NATIONAL ENERGY TECHNOLOGY LABORATORY

# Fuels to Energy Conversion – the New Combustion

Council of Industrial Boiler Owners 33rd Annual Meeting
October 12-14, 2011 Ft. Lauderdale, Florida

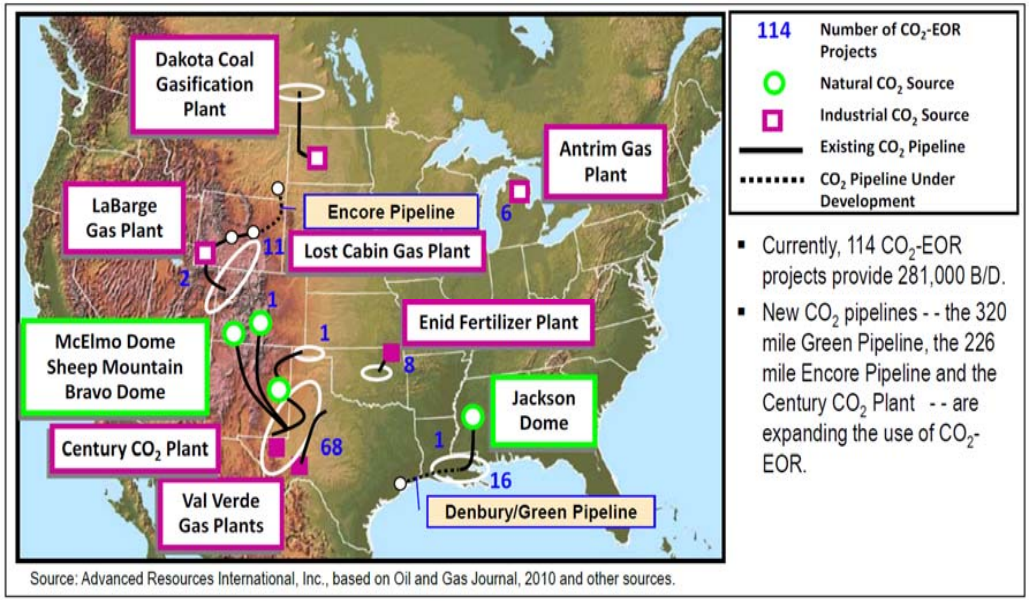
*Acknowledgements:*
*…too many names to list…*

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

U.S. DEPARTMENT OF ENERGY

# Why this talk?

- **Describe a new research and development effort at the National Energy Technology Laboratory (NETL).**
  - New technology for future boiler applications.
  - Technology may address changing regulations for emissions?
  - Simple, low-cost $CO_2$ separation.
  - $CO_2$ ready for storage or Enhanced Oil Recovery (EOR)*:
    - $CO_2$- EOR accounts for ~6 % of U.S. Crude Oil Production
    - $CO_2$-EOR assisted by low-cost $CO_2$ ("low" depends on oil price)




*** Improving Domestic Energy Security and Lowering CO2 Emissions with Next Generation CO2-Enhanced Oil Recovery, *DOE/NETL-2011/1504, June 2011, available at www.netl.doe.gov***

# Industrial Carbon Management Initiative

- **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?

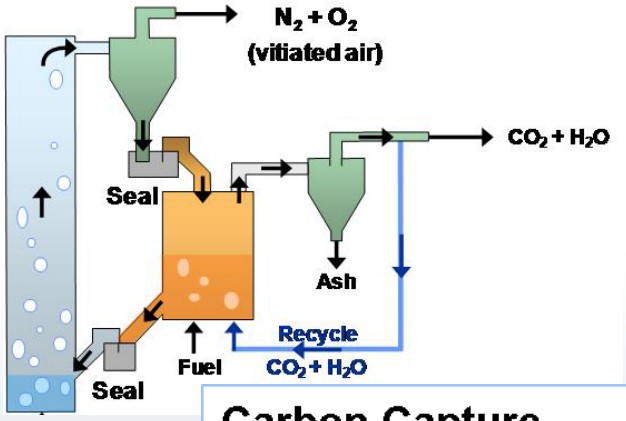
- **NETL's Strategic Center for Coal (SCC) provides funding and acts as a Technical Monitor for the project.**
- **NETL's Office of Research and Development (ORD) provides overall technical leadership and performs a portion of the research.**
- **URS was awarded under an existing contract to provide 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

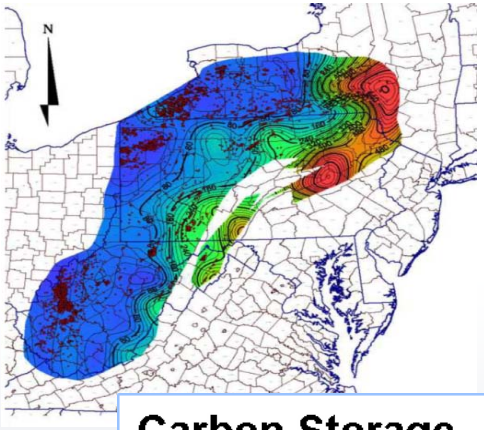
NETL-RUA
Regional University Alliance

# ICMI

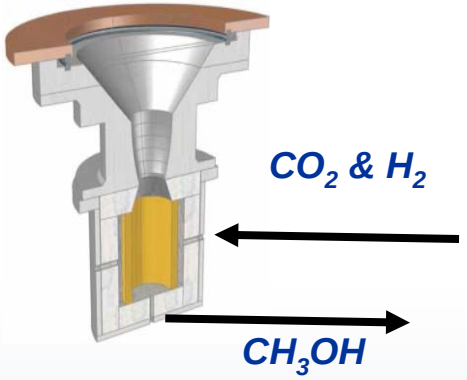
*Industrial Carbon Management Initiative*




**Carbon Capture**
Chemical Looping Combustion

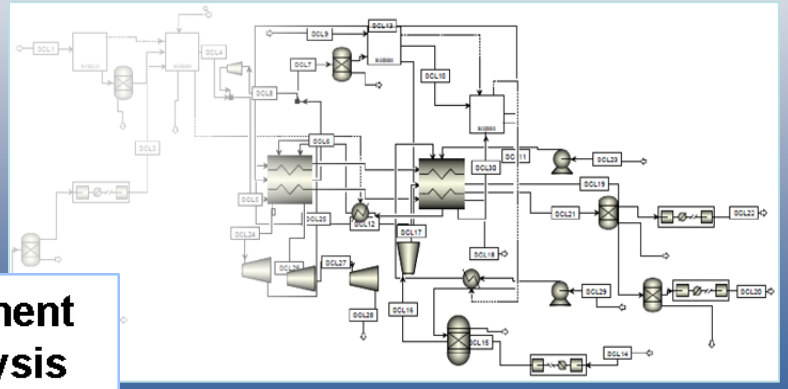



**Carbon Storage**
Depleted Shale Fields




**Carbon Utilization**
Photocatalytic Conversion

## CCUS for Industrial Applications

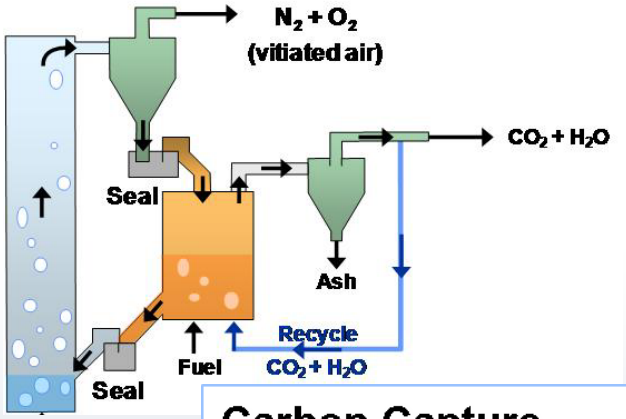


**Industrial assessment and systems analysis**

NETL-RUA
Regional University Alliance

# ICMI

*Industrial Carbon Management Initiative*

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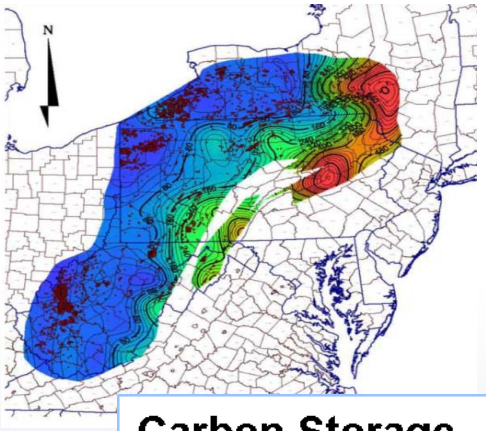


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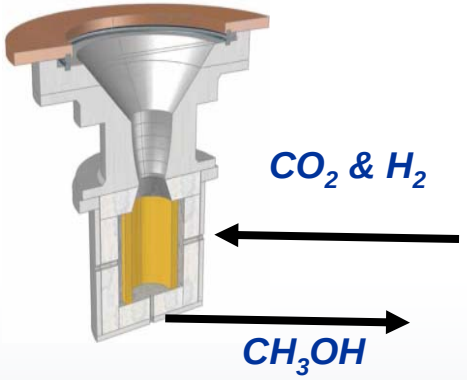


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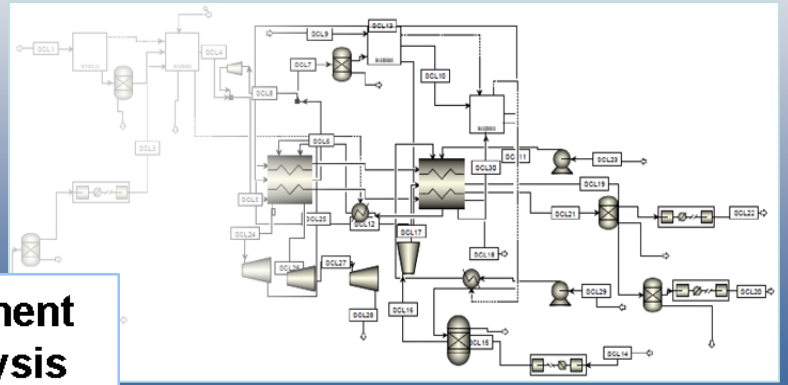
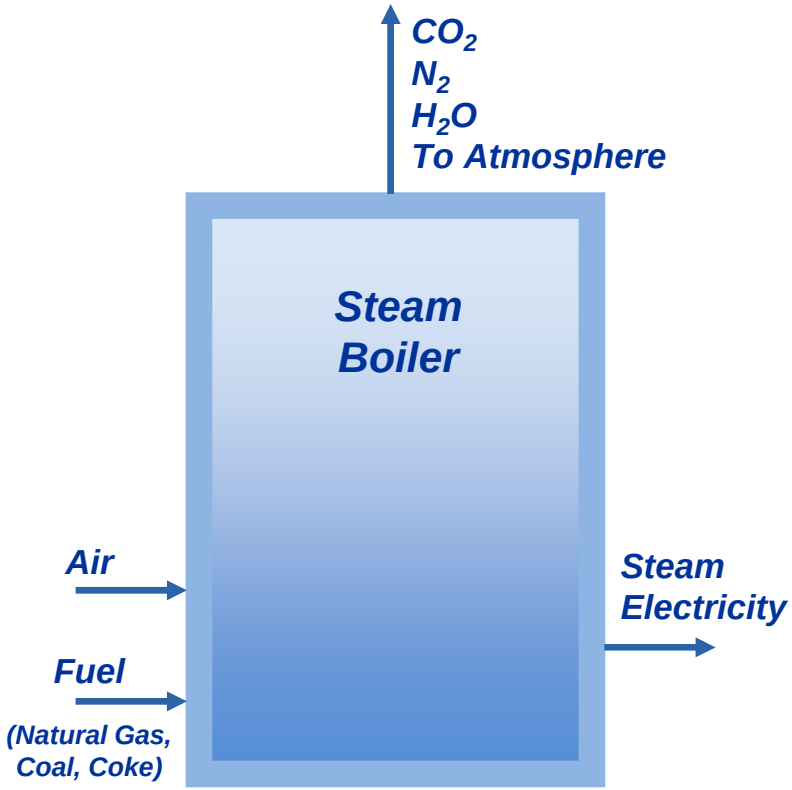
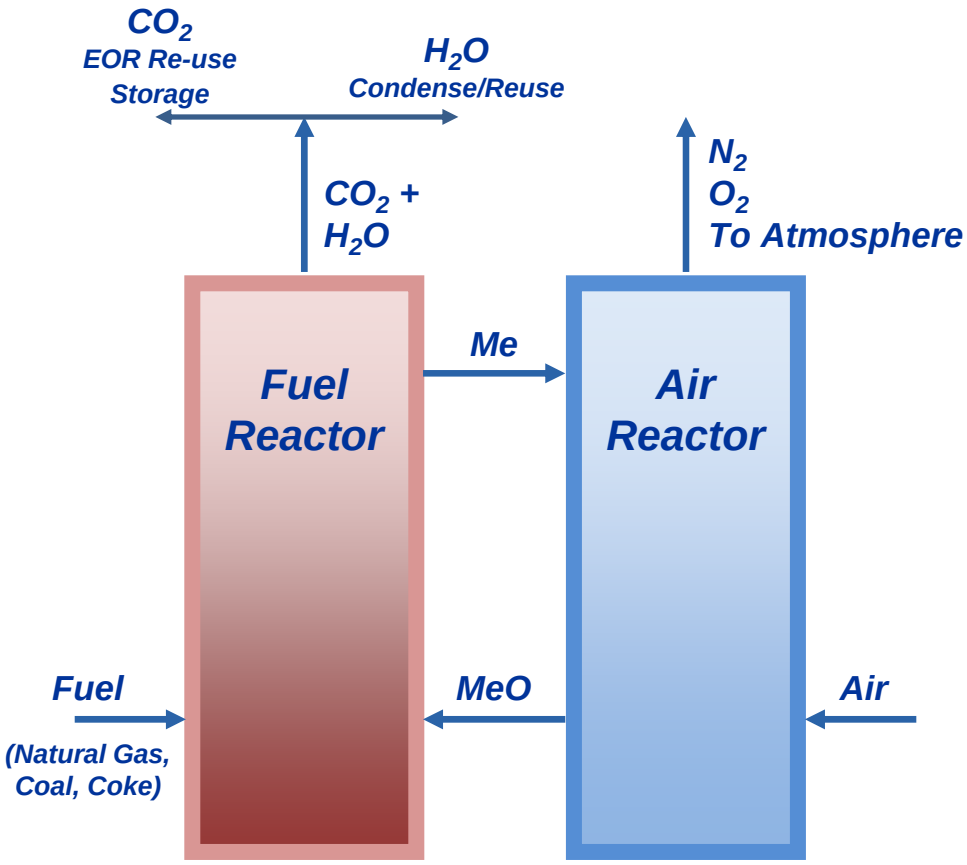


**Industrial assessment and systems analysis**

# Chemical Looping Process Description




Conventional Boiler

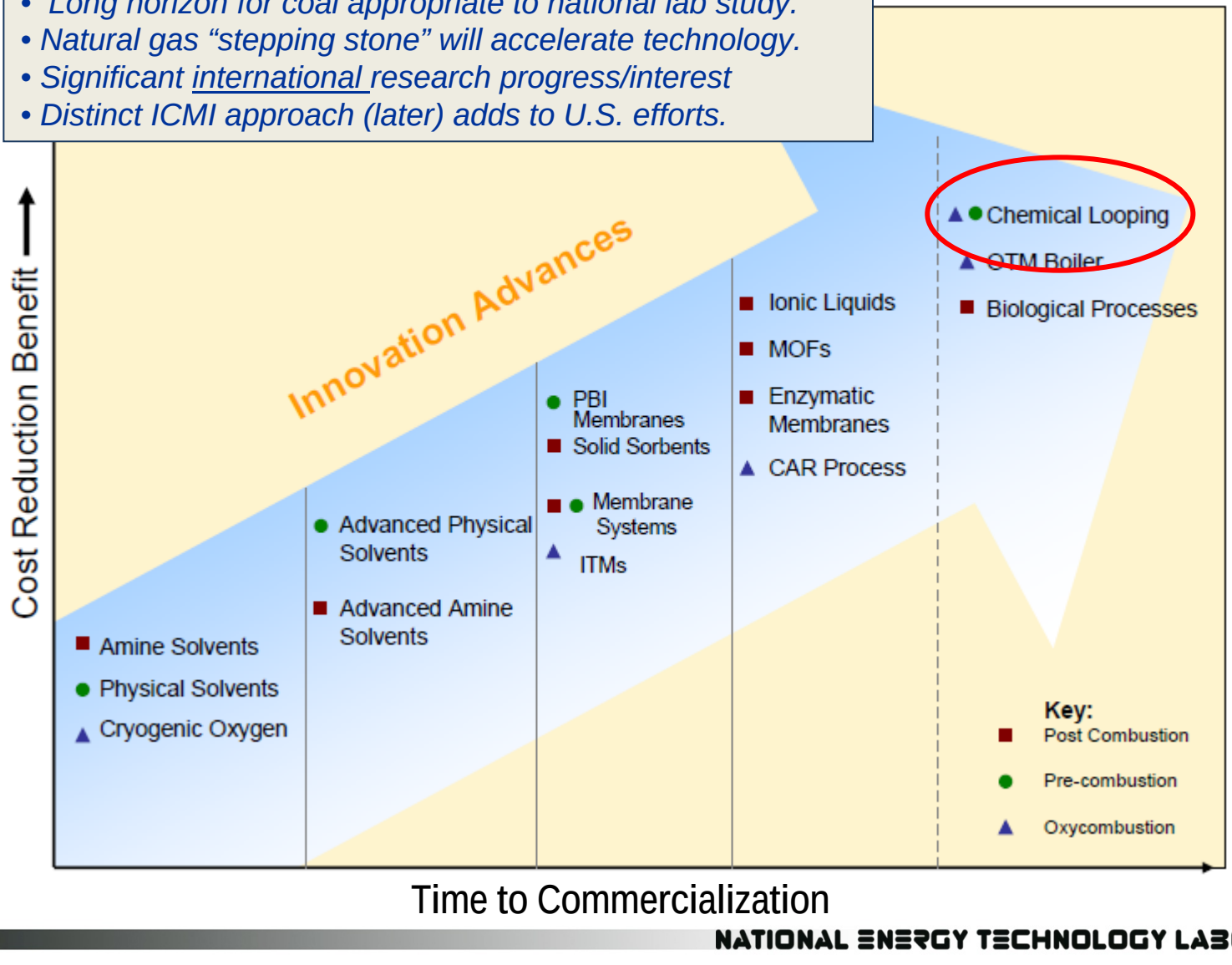



Me = Metal (Oxygen Carrier)
MeO = Metal Oxide

Chemical Looping

# Chemical Looping : Low Cost $CO_2$ Capture

- *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 |

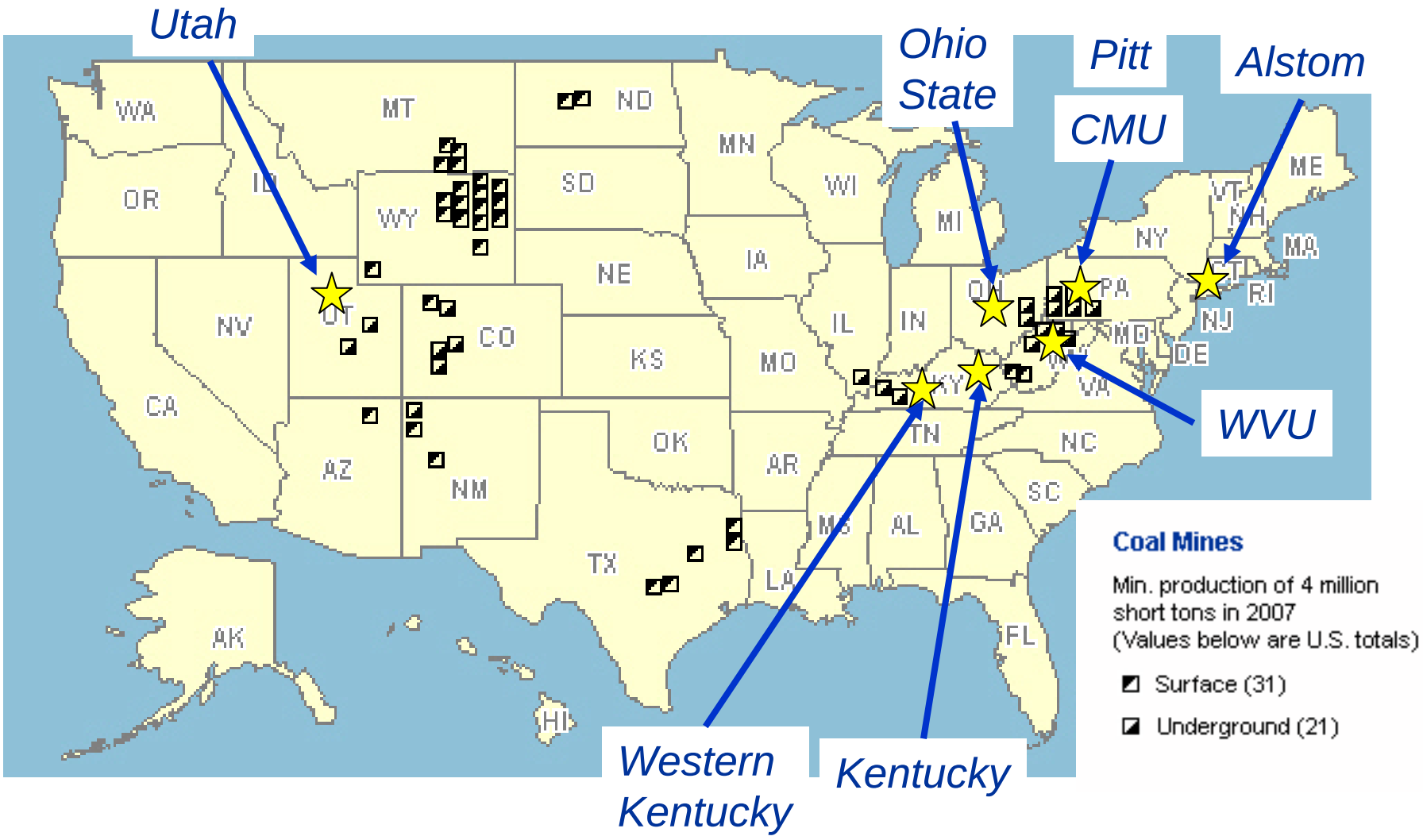
*Both items above: directly from Henrik Leion and Adel Sarofim, Chemical-Looping Tutorial , The 36th International Technical Conference on Clean Coal & Fuel Systems, June 5-9, 2011.*

(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?



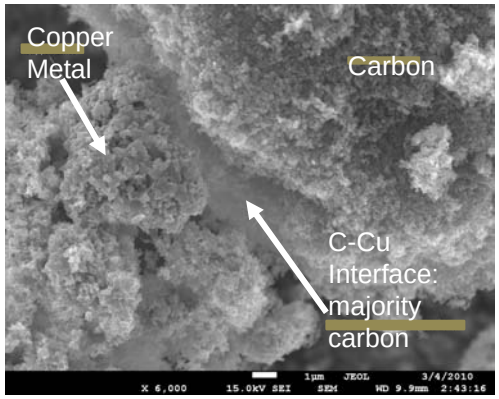
# Industrial Chemical Looping (natural gas and coal)

## Technical Approach:

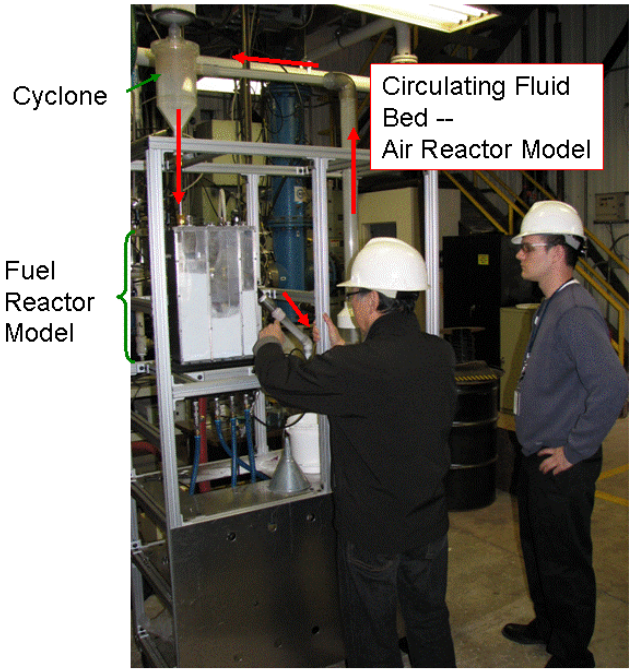
- **Research on oxygen carriers, hydrodynamics, process design for:**
  - Industrial applications (heat, steam)
  - Power
- ***Not a single design*, but data to enable design choices explored with numeric simulations.**
- **Complements specific developments by others.**
- **Assess process economics,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



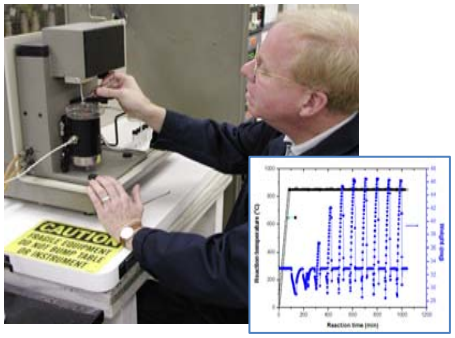
# Simulation and Experimental Facilities

### Existing Clusters

### Attrition Tests


### Fluid Bed Reactors


### Existing TGA Lab




*NETL O2 carrier - cyclic studies in progress*

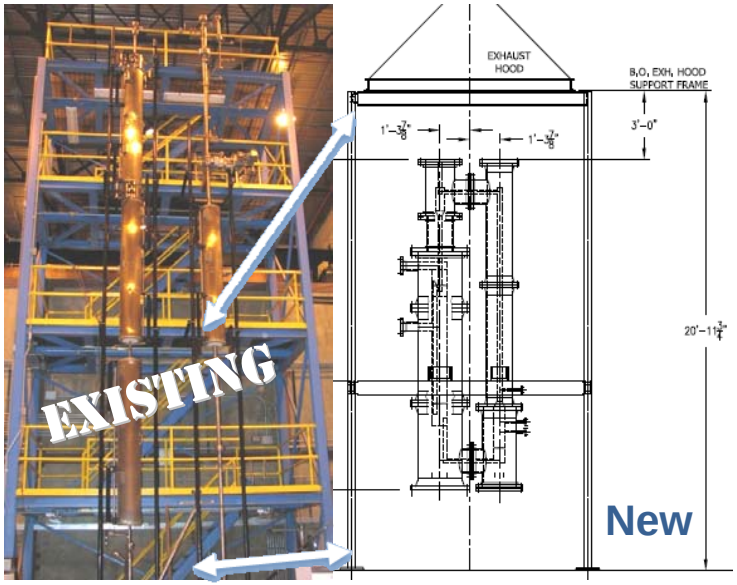
### Candidate SBEUC Systems


*Portable Modular System*

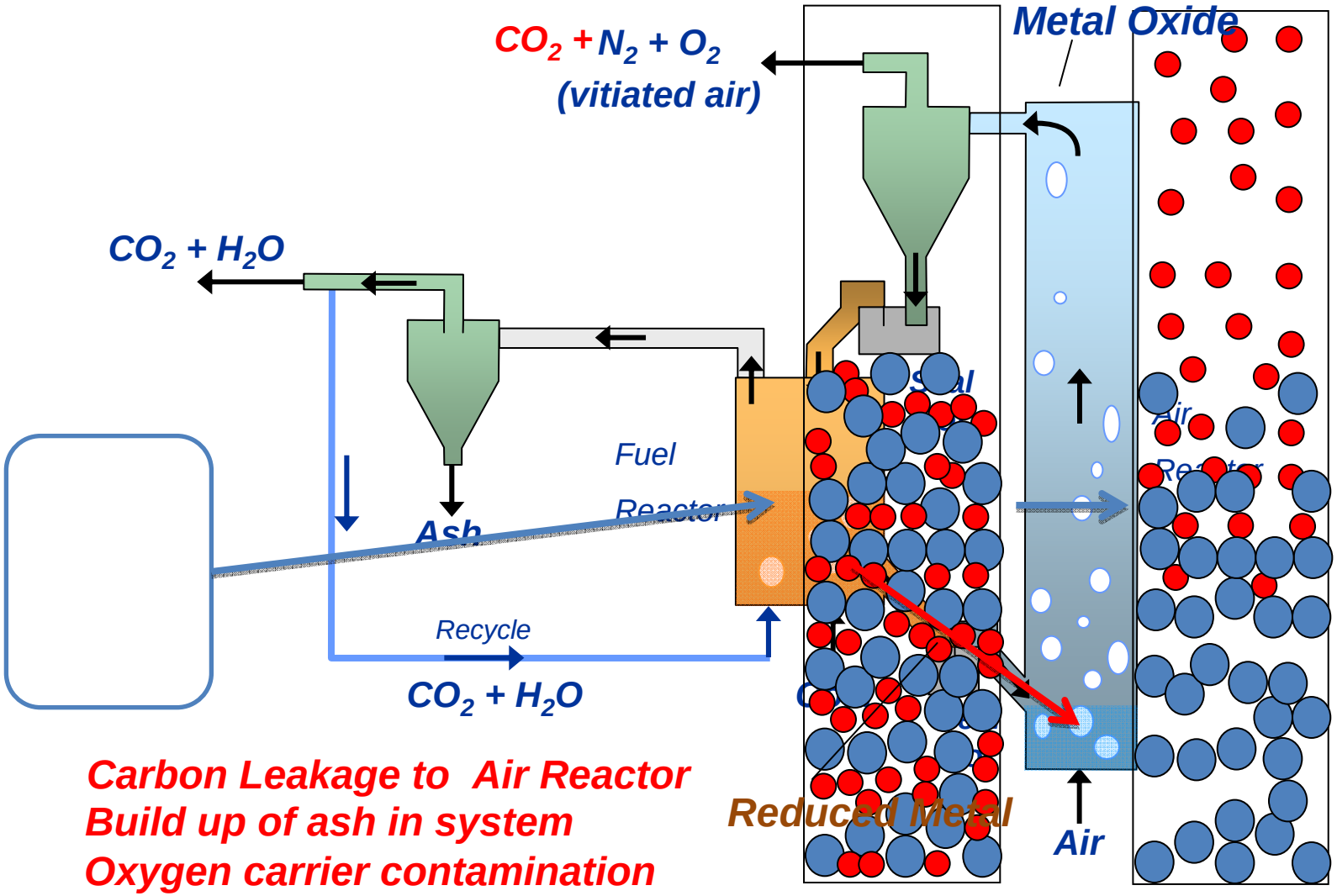

*Performance Optimized System*

### Cold Flow with ECVTs

### Integrated Chemical Looping Reactor

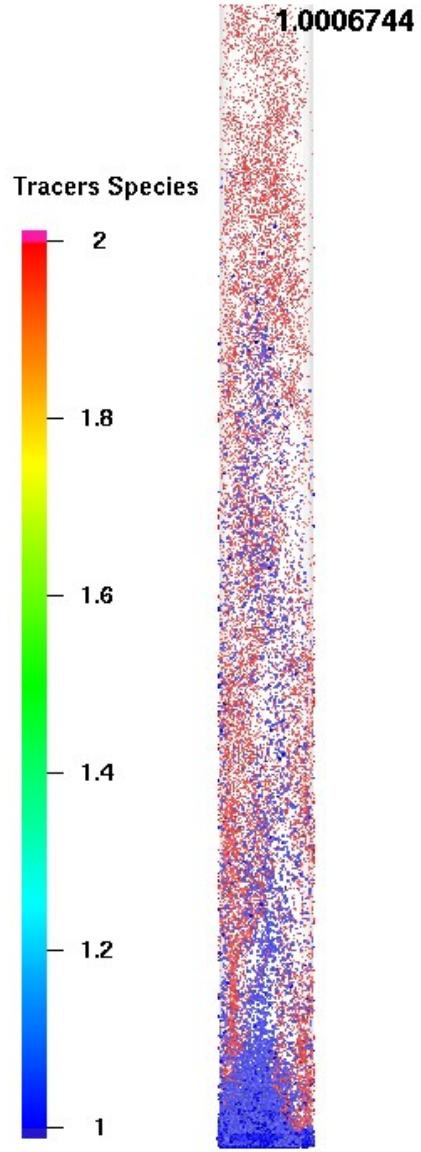


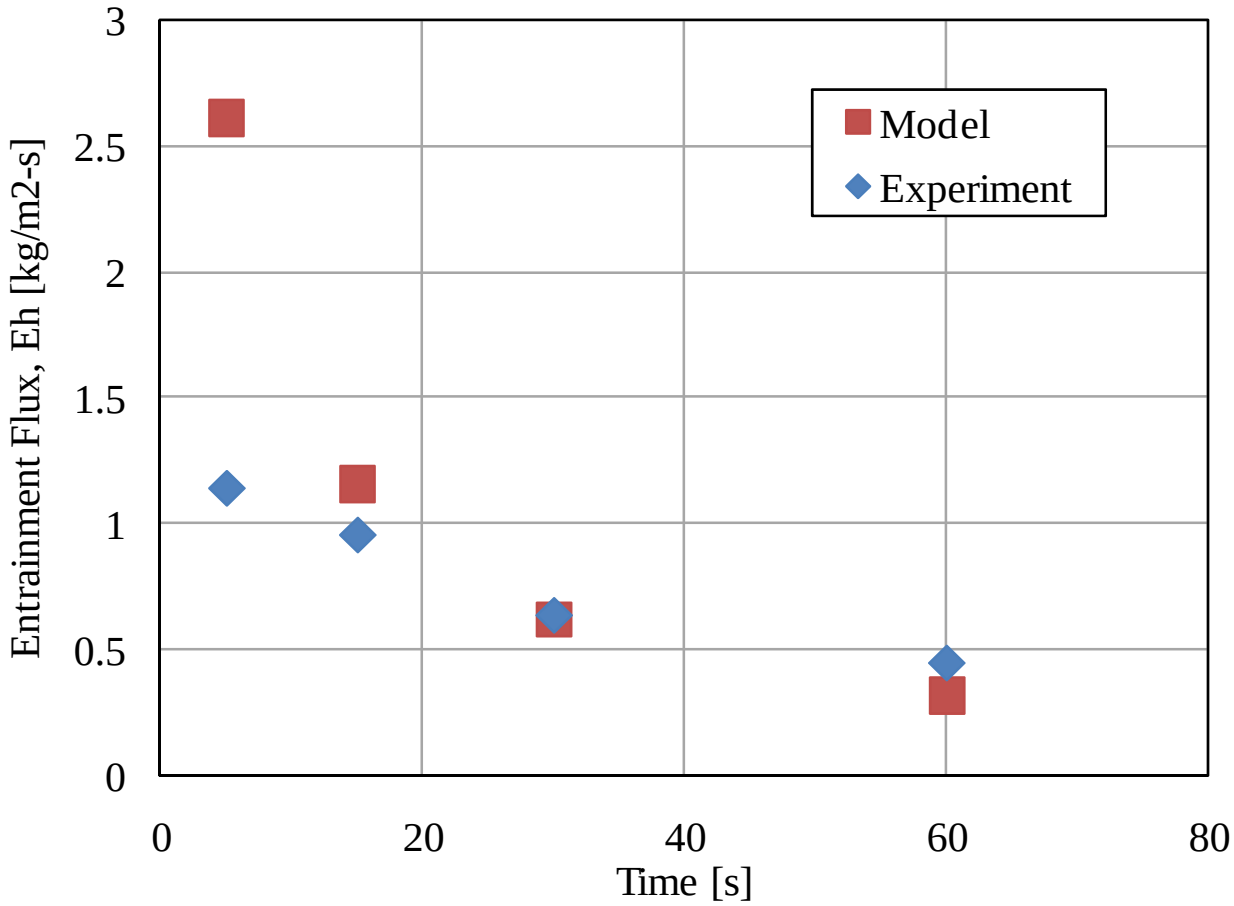
# Solutions: Aerodynamic CO2 Separation




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

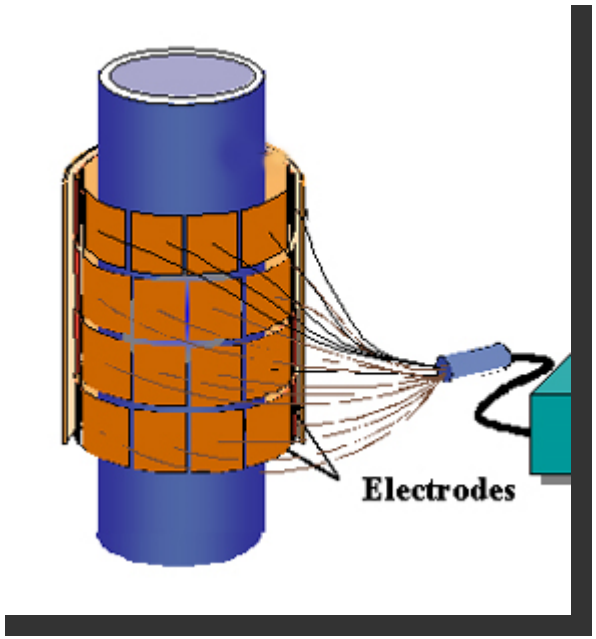
# How does CFD Compare?

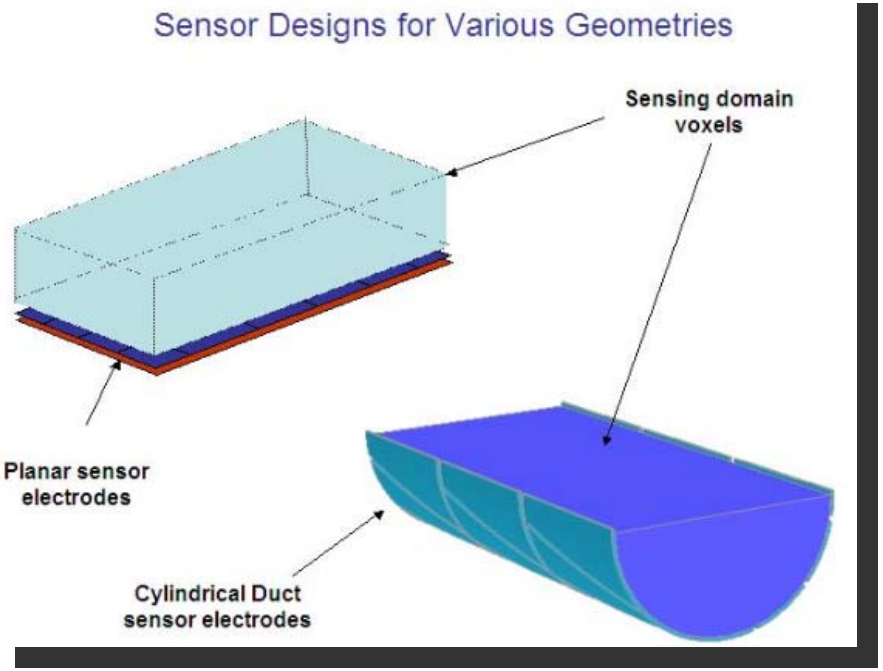



- **CPFD's Barracuda**
- **43k cells**
- **CuO/Acrylic 1.5*Ut**

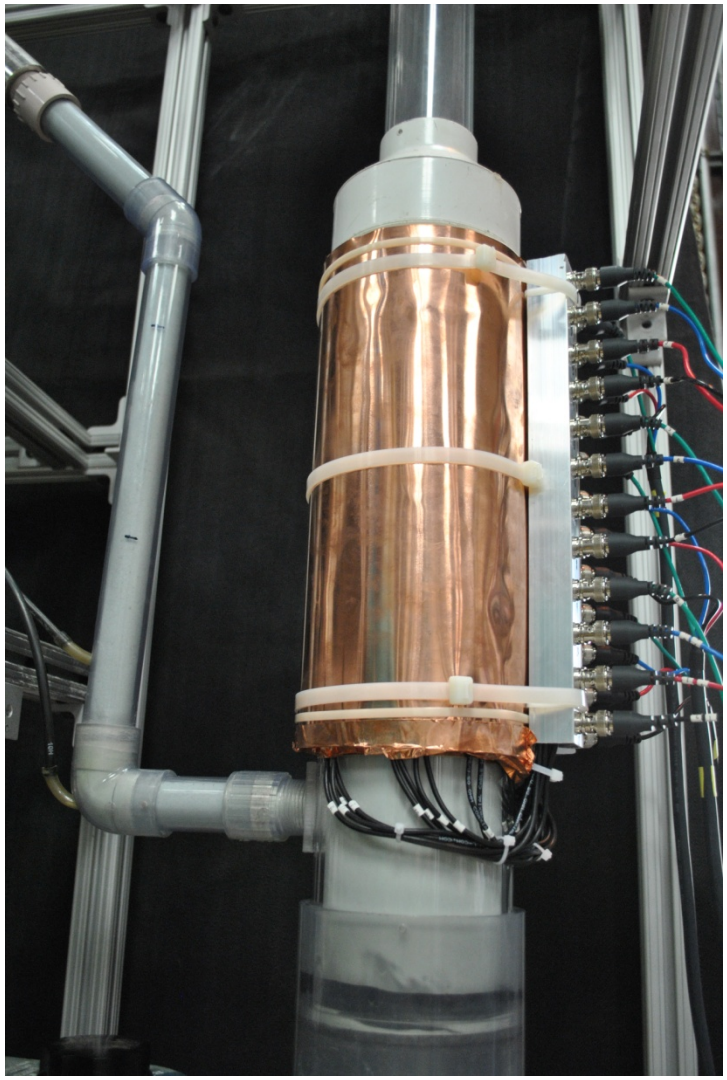
# ECVT Sensor Overview
# (From Tech4 Imaging)



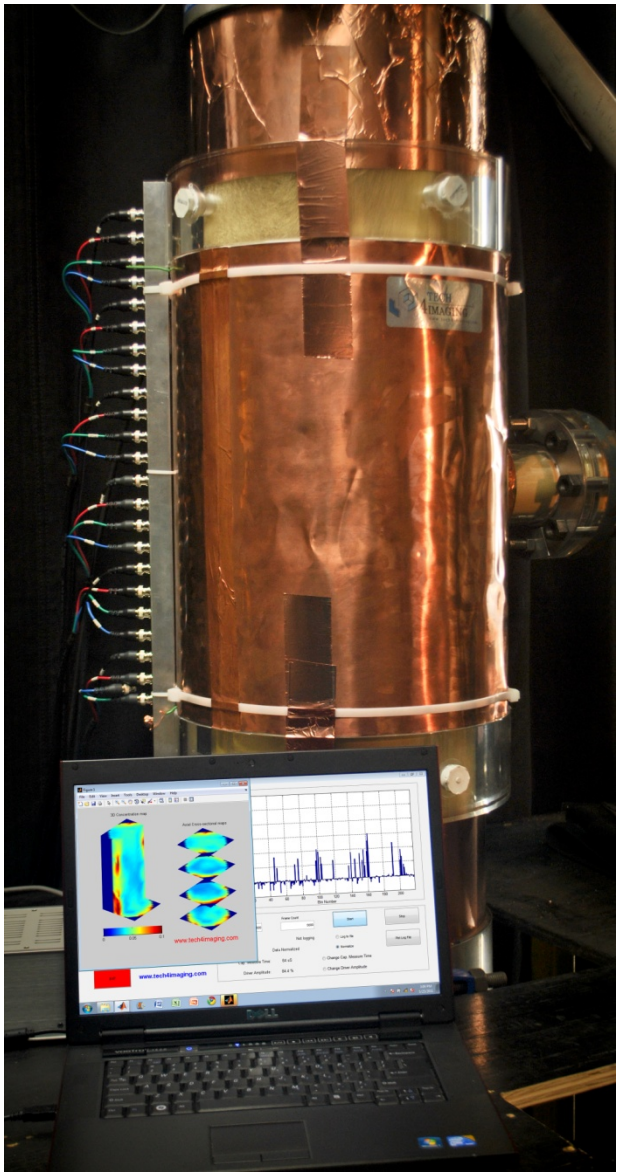




Data Collection → Reconstruction → Post Processing

*1 Frame ~1s*



*4in ECVT sensor on CLC Demo Unit*



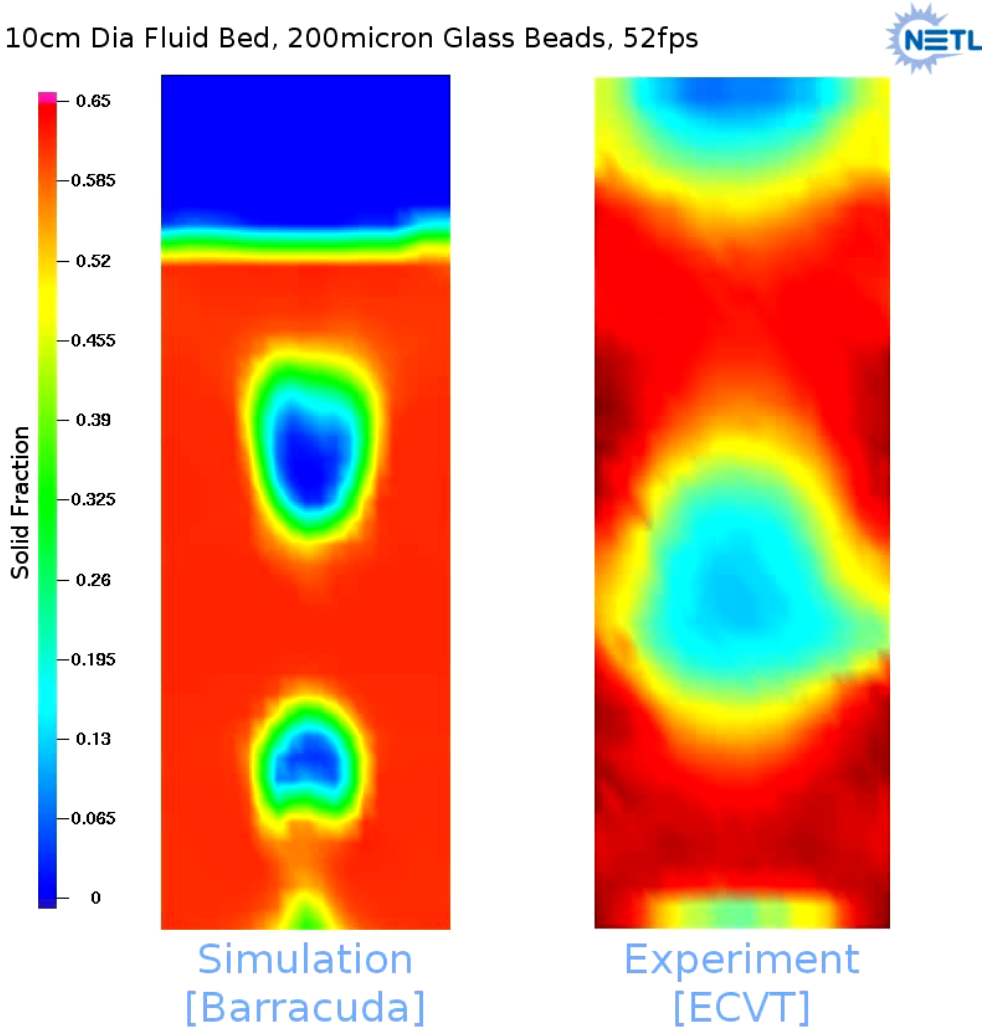
*12in ECVT sensor on CFB*

# CFD and Measurements in the CL reactor

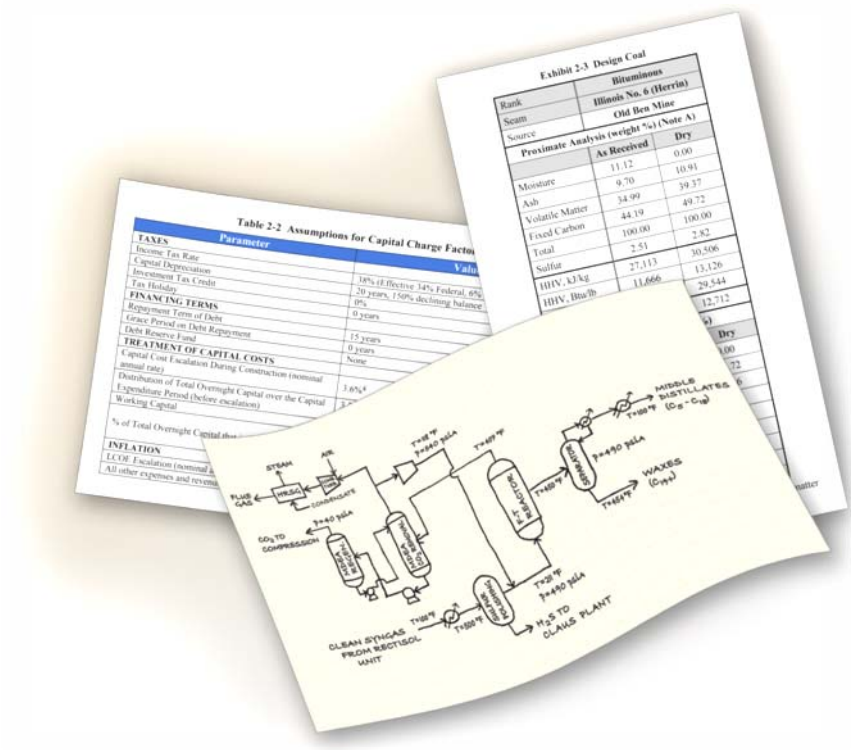
**Fast model useful to explore design options.**

**Large bubbles may limit conversion.**

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

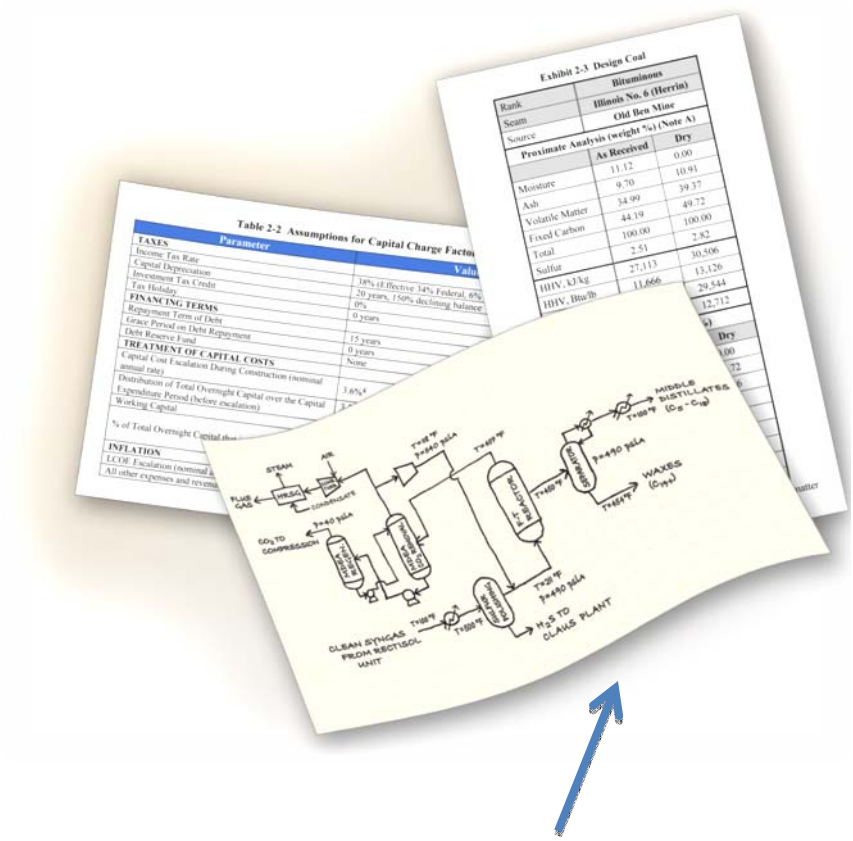


# Technical and Economic Analysis




- **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.**

# Technical and Economic Analysis




*Your process goes here….*
*…..comments welcome!*

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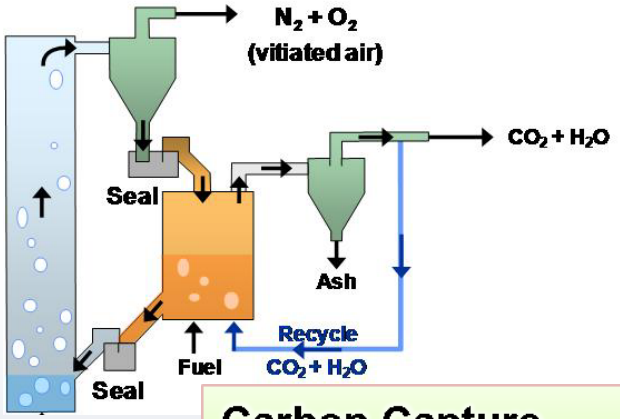
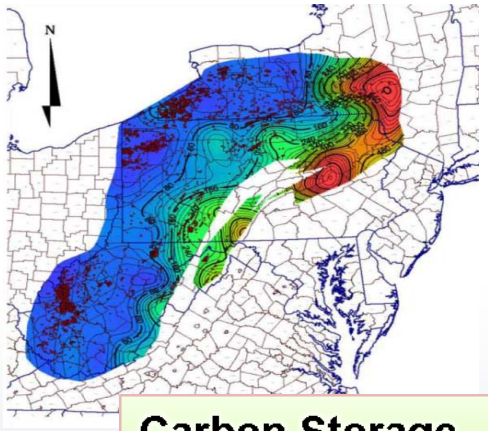



**Carbon Capture**
Chemical Looping Combustion

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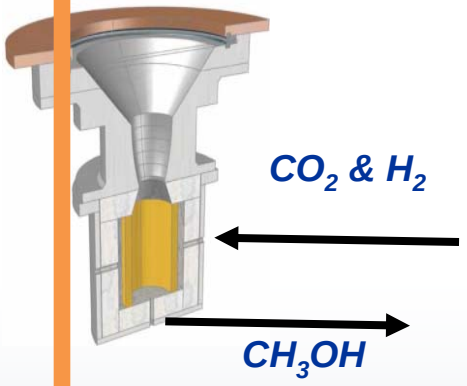
Depleted Shale Fields




**Carbon Utilization**
Photocatalytic Conversion

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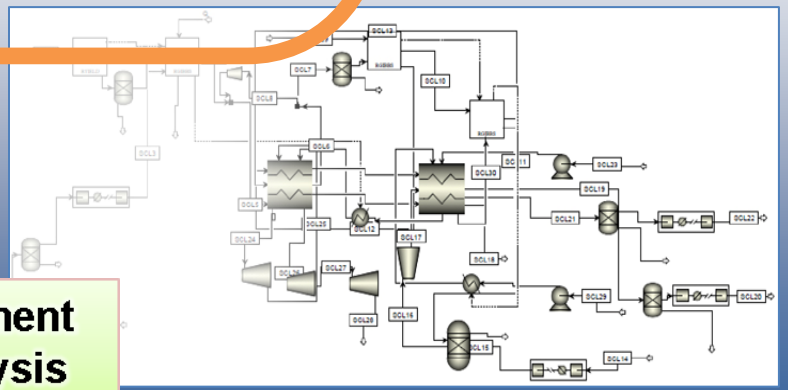
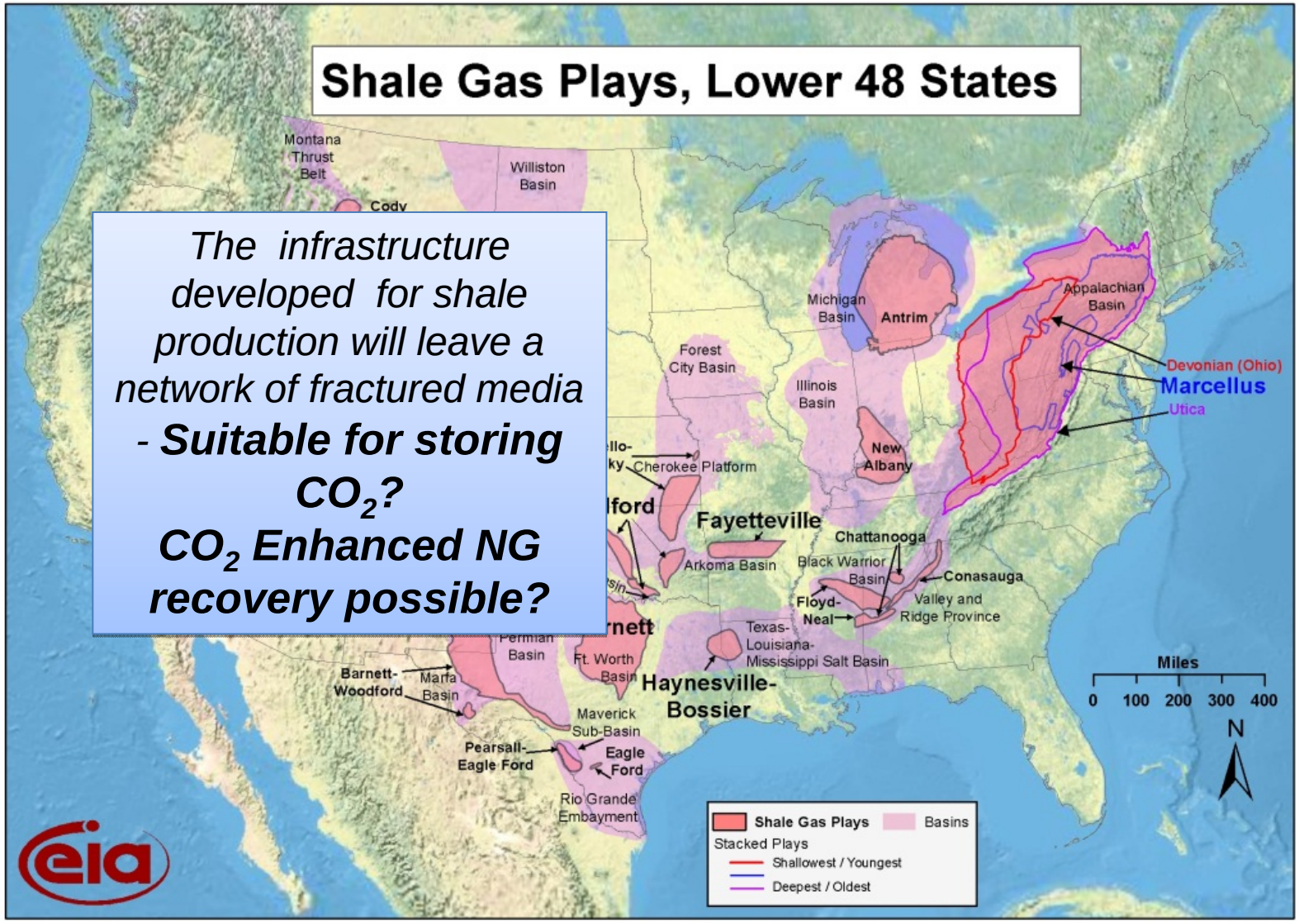


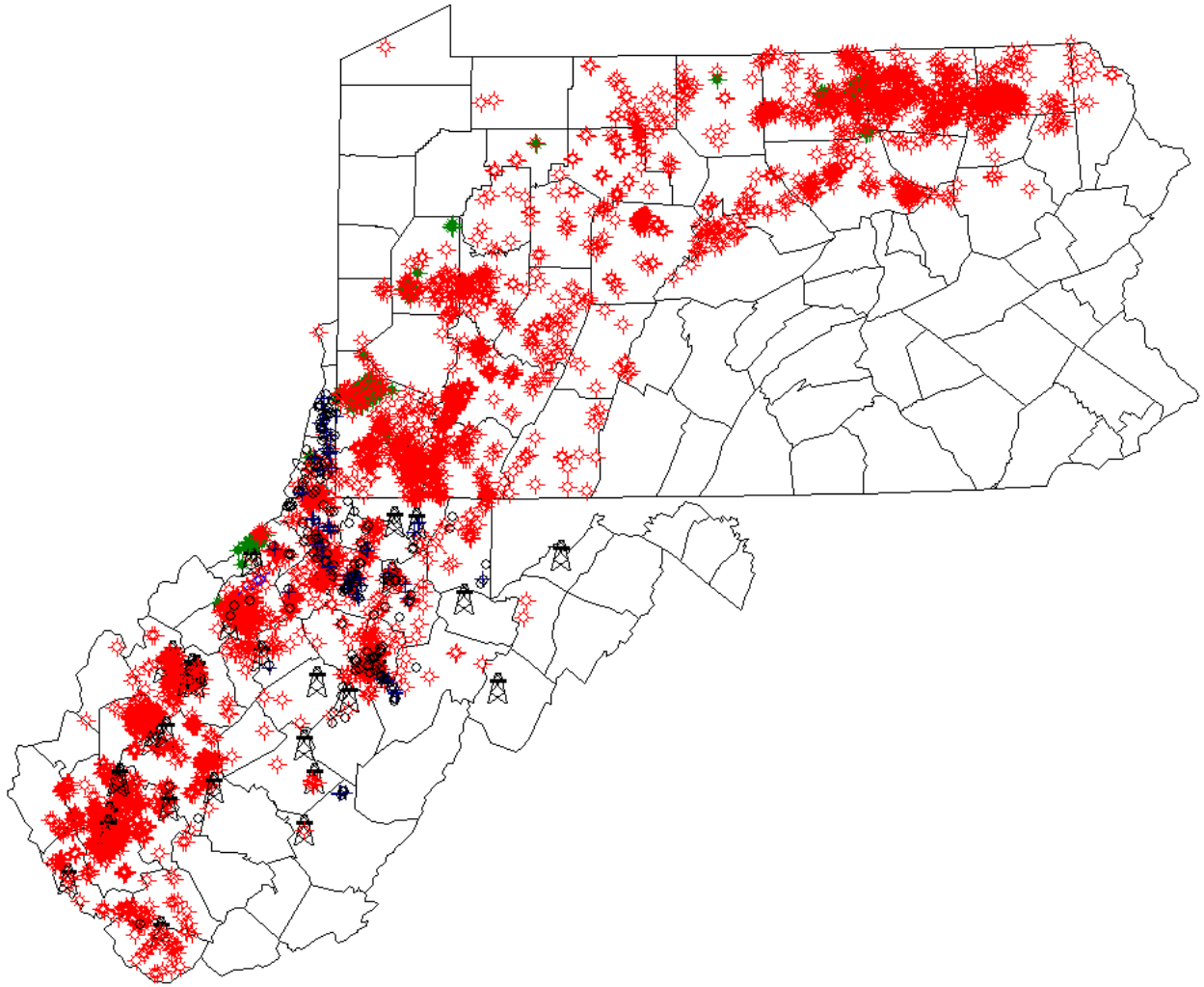
**Industrial assessment and systems analysis**




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

# Cumulative Marcellus Wells

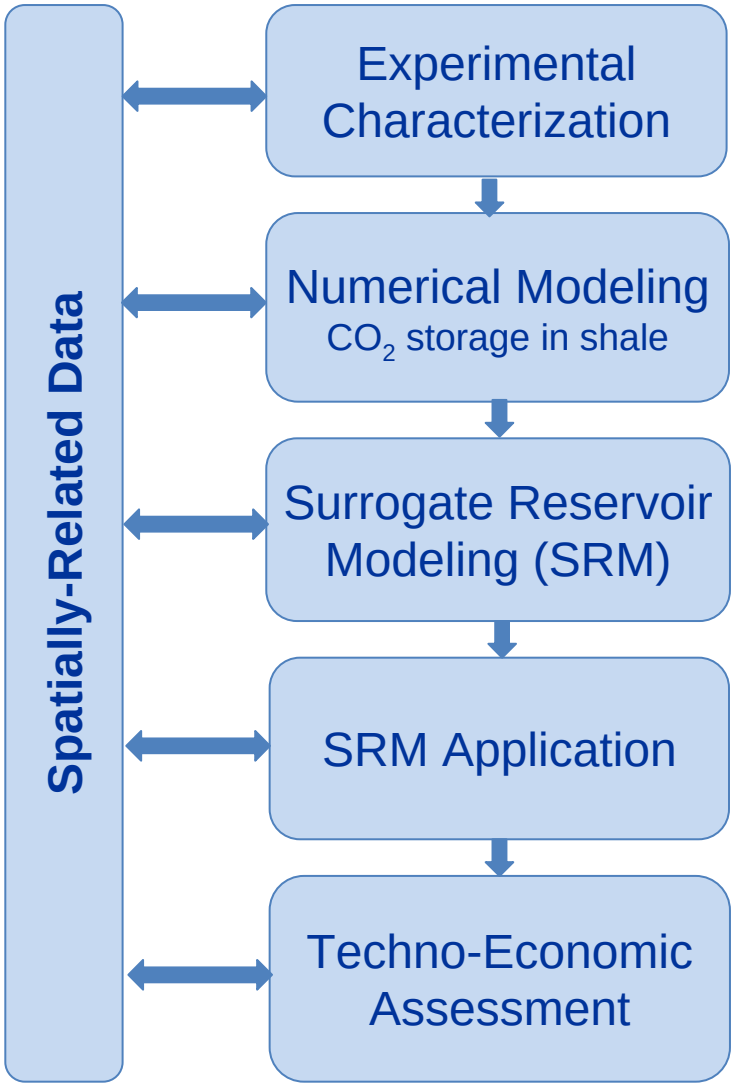
## 2011





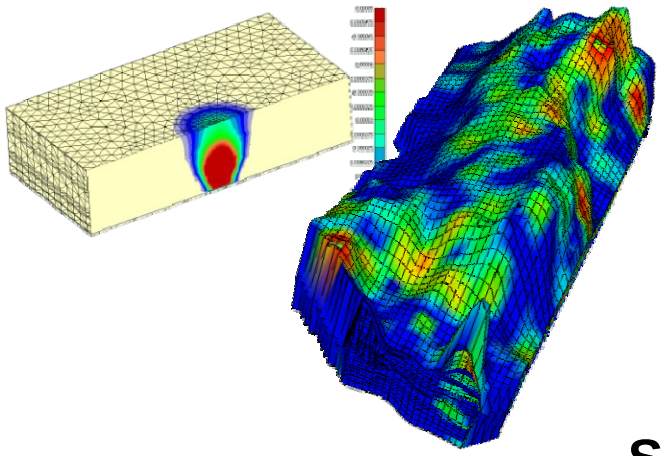
***Source:*** *Carr, Timothy. "Gas Shale in the Appalachian Basin Technical and Societal Challenges and Opportunities"*

# Overview of Technical Approach




# Developing Surrogate Models from Numerical Reservoir Models

**Full-Field Numerical Model**

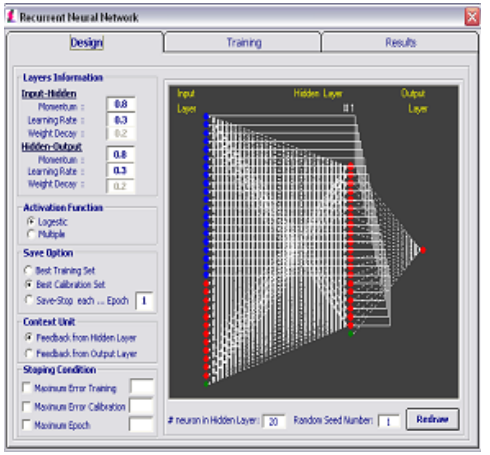


**Database of 10-20 Simulation Runs**

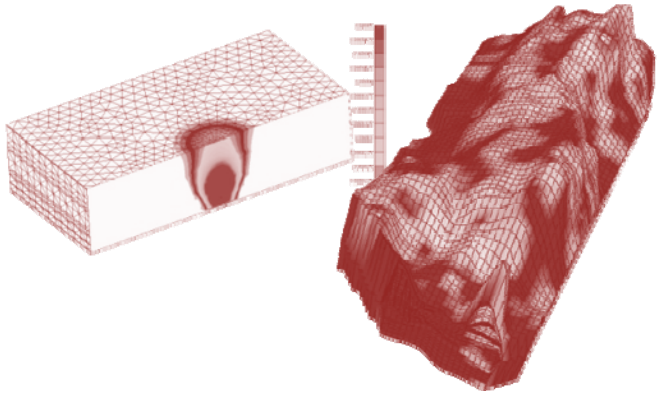
**SRM Training**

**Pattern Recognition**

**(fuzzy set theory and Artificial Neural Networks)**




**SRM Mimics Behavior of Full-Field Model**

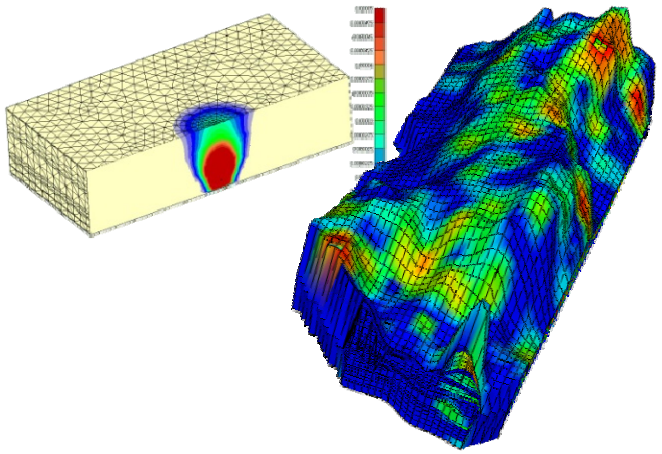


**Explore Reservoir Behavior**

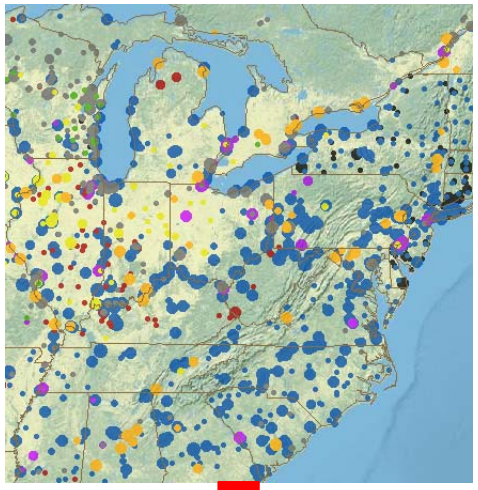
**(Sensitivity and Uncertainty Analyses, and Scenario Evaluation)**

# 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 × L × (330.5 × D² + 686.7 × D + 26,960) |
| *Labor* | $ Diameter (inches), Length (miles) | $341,627 + $1.85 × L × (343.2 × D² + 2,074 × D + 170,013) |
| *Miscellaneous* | $ Diameter (inches), Length (miles) | $150,166 + $1.58 × L × (8,417 × D + 7,234) |
| *Right of Way* | $ Diameter (inches), Length (miles) | $48,037 + $1.20 × L × (577 × D + 29,788) |
| **Other Capital** | | |
| *$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*

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# ICMI

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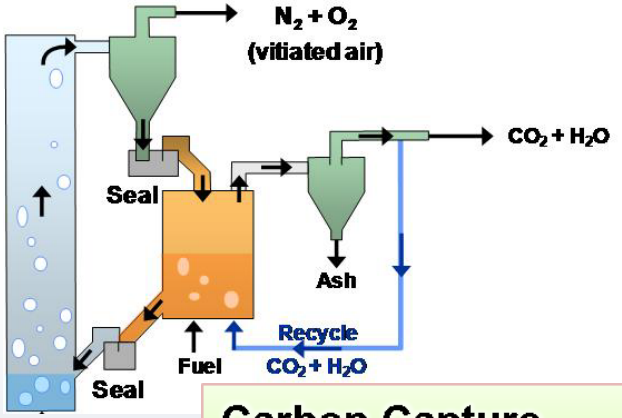
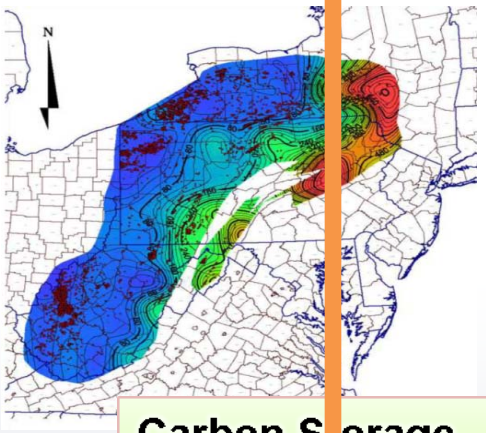
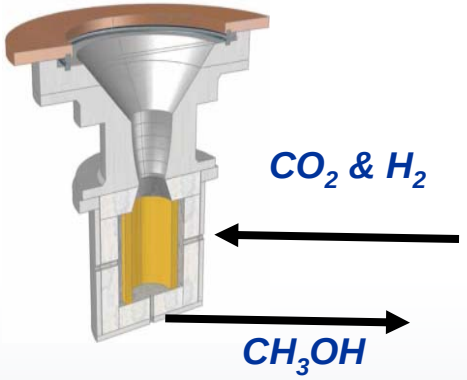



**Carbon Capture**
Chemical Looping Combustion

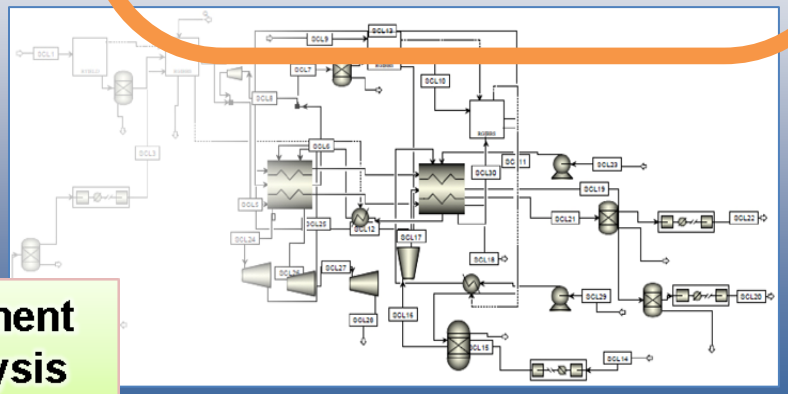



**Carbon Storage**
Depleted Shale Fields




**Carbon Utilization**
Photocatalytic Conversion

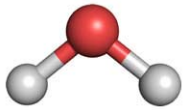
## CCUS for Industrial Applications



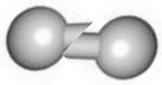
**Industrial assessment and systems analysis**

# $CO_2$ as a Chemical Feedstock

*$CO_2$*



*$H_2O$*



*$H_2$*

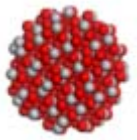
+

*Sun*

*Electricity & Waste Power*

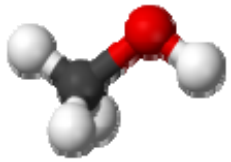
*Industrial Waste Heat*

+



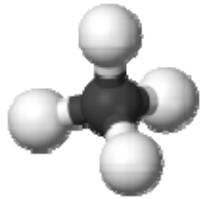
*Catalyst*

**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)**

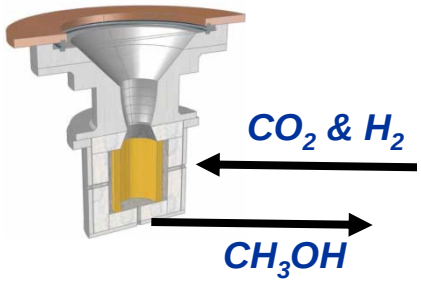
**Transportation/Military Fuels**

**Methane Reforming to $H_2$ and other fuels**

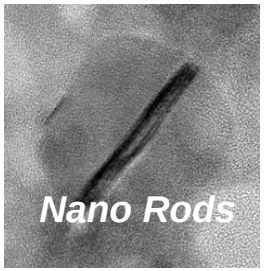
# Scalable Processes with Copper Based Catalysts

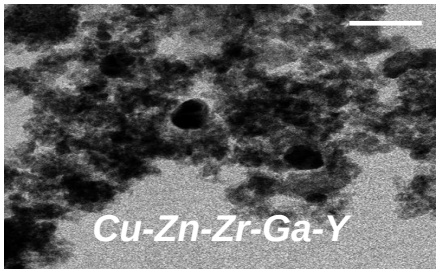
*Waste Heat or Solar-Thermal Energy Converts $CO_2$ & $H_2$ to Methanol*

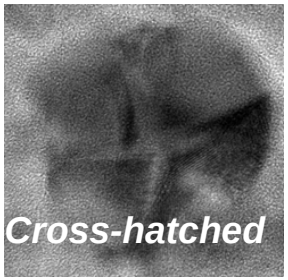
## *Reactor Using Low - Temperature Heat*



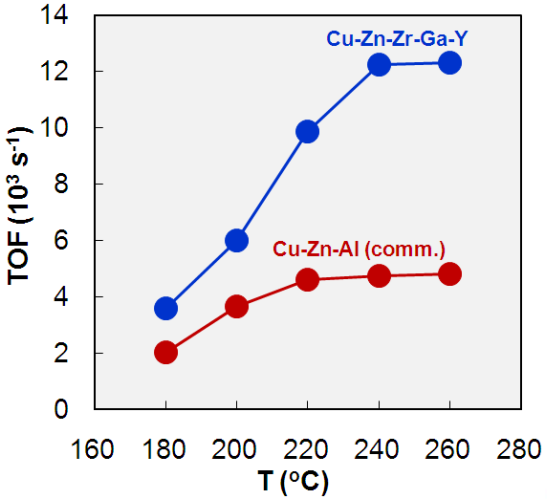

## *Nanostructured Cu is Highly Reactive*



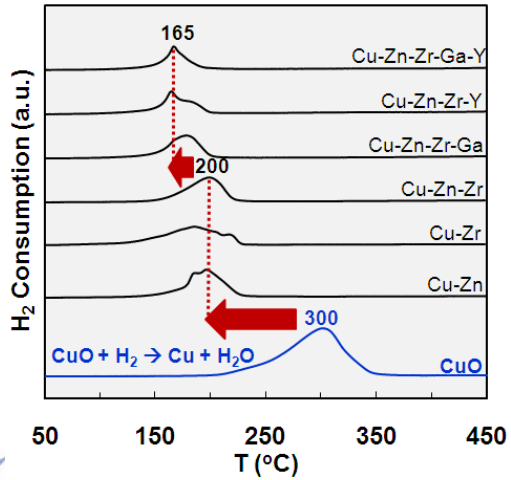



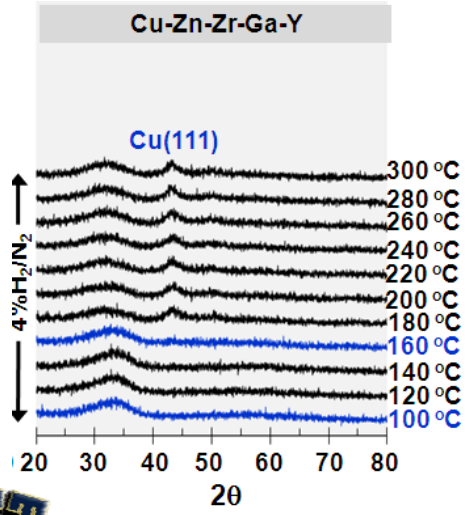

## *Cu-based Catalysts Outperform Commercial Systems*




## *Improved Reducibility (Easily Activated)*

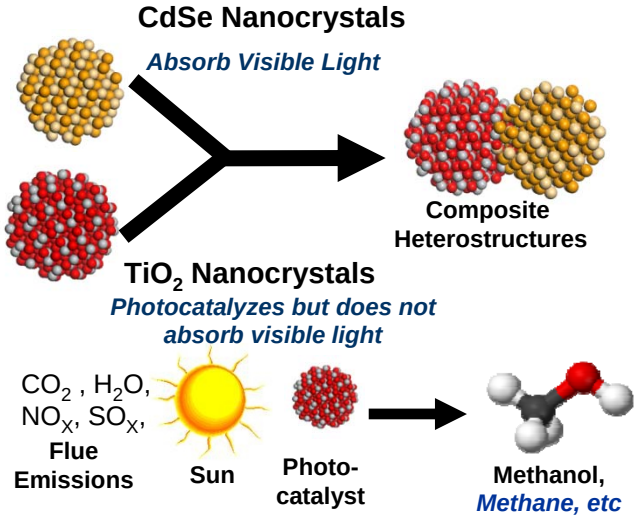



## *Cu Catalysts are Resistant to Sintering*

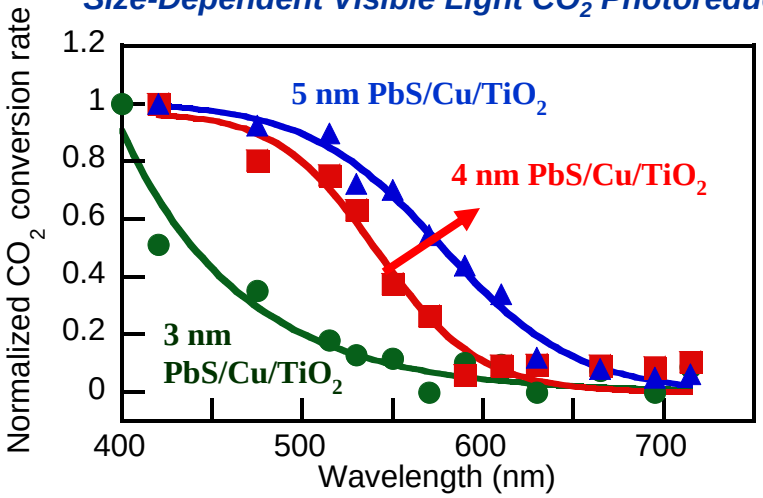


# Visible Light Photocatalysts for Carbon Dioxide Reuse

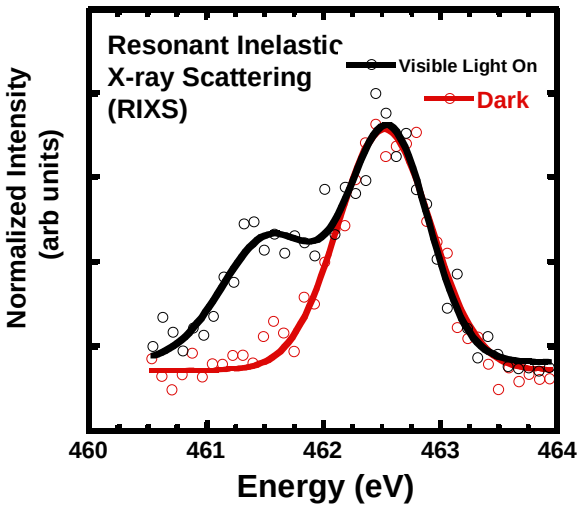
***Semiconductor nanocrystals enhance the visible-light photoactivity of $TiO_2$***

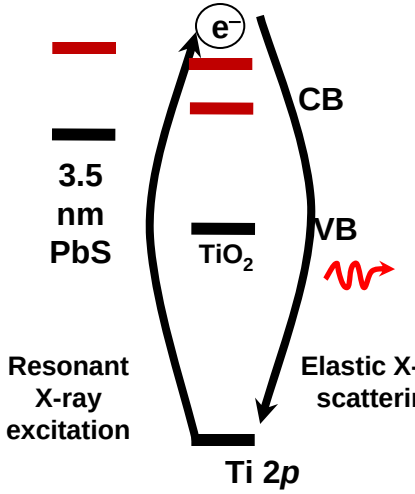


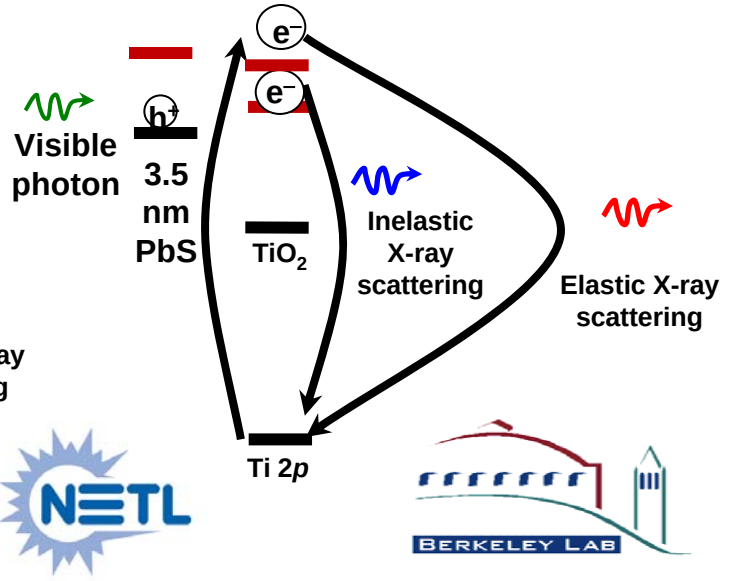

***Size-Dependent Visible Light $CO_2$ Photoreduction***




***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**