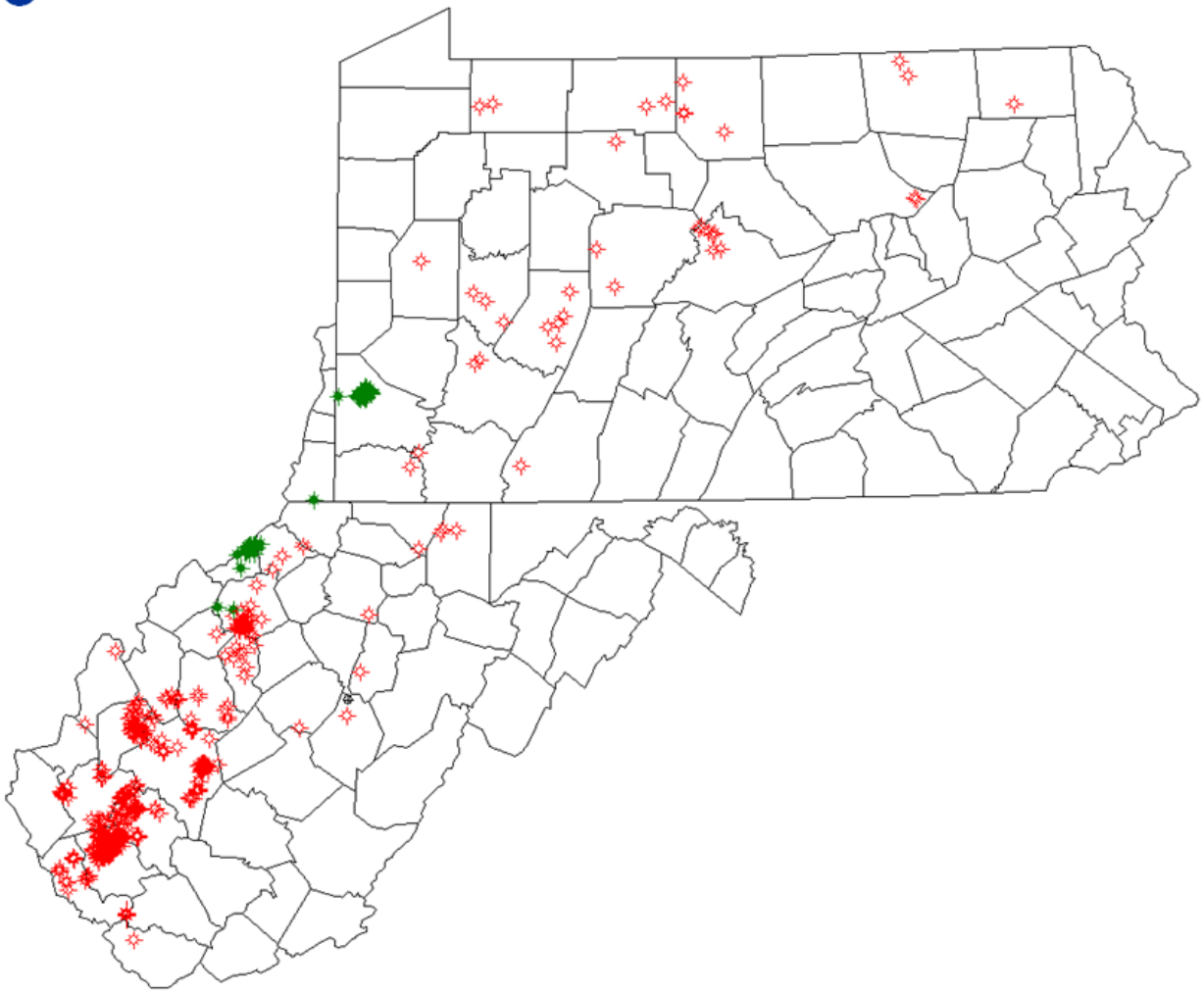
Cumulative Marcellus Wells

2005



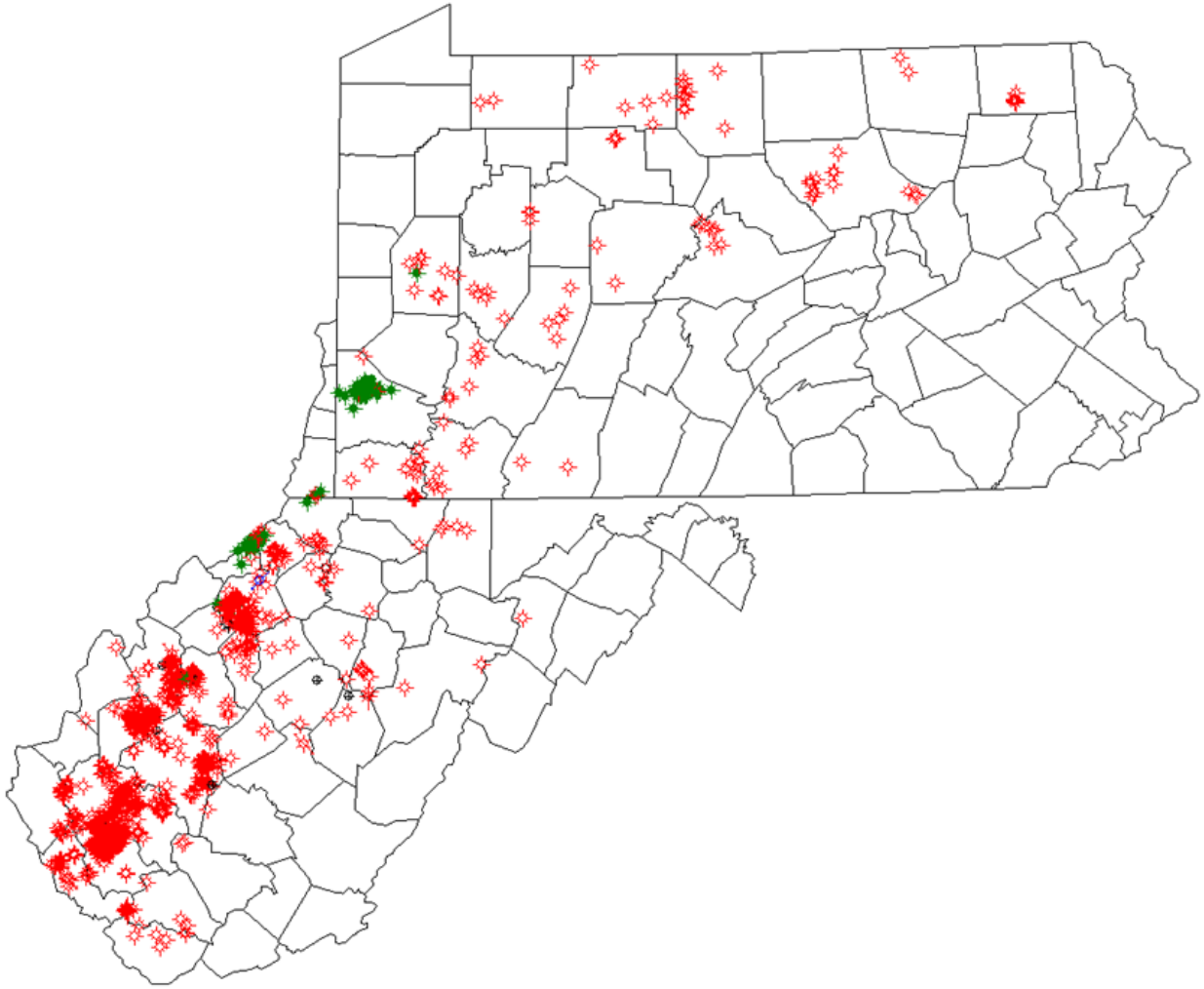
Cumulative Marcellus Wells

2006



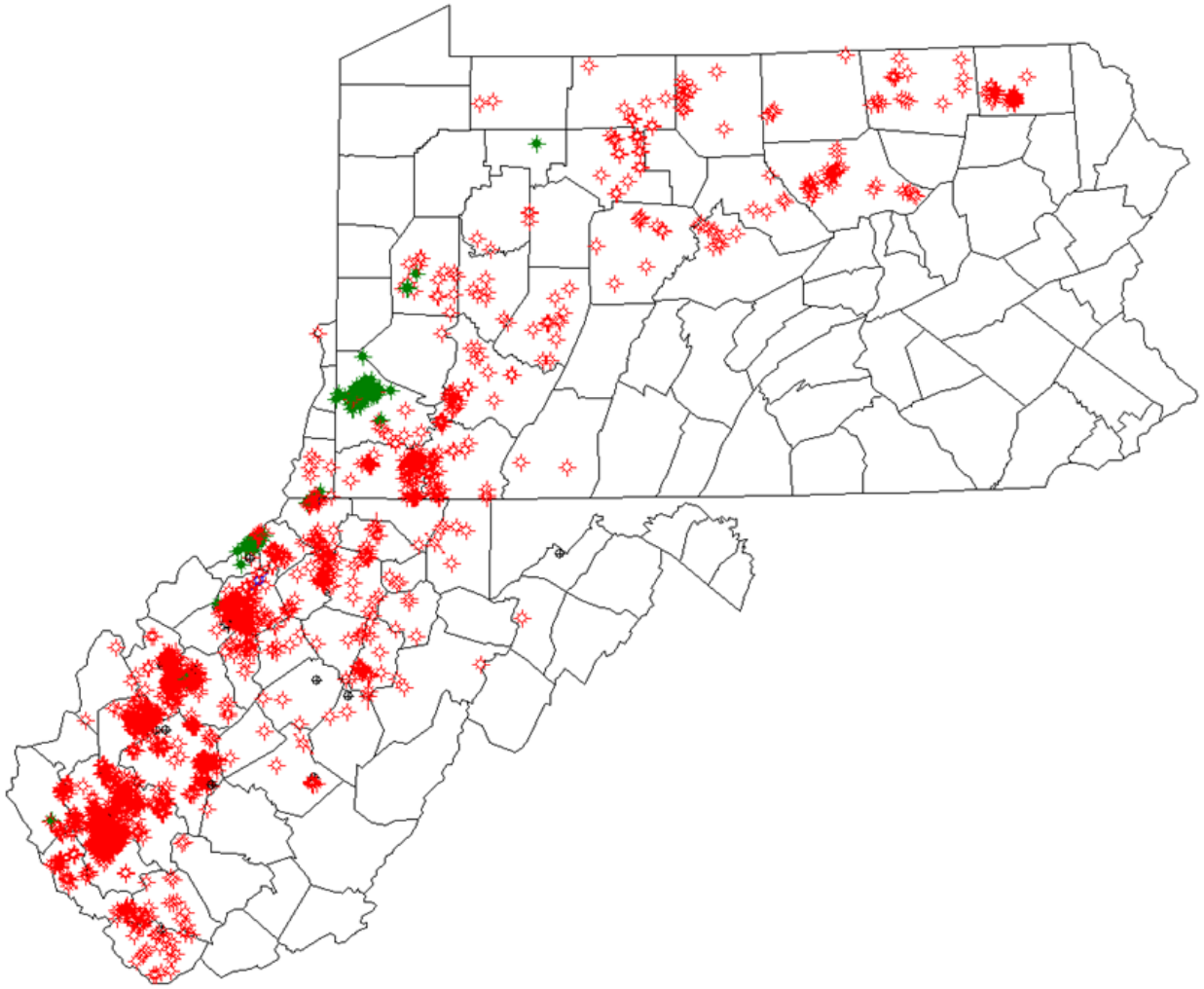
Cumulative Marcellus Wells

2007



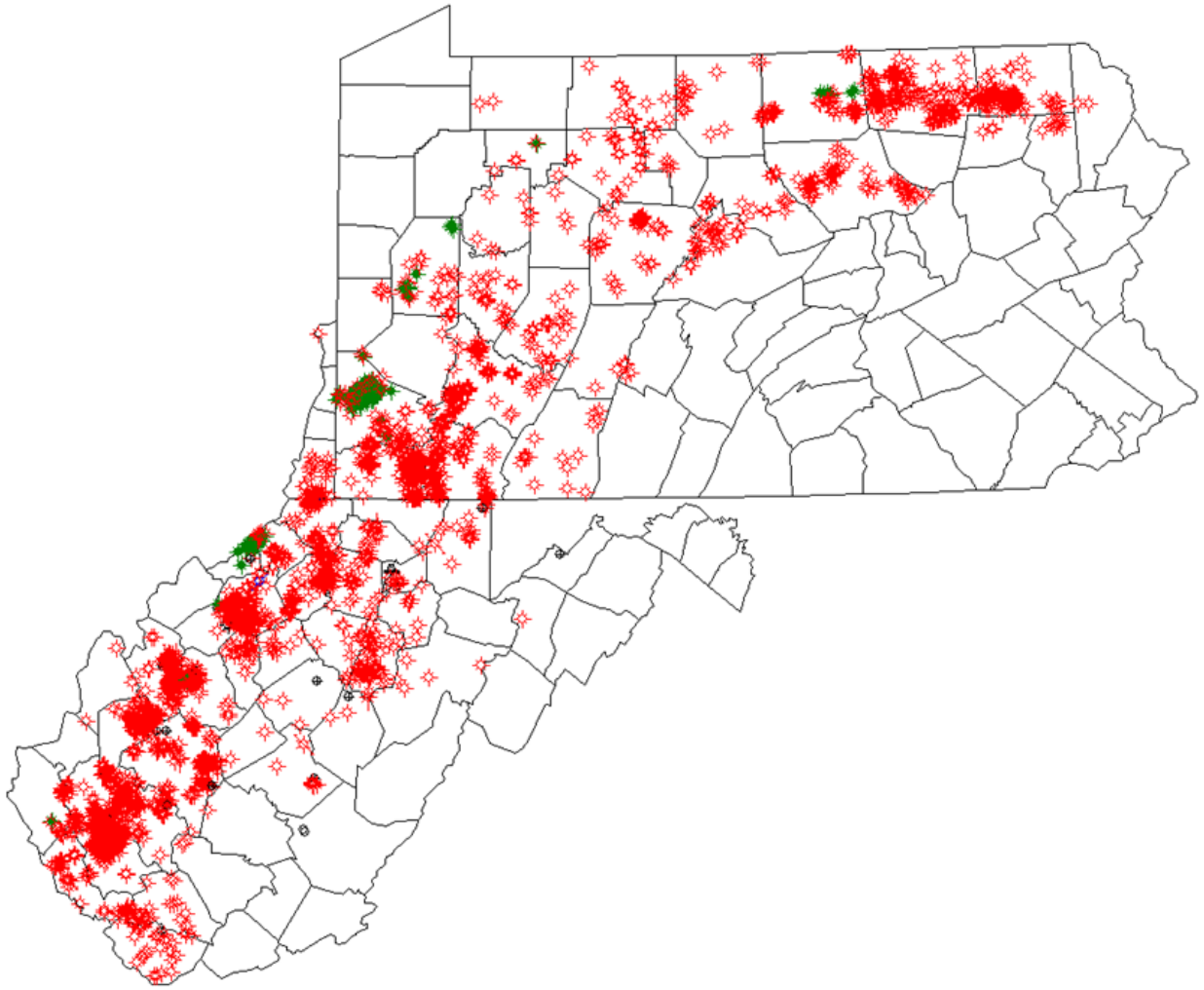
Cumulative Marcellus Wells

2008



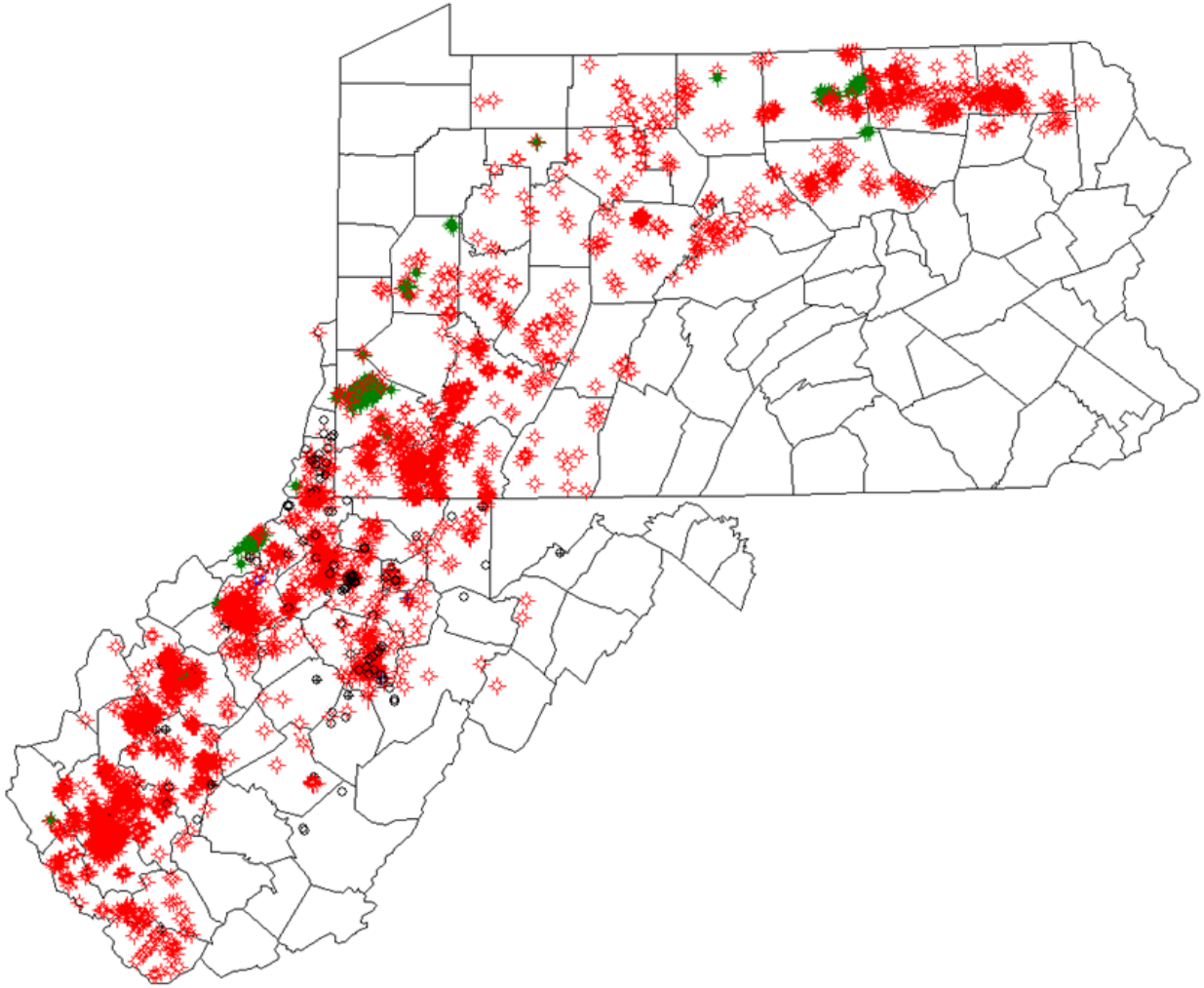
Cumulative Marcellus Wells

2009



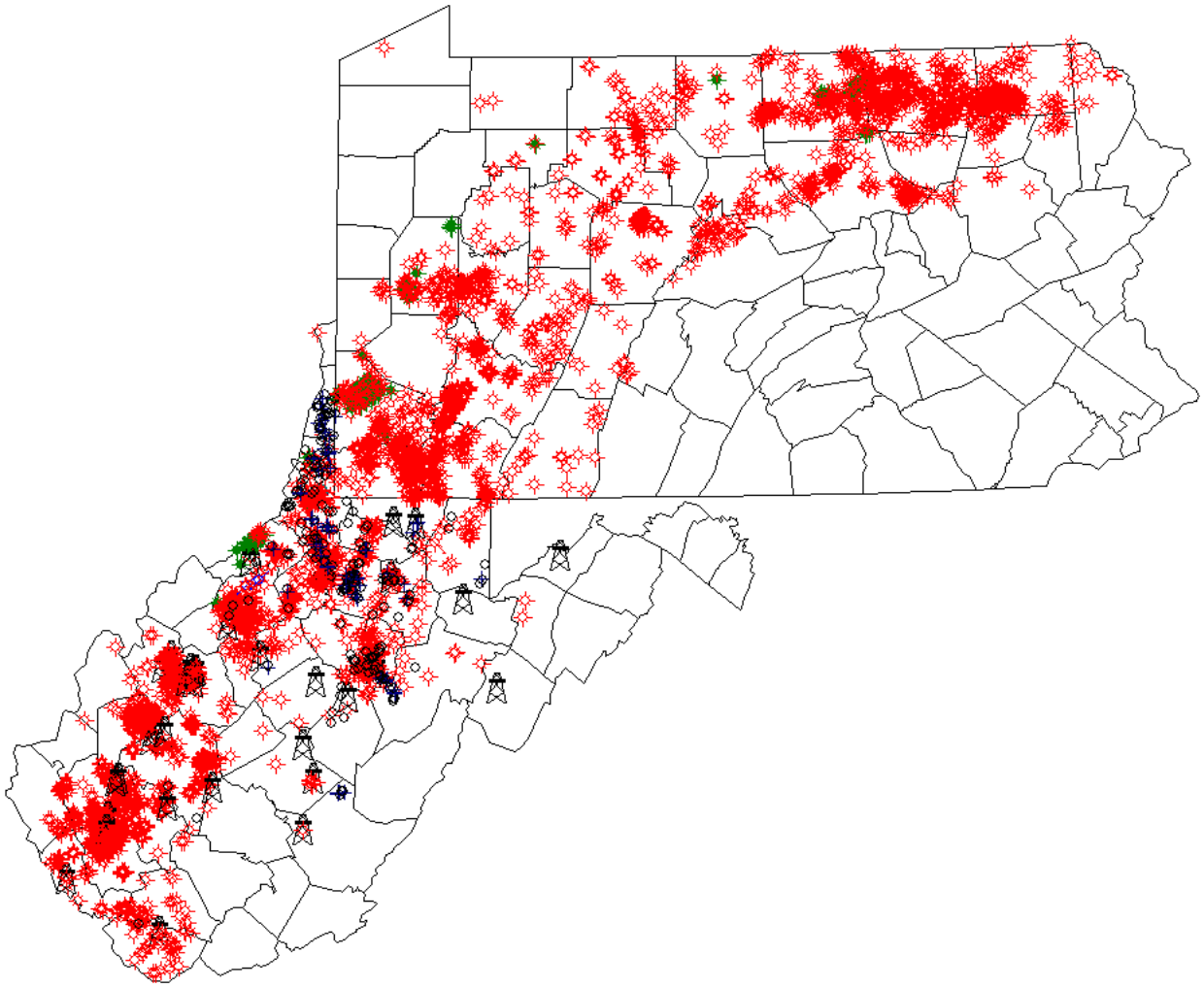
Cumulative Marcellus Wells

2010



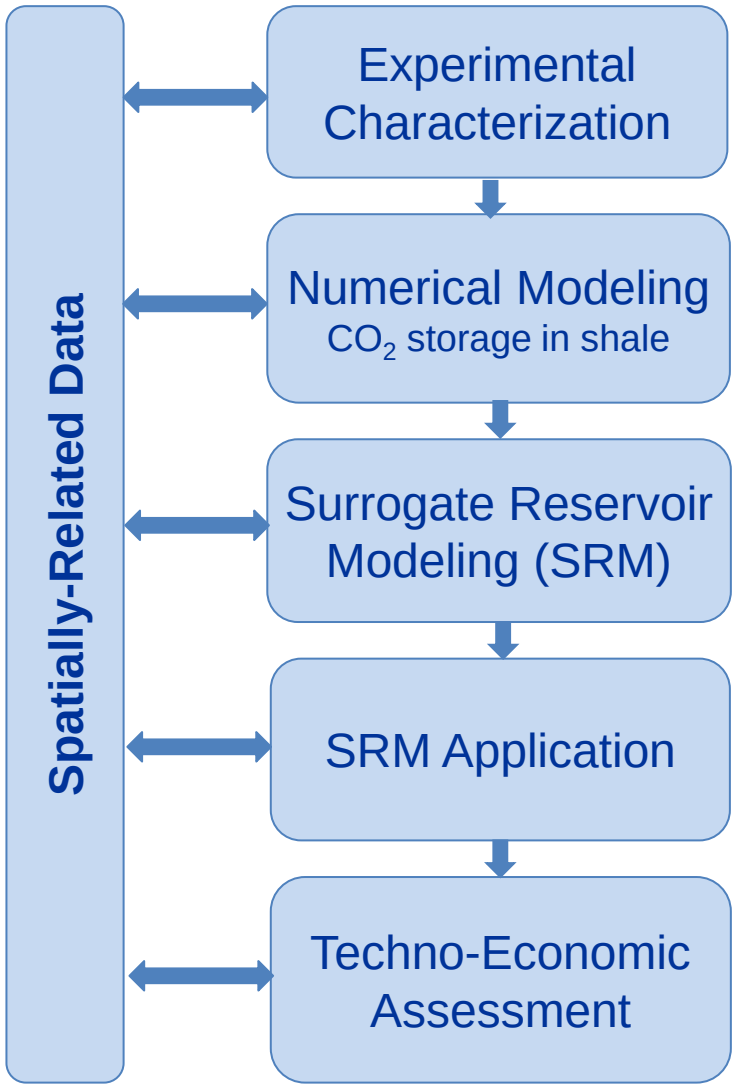
Cumulative Marcellus Wells

2011



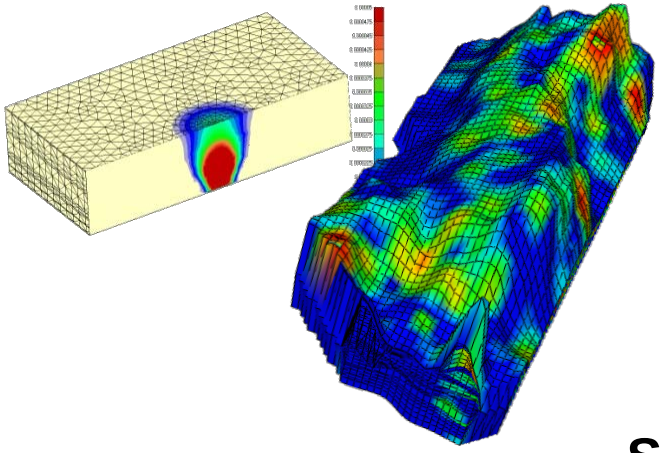
Source: *Carr, Timothy. "Gas Shale in the Appalachian Basin Technical and Societal Challenges and Opportunities"*

Overview of Technical Approach



Developing Surrogate Models from Numerical Reservoir Models

Full-Field Numerical Model

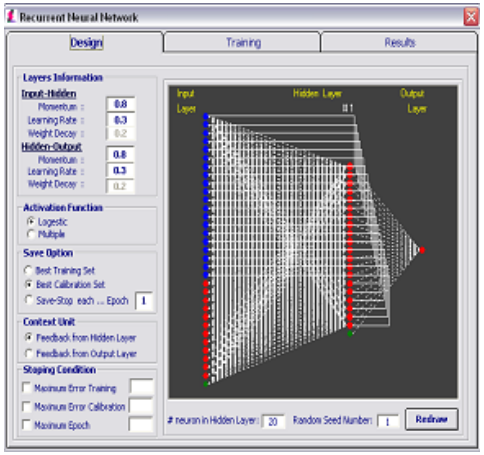


Database of 10-20 Simulation Runs

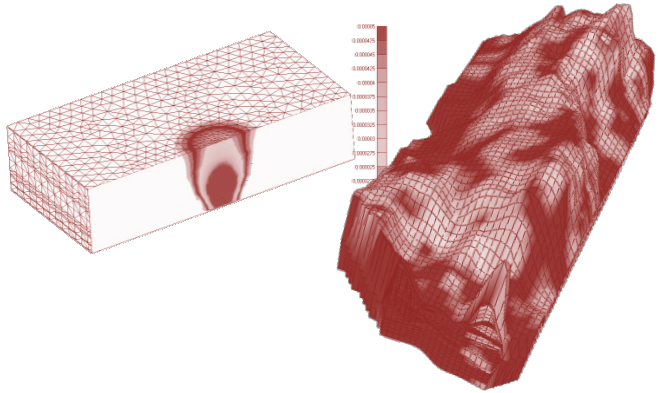
SRM Training

Pattern Recognition

(fuzzy set theory and Artificial Neural Networks)



SRM Mimics Behavior of Full-Field Model

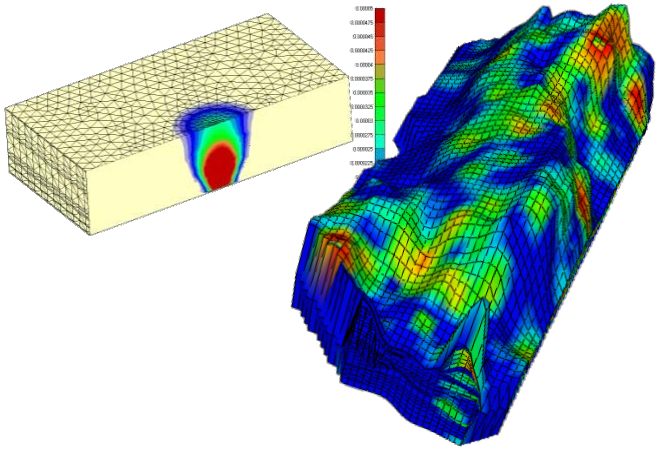


Explore Reservoir Behavior

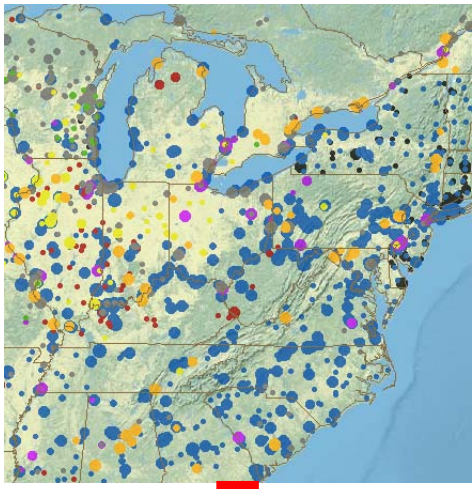
(Sensitivity and Uncertainty Analyses, and Scenario Evaluation)

Surrogate Reservoir Modeling

SRM-Based Scenario for CO2 Storage and EGR



Geospatial Data on CO_2 Sources/Sinks



Parameterized Cost of CO_2 Transport & Storage in Shale

Table 2: Pipeline Cost Breakdown [4, 6, 7]

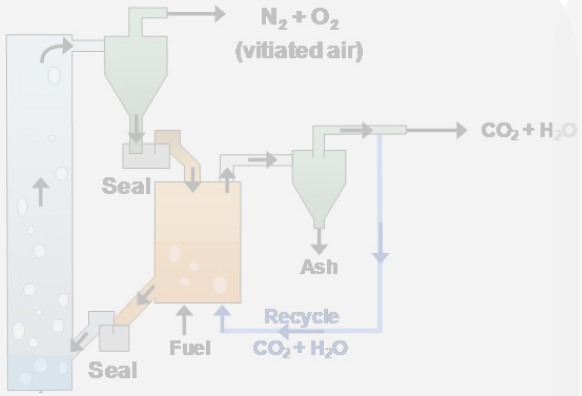
Cost Type	Units	Cost
Pipeline Costs		
Materials	$ Diameter (inches), Length (miles)	$\$64{,}632 + \$1.85 \times L \times (330.5 \times D^2 + 686.7 \times D + 26{,}960)$
Labor	$ Diameter (inches), Length (miles)	$\$341{,}627 + \$1.85 \times L \times (343.2 \times D^2 + 2{,}074 \times D + 170{,}013)$
Miscellaneous	$ Diameter (inches), Length (miles)	$\$150{,}166 + \$1.58 \times L \times (8{,}417 \times D + 7{,}234)$
Right of Way	$ Diameter (inches), Length (miles)	$\$48{,}037 + \$1.20 \times L \times (577 \times D + 29{,}788)$
Other Capital		
CO_2 Surge Tank	$	$1,150,636
Pipeline Control System	$	$110,632
O&M		
Fixed O&M	$/mile/year	$8,632

Least Cost Assessment and Comparison with Saline Sequestration

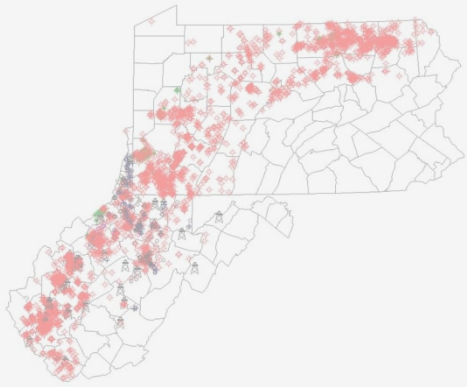
Techno-Economic Assessment CO_2 Storage in Shale

SOURCES: 1) Crandal, Dustin; 2) NATCARB 3) Tarka, Thomas J. "QGESS: Estimating Carbon Dioxide Transport and Storage Costs ." Publication Number: DOE/NETL-400/2010/1447. Publication Date: Sep 2010. Accessed online 7/28/2011 from : http://www.netl.doe.gov/energy-analyses/refshelf/PubD

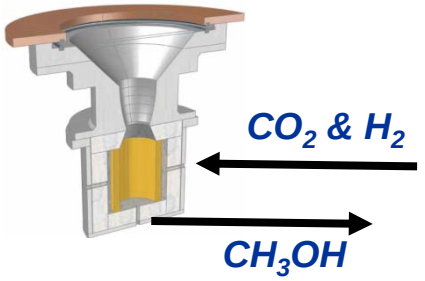
ICMI's Main Research Activities



CL Process diagram



2011 Marcellus Shale Wells



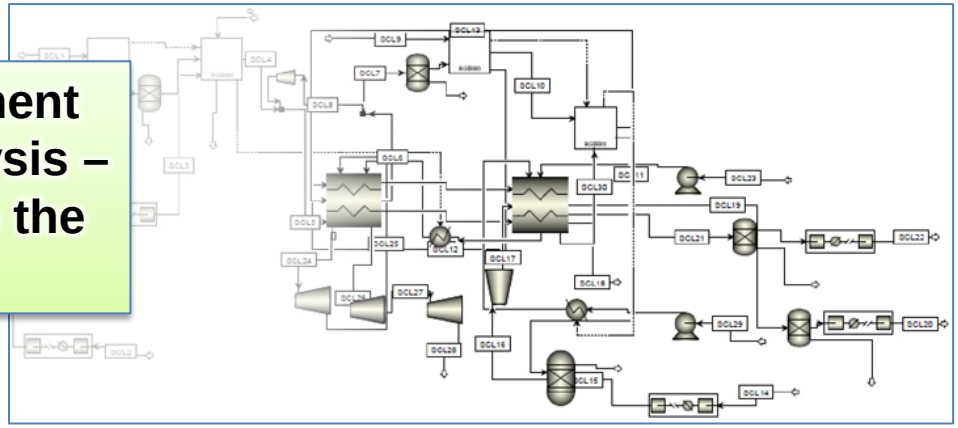
Low-Temperature Reactor

Capture - chemical looping technology evaluation.

Storage – shale gas reservoir sequestration.

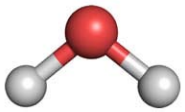
Re-use – Photoactive and thermal CO2 conversion.

Industrial assessment and systems analysis – identify & evaluate the application

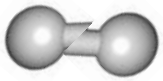


CO_2 as a Chemical Feedstock

CO_2



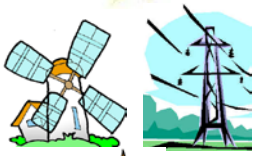
H_2O



H_2

+

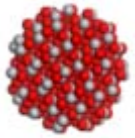
Sun



Electricity & Waste Power

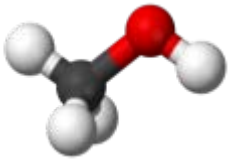
Industrial Waste Heat

+



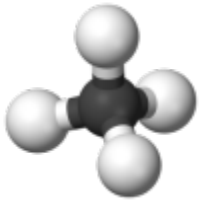
Catalyst

Are there niche Industrial markets where this is profitable?



Methanol

+



Methane

Use directly as fuel or convert to other chemicals

Methanol to DME Diesel via (H-ZSM etc)

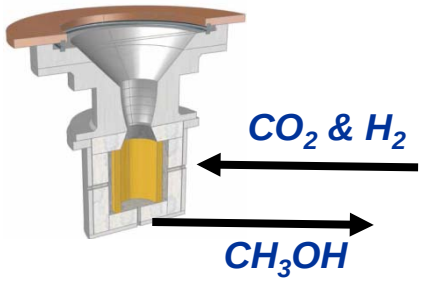
Transportation/Military Fuels

Methane Reforming to H_2 and other fuels

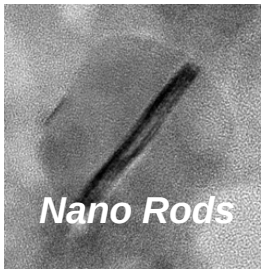
Scalable Processes with Copper Based Catalysts

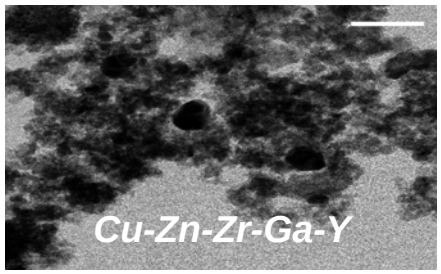
Waste Heat or Solar-Thermal Energy Converts CO_2 & H_2 to Methanol

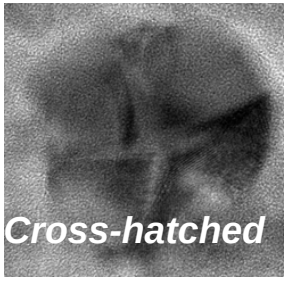
Reactor Using Low - Temperature Heat



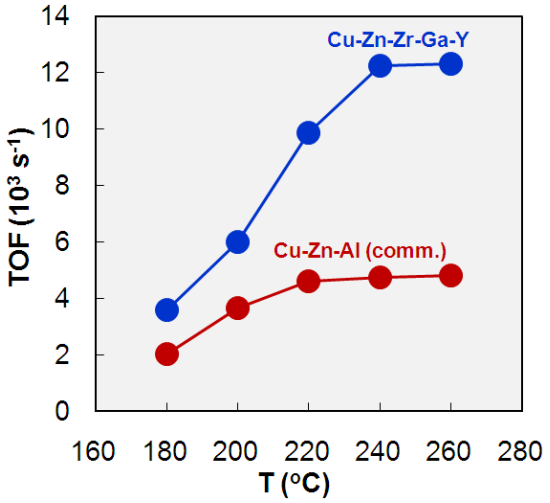
Nanostructured Cu is Highly Reactive



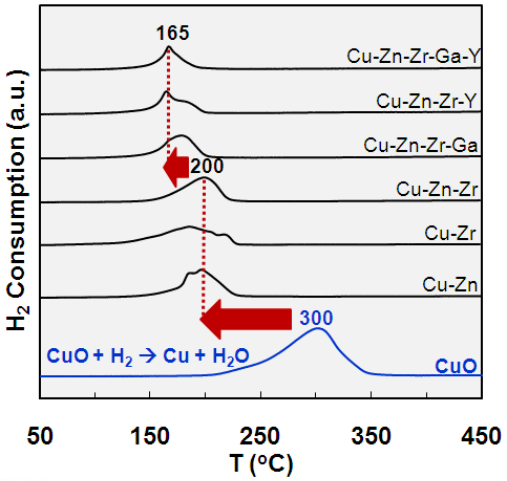




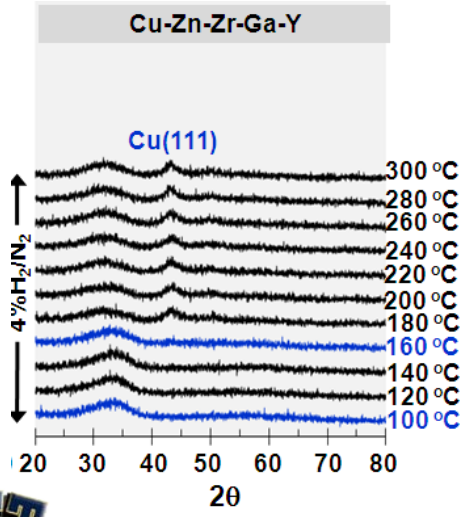
Cu-based Catalysts Outperform Commercial Systems



Improved Reducibility (Easily Activated)

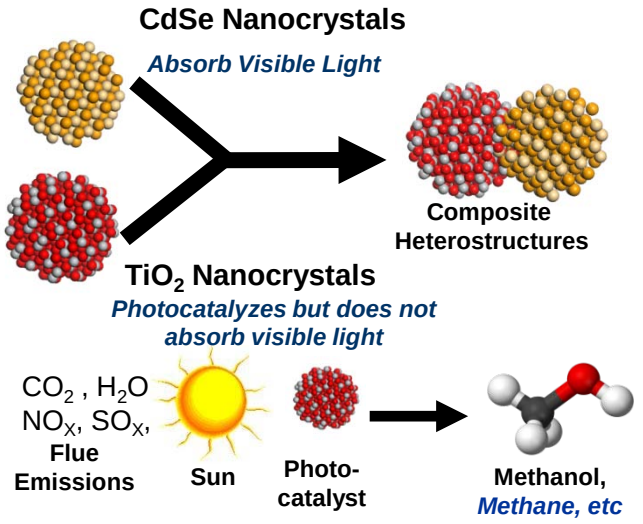


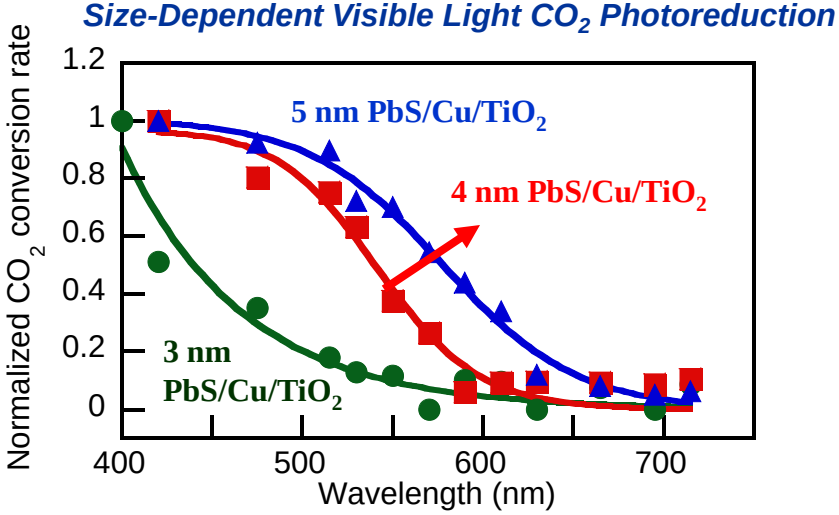
Cu Catalysts are Resistant to Sintering



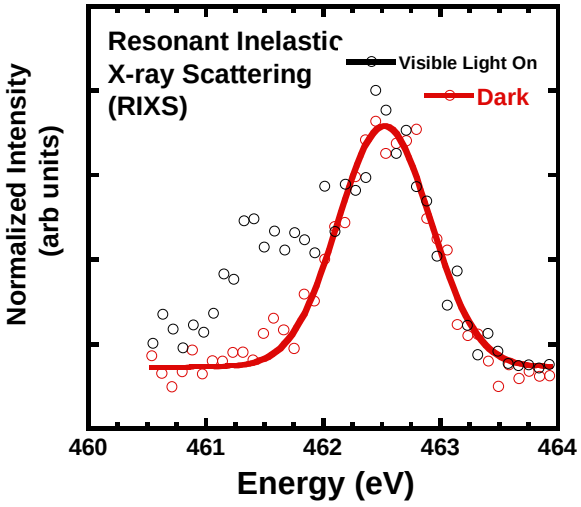
Visible Light Photocatalysts for Carbon Dioxide Reuse

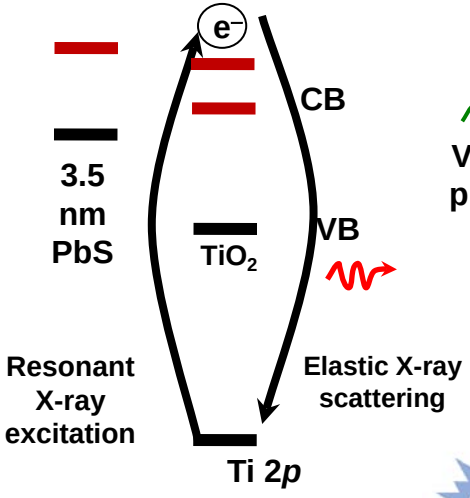
Semiconductor nanocrystals enhance the visible-light photoactivity of TiO_2

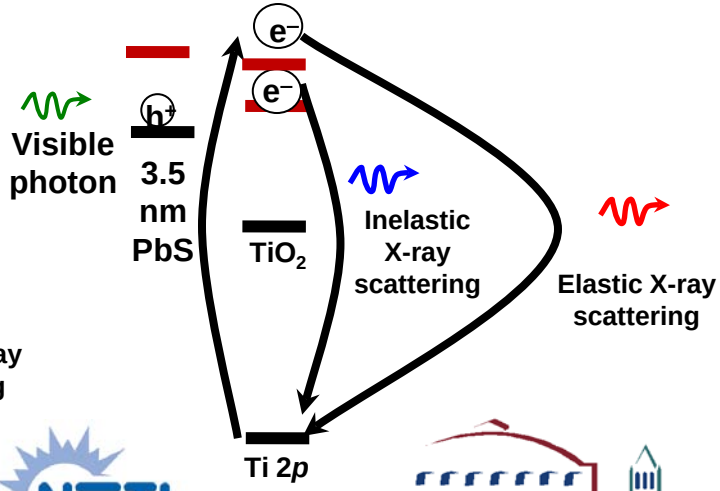




X-ray Synchrotron Studies







Summary

- **ICMI is a 3-year effort developing/assessing:**
  - Chemical looping concepts for industrial CO2 capture.
  - Assessment of gas-shale for CO2 storage/enhanced recovery.
  - Potential CO2 re-use options.
- **Techno-economic studies will guide the work and quantify benefits.**
- **Commercial interest/application invited!**

Industrial Carbon Management Initiative

ICMI