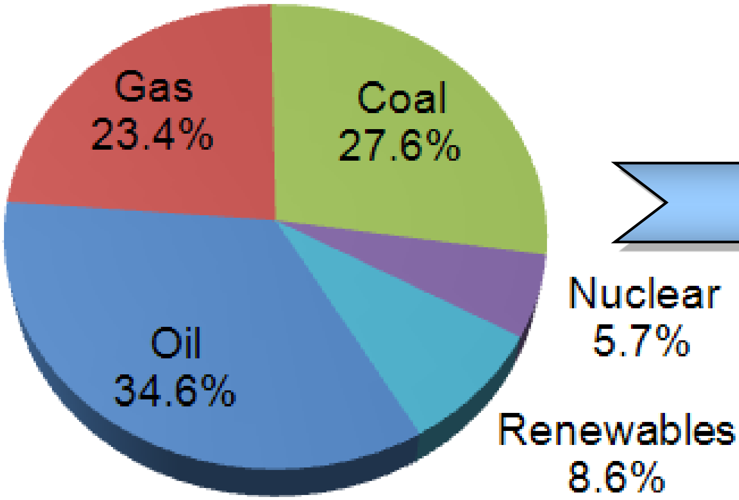
NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. Department of Energy's Carbon Capture and Storage Efforts and Results

Charles E. Taylor – Director,
Chemistry and Surface Science Division

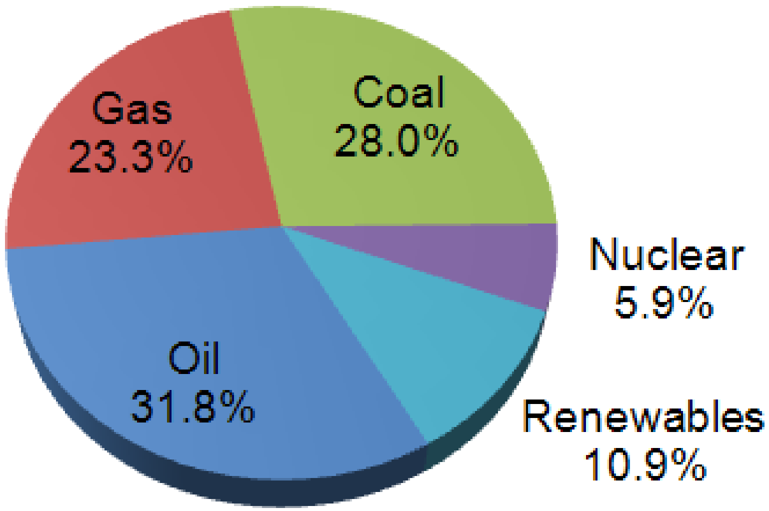
World Energy Demand Today

500 QBtu / Year
86% Fossil Energy



World Energy Demand 2030

678 QBtu / Year
83% Fossil Energy



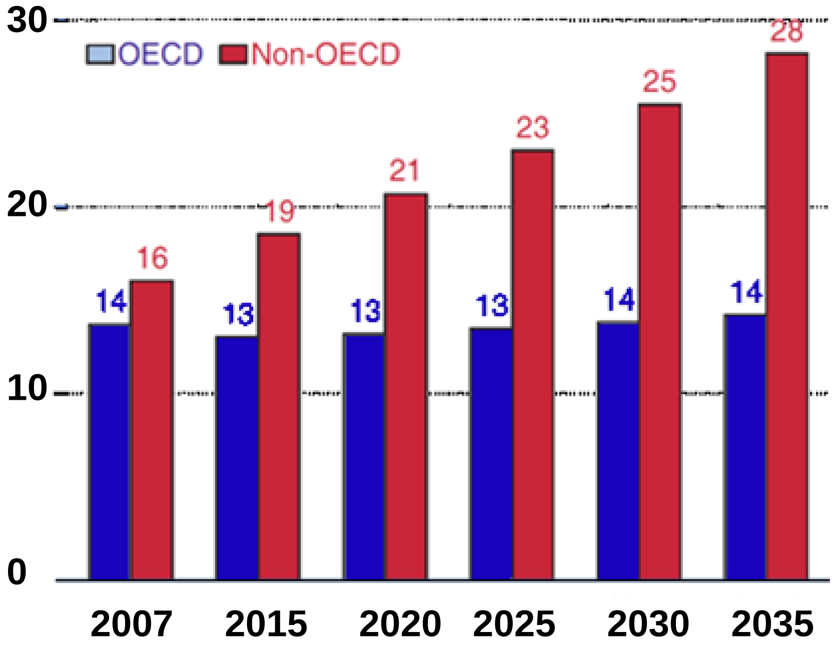
Fossil Energy Will Continue to Provide Primary Supply

U.S. data from EIA Annual Energy Outlook 2009 with Projections to 2030 Report #:DOE/EIA-0383(2009). World data from EIA International Energy Outlook 2009 Report #:DOE/EIA-0484(2009)

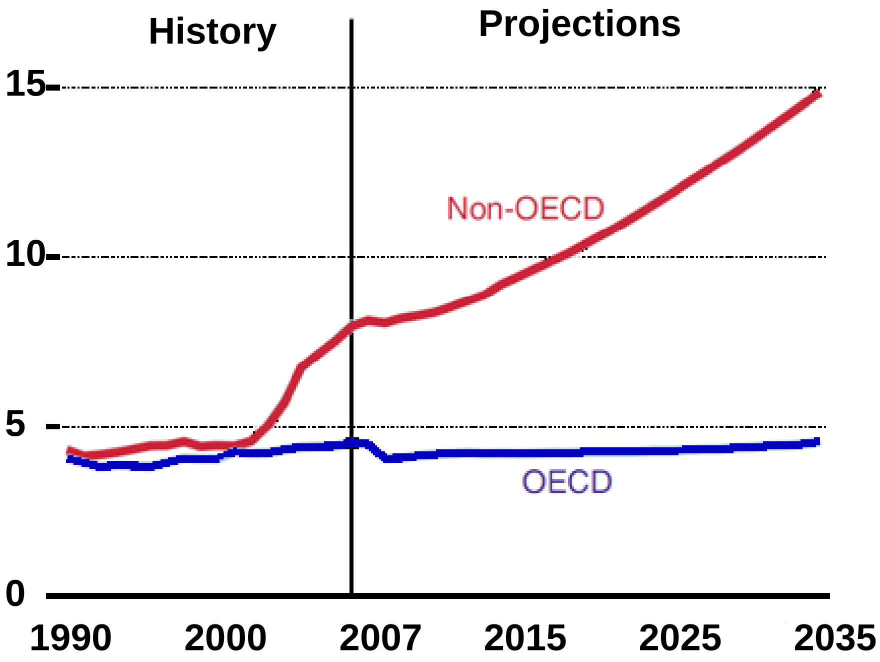
Projected World Growth in CO_2 Emissions

(EIA-IEO 2010 BAU Projection)

World energy-related CO_2 emissions (gigatonnes)



World CO_2 emissions from coal combustion (gigatonnes)



EIA's International Energy Outlook 2010 *Reference case -- current laws and policies remain unchanged*

Report #:DOE/EIA-0484(2010), July 2010 http://www.eia.gov/oiaf/ieo/index.html

FE Coal R&D Program

A History of Innovative Solutions

1970's	1980's	1990's	2000's	
Clean Air Act	Oil Embargo	Acid Rain	Utility Deregulation	Climate Change
➢ National response to address air quality concerns ➢ Profound impact on existing (and future) coal burning power plants	➢ Exposed the Nation's vulnerability to oil supply disruptions ➢ U. S. imposes price controls on domestic oil – search for alternatives	➢ National trans-boundary response to natural resource preservation ➢ Identifies SO_2 and NOX from fossil energy use as principal culprits	➢ Changed utility business model ➢ Competitive pricing drives investment efficiency - private sector investment in R&D reduced	➢ A global issue ➢ President targets 80% reduction in CO_2 by 2050 ➢ Congress considers cap-and-trade

✓ New power system technology (CFBC)
✓ Emission control technologies for existing plants target NOX, SO_2, and Particulates
- Installed on 75% of U.S. coal plants; 1/2 to 1/10 cost of older systems

… fossil's programs made a significant contribution to the well-being of the United States, lead to realized economic benefits, energy options for the future, and significant knowledge …
National Academy of Sciences 2001: "Energy Research at DOE (1978-2000) - Was it Worth it?

✓ Coal processing technology advances - but markets fail to develop
- Successful demonstrations (coal liquids, SNG, chemicals)
- First gasification-based pioneer plants – Dakota Gasification

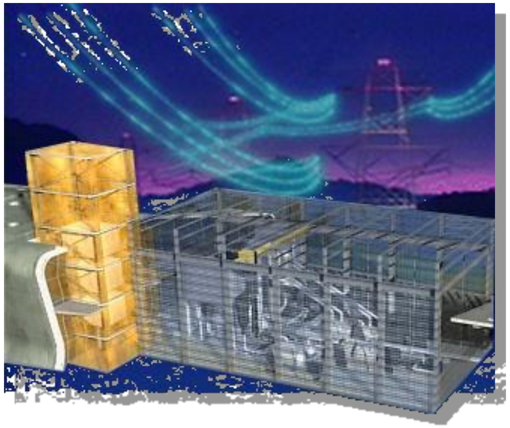
… technology advancements were achieved that can provide energy security benefits and are available to be deployed if market conditions materialize … the ability to use the nation's large coal reserves in an efficient manner was improved substantially …
National Academy of Sciences 2001: "Energy Research at DOE (1978-2000) - Was it Worth it?

✓ Integrated CCS energy systems (highly efficient, zero emission, affordable)
- CCS (pre & post-combustion capture, site characterization, MVA, Best Practices)
- Fuel processing & separation (gasifiers, O_2/H_2 membranes, feed-pump, gas cleaning
- Power generation (H_2 turbines, SECA-SOFC, oxy-combustion, chemical looping)

…the Regional Partnerships is an excellent program that will achieve significant results for CCS in the United States, Canada and internationally … the Partnerships Programme will significantly advance and accelerate the CCS field. The individual projects will together build a comprehensive and expansive research programme, the size and scope of which is unique throughout the world …
IEA 2008: "Expert Review of Regional Carbon Sequestration Partnerships Phase III".

Coal Program R&D Evolution

PAST		PRESENT
Power Generation		Power and Multiple Products
Efficiency		Efficiency
Reliability		Reliability
Criteria Pollutants		Air Toxics
		Water Use
		Greenhouse Gases



Technology Bridge to Future Energy Fleet

Deployment 1985 - 2020 2020 - 2050

Challenges for Fossil Energy CCS

- **Reducing COE Penalty for CCS**
  - 30 - 40% increase for IGCC with current technology
  - 70 - 80% increase for PCC with current technology
- **Proving the capability and capacity for geologic storage**
- **Finding viable beneficial uses for CO_2**
- **Reducing regulatory and financial uncertainty to encourage private investment**
  - Establish the regulatory framework
  - Resolve pore-space ownership
  - Provide long term stewardship
  - Address liability issues
- **Developing needed infrastructure**
- **Obtaining public acceptance**
- **Deploying cost-competitive CCS technology for both new <u>and</u> existing power plants**

CCS Commercial Experience

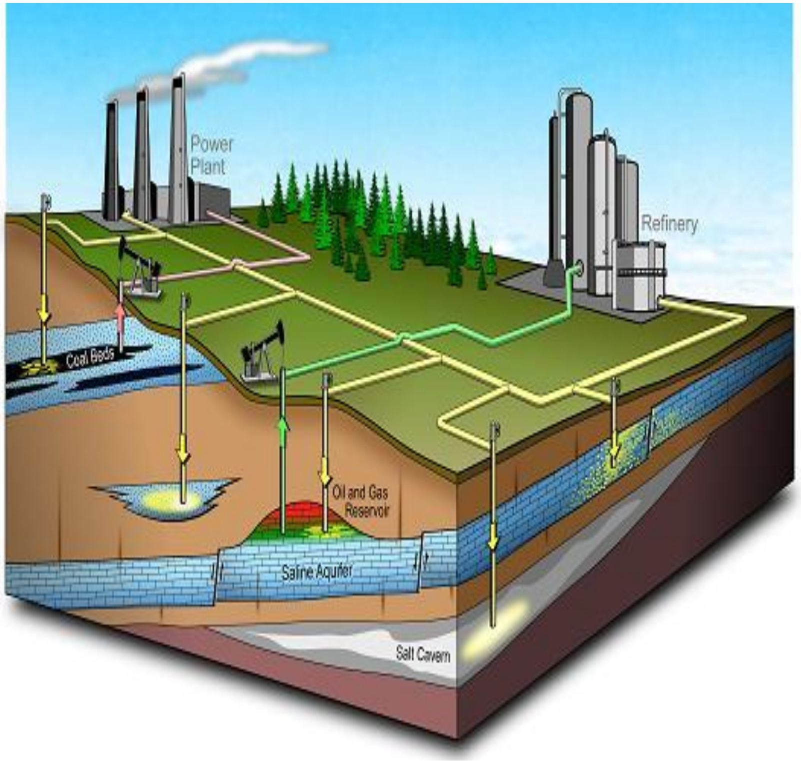
- **Carbon capture technology is commercially available**
  - Post-combustion capture at 20-80 MWe coal power plants
  - Pre-combustion (coal gasification) capture at full scale
- **CO_2 injection into geologic formations is widely practiced today**
  - EOR: 48 million TPY in 2007
  - 3,900 mile pipeline network
  - 50 Acid gas injection projects
  - Megatonne/yr injection projects
    - Weyburn-Midale
    - Sleipner
    - In Salah
    - Others

Photo sources: E.S. Rubin, Carnegie Mellon, Statoil

Carbon Storage Program Goals

Develop Technology Options That...

- **Deliver technologies & best practices that provide Carbon Capture and Safe Storage (CCSS) with:**
  - 90% CO_2 capture at source
  - 99% storage permanence
  - < 10% increase in COE
    - Pre-combustion capture (IGCC)
  - < 30% increase in COE
    - Post-combustion capture
    - Oxy-combustion



CCS Program Objectives

- **Develop and demonstrate advanced, increasingly cost-effective capture (separation and compression) technologies, enabling commercial deployment beginning in 2020.**
  - Must be applicable to situations in developing economies,
  - Must be retrofittable to existing facilities, i.e. cost effective, low energy penalty, compact physical footprint.
- **Characterize U.S. geologic source and sink potentials and infrastructure configurations for CCS by 2020 for the majority of U.S. stationary source CO2 emissions. (including offshore sub-seabed formations)**
- **Validate scientifically and technically-based tools and practices to determine safe, effective long-term geologic storage by 2020.**
- **Demonstrate large-scale integrated next generation game-changing technologies for stack capture while improving efficiency, capacity and minimizing water impacts associated with capture.**
- **Enable early, broad-scale CCS opportunities for beneficial use of CO2 via demonstrations.**
- **Collaborate on and leverage international CCS RD&D activities.**

U.S. DEPARTMENT OF ENERGY • OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

CARBON SEQUESTRATION PROGRAM with ARRA Projects

Core R&D

- Pre-combustion Capture
- Geologic Storage
- Monitoring, Verification, and Accounting (MVA)
- Simulation and Risk Assessment
- CO_2 Use/Reuse
- ARRA: University Projects

Technology Solutions

Lessons Learned

Benefits

- Reduced cost of CCS
- Tool development for risk assessment and mitigation
- Accuracy/monitoring quantified
- CO_2 capacity validation
- Indirect CO_2 storage

Infrastructure

Regional Carbon Sequestration Partnerships

- Characterization
- Validation
- Development

ARRA: Development of Technology Transfer Centers

ARRA: Site Characterization

Other Large-Scale Projects

Technology Solutions

Lessons Learned

Benefits

- Human capital
- Stakeholder networking
- Regulatory policy development
- Visualization knowledge center
- Best practices development
- Public outreach and education

Global Collaborations

- North America Energy Working Group
- Carbon Sequestration Leadership Forum

International Demonstration Projects

Canada (Weyburn, Zama, Ft. Nelson)
Norway (Sleipner and Snovhit)
Germany (CO2Sink)
Australia (Otway)
Africa (In-Salah)
Asia (Ordos Basin)

Benefits

- Knowledge building
- Project development
- Collaborative international knowledge
- Capacity/model validation
- CCS commercial deployment

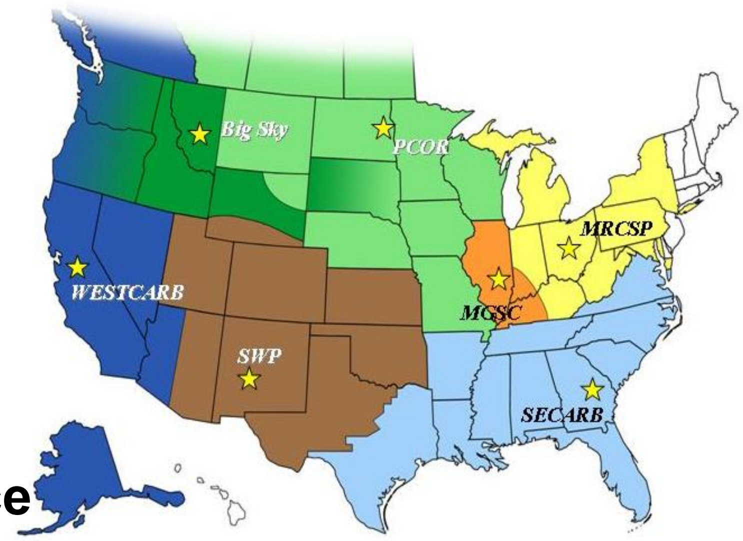
Demonstration and Commercialization Carbon Capture and Storage (CCS)

Mission & Approach

Critically Linked to DOE Climate & Security Goals

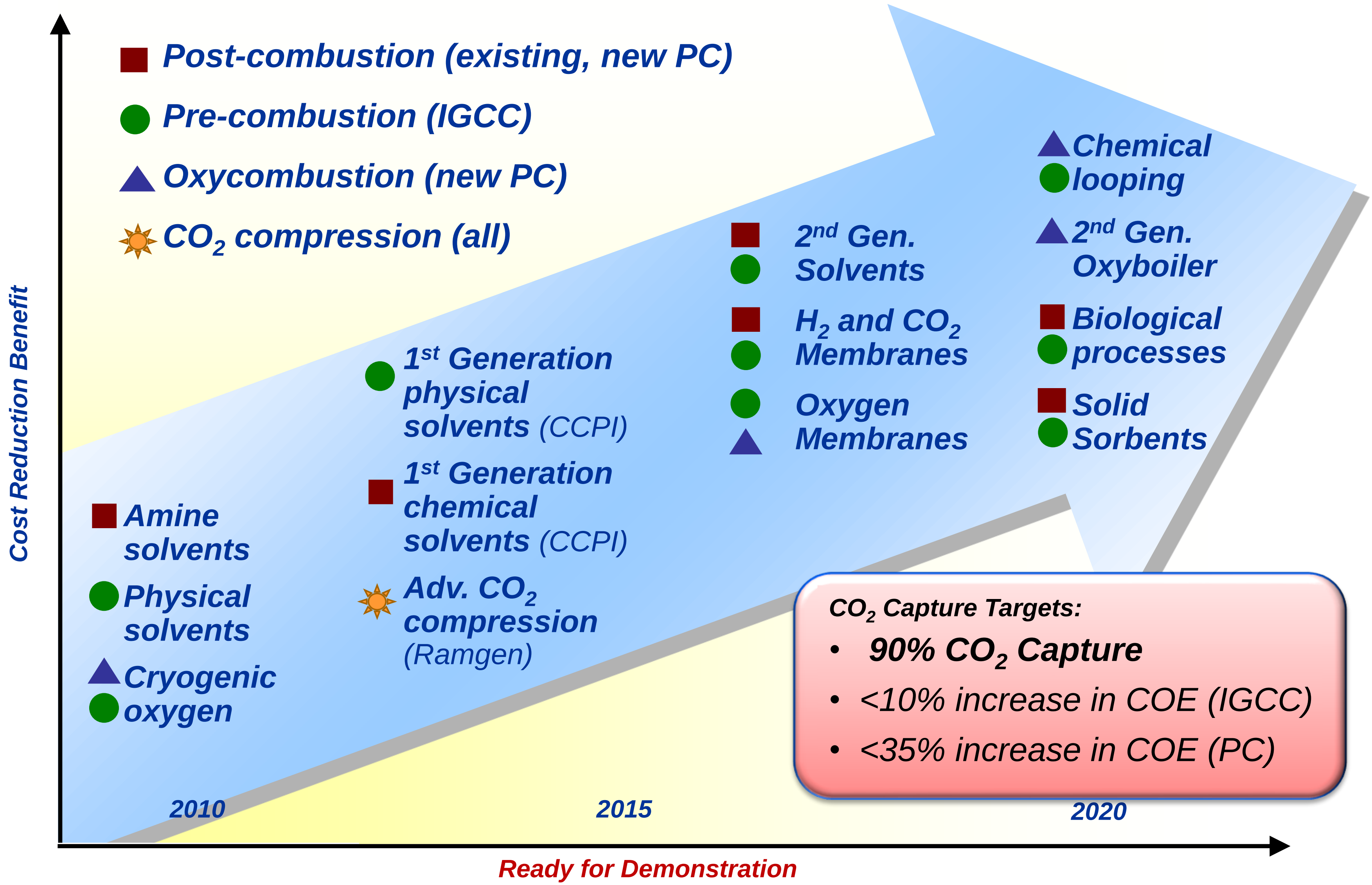
Develop Technologies and Best Practices That Facilitates Wide Scale Deployment of Coal Based Energy Systems Integrated With CCS

- **Develop plant designs & components optimized for CCS**
- **Reduce capture costs**
- **Validate storage capacity**
- **Validate storage permanence**
- **Create private/public partnerships**
- **Promote infrastructure development**
- **Put "first of kind" field projects in place**
- **Develop tools, protocols & best practices**



DOE Regional Carbon Sequestration Partnerships

Fossil Energy CO_2 Capture Solutions



Coal Funding Cross-Cut

($ in Thousands (US))	FY09 Enacted	FY 2010 Enacted	FY2011 Request	Areas Targeted
Capture	66,000	66,500	81,200	Pre- and Post- combustion capture, with emphasis on Post-combustion. Technologies will reduce capture cost and energy penalties.
Storage	134,000	139,500	126,800	Regional Partnerships, MVA, Simulations, Risk Assesment
Efficiency Improvements	176,236	170,000	148,000	ITM - O2 Separation; H2 Turbines; Materials for USC Systems;Gas cleaning, Advanced CO2 compression; MW-scale Fuel Cells
Cross Cutting Research	28,000	28,000	47,850	FY2011, new multi-year national laboratory partnership for physics-based computer modeling and simulation from the molecular level to the integrated plant level, and geologic reservoir modeling
CCS Demos	288,174	0	0	Large scale CCS demonstrations are currently funded by Recovery Act and prior year approps.
TOTAL COAL	**692,410**	**404,000**	**403,850**	

Bottom line FY2011 Coal request is nearly identical to FY2010 enacted level, with budget shifts to focus on post-combustion carbon capture and a new laboratory modeling and computer simulation effort.

Interagency Task Force on CCS

- **Established by President Obama on Feb 3, 2010**
- **Co-Chaired by DOE and EPA;**
  participation of 14 Executive Departments and Federal Agencies
- **Charged to develop a plan to overcome the barriers to deployment of CCS within 10 years**
  – Goal of bringing 5 to 10 commercial demonstration projects online by 2016

Conclusions/Recommendations

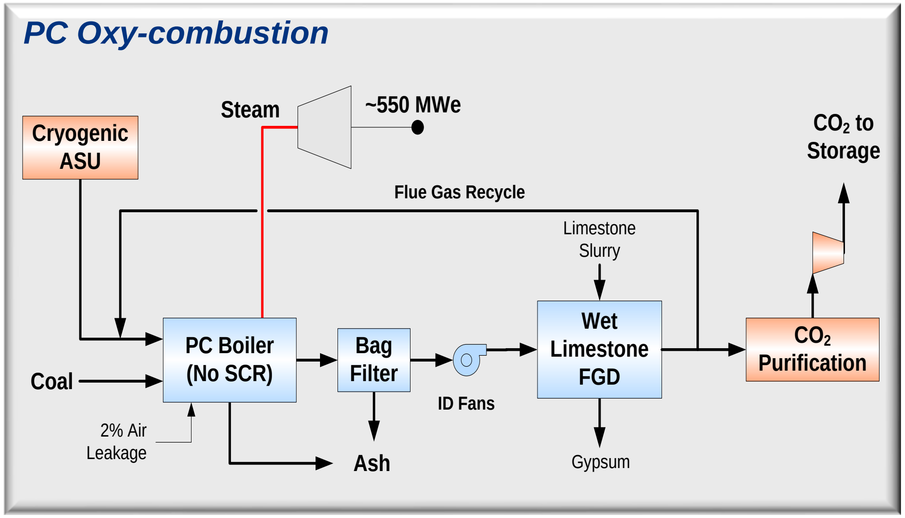
- **"Scaling up" existing CCS processes and integrating them with coal-based power generation poses technical, economic, and regulatory challenges**
- **RD&D programs such as those currently being conducted by DOE can help reduce project uncertainty and improve technology cost and performance**
- **Long-term integrated testing and validation programs are needed**
- **Barriers to CCS Deployment:**
  – ***The lack of comprehensive climate change legislation is the key barrier***
  – Challenges such as legal and regulatory uncertainty can hinder project development
  – Public awareness and support are critical
- **DOE and EPA should create a Federal agency roundtable to act as a single P.O.C. for project developers**
- **Continue to support international collaboration**
- **Federal agencies must work together to design regulatory requirements for CCS using existing authorities**
- **Efforts to improve long-term liability and stewardship frameworks should continue.**
  – Open-ended Federal indemnification should not be used to address long-term CO_2 storage liabilities
- **DOE and EPA should develop a comprehensive outreach strategy**

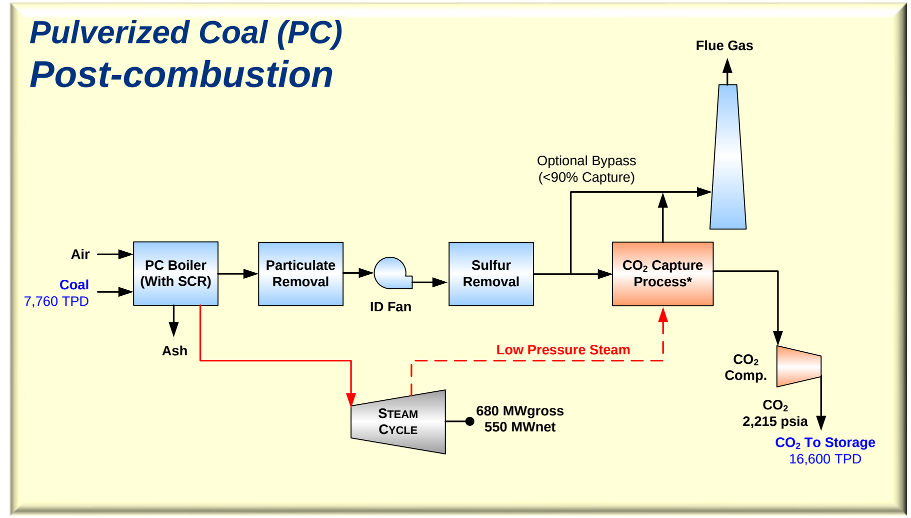
http://www.whitehouse.gov/administration/eop/ceq/initiatives/ccs

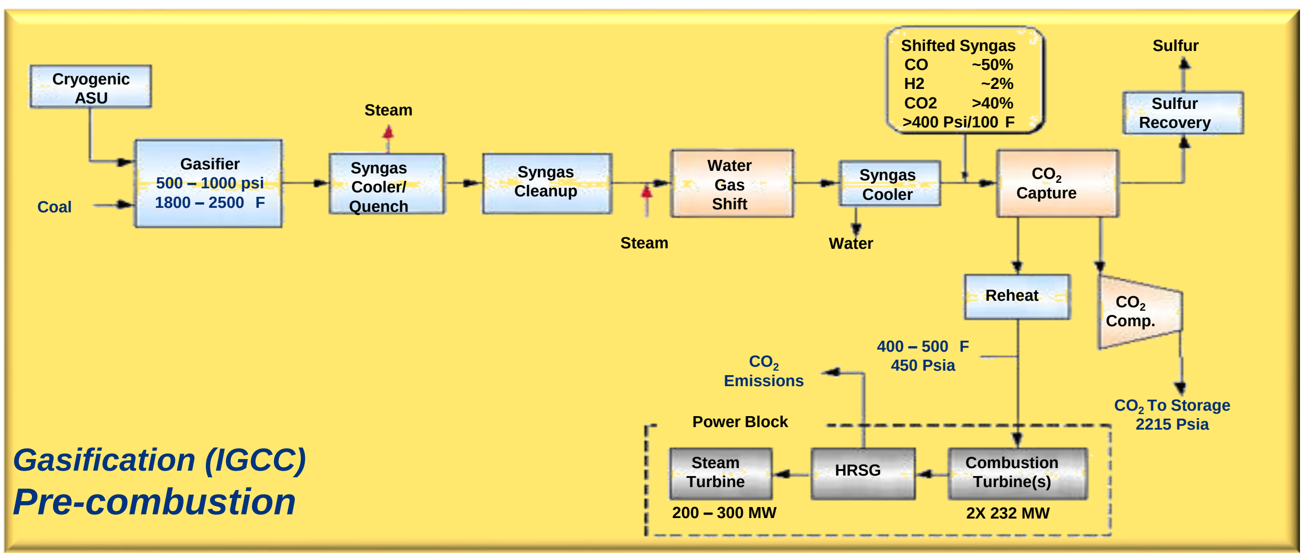
The American Recovery and Reinvestment Act of 2009 (ARRA)

- **Provides and Additional $3.4 Billion for Fossil Energy Research and development to:**
  - Develop and Demonstrate CCS Technology in partnership with Industry
  - Transition this technology to Industry for their Deployment and Commercialization
- **Objectives of FE's Portion of ARRA are:**
  - Demonstrate CCS technology to reduce Greenhouse gas emissions from the Electric Power and Industrial sectors of the economy
  - Become the World's Leader in Science and Technology
  - Implement Projects to Support Economic Recovery

Fossil Energy CO_2 Capture Options



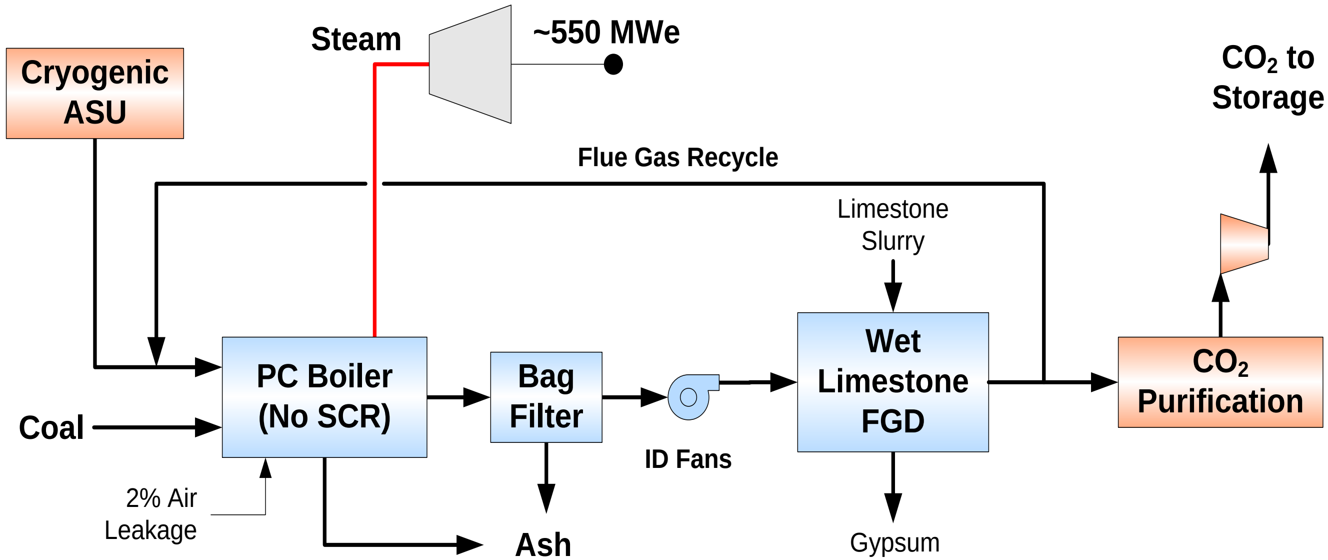




Source: Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity; NETL, May 2007.

Pulverized Coal Oxy-combustion

$$\text{Coal} + O_2 \longrightarrow CO_2 + H_2O$$



Challenges:

- Cryogenic ASUs are capital and energy intensive
- Existing boiler air infiltration
- Corrosion and process control
- Excess O_2 and inerts (N_2, Ar) ↑ CO_2 purification cost

Advantages:

- Plant vs. unit operation—multiple cost reduction opportunities
- Applicable to new and existing PC power plants
- Current designs lower cost than amine wet scrubbing
- Co-sequestration options

Reference: Pulverized Coal Oxycombustion Power Plants—Volume 1 Bituminous Coal to Electricity, U.S. Department of Energy/National Energy Technology Laboratory, Revision 2 Final Report, August 2008

Oxycombustion: O_2 Membrane

Advantages:

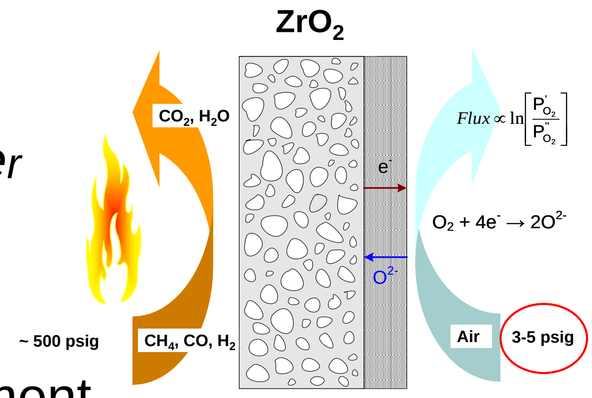
- O_2 consumed as it is made
  - *"OTM Boiler"*
- *>70% reduction in ASU power*

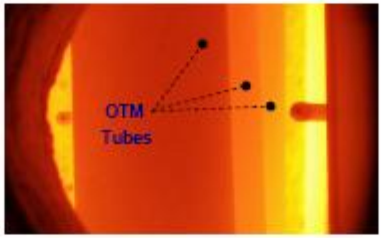
Challenges:

- Reliability of OTM tubes
- Engineering design of equipment
- Meeting cost & performance targets
- Pulverized coal applications

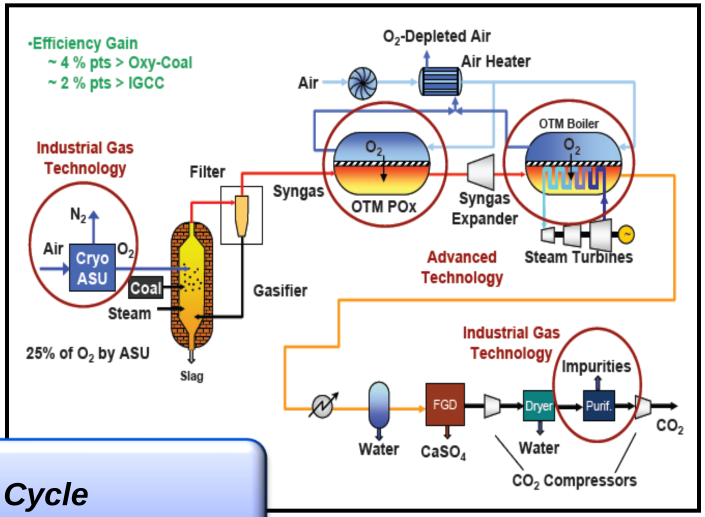
Current State: Laboratory Scale

- Significant improvement in O_2 flux/fuel utilization → met R&D performance targets





Combustion on OTM Surface
Looking through reactor port



OTM Power Cycle

Oxycombustion: Chemical Looping

Chemical Looping Advantages:

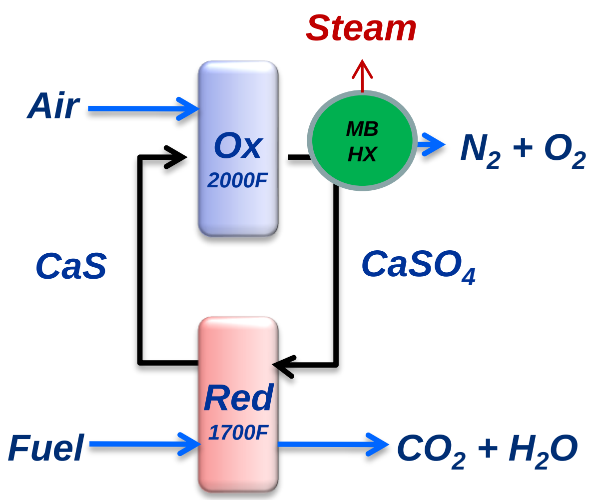
- ***Oxy-combustion <u>without</u> an O_2 plant***
- ***Potential lowest cost option for near-zero emission coal power plant <20% COE penalty***
- ***New <u>and</u> existing PC power plant designs***

Key Challenges

- ***Solids transport***
- ***Heat Integration***

Air Reactor (Oxidizer)

$CaS + 2O_2 \rightarrow CaSO_4 + Heat$



Fuel Reactor (Reducer)

$CaSO_4 + 2C + Heat \rightarrow 2CO_2 + CaS$

$CaSO_4 + 4H_2 + Heat \rightarrow 4H_2O + CaS$

Oxy-Firing without Oxygen Plant

- Solid Oxygen Carrier circulates between Oxidizer and Reducer
- Oxygen Carrier: Carries Oxygen, Heat and Fuel Energy
- Carrier picks up O_2 in the Oxidizer, leaves N2 behind
- Carrier Burns the Fuel in the Reducer
- Heat produces Steam for Power

Status

2010 Alstom Pilot test (1 MWe)

- ✓ ***1000 lb/hr coal flow***
- ✓ ***1st Integrated operation***
- ✓ ***1st Autothermal Operation***

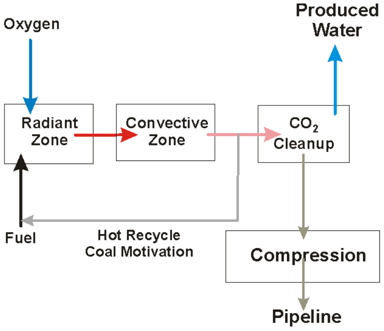
Oxycombustion: Advanced Boilers

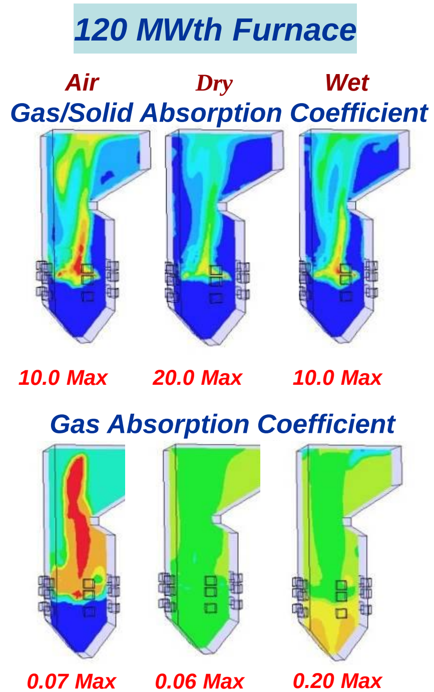
Research

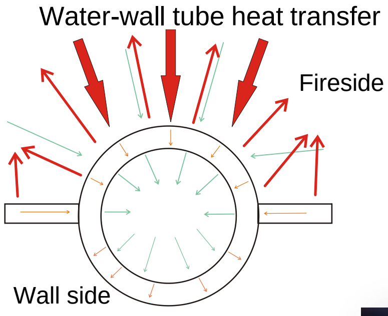
- Develop models for combustion, radiation, heat transfer
- Investigate methods to integrate CO_2 purification with thermal cycle
- Evaluate material performance in existing (600 °C)/advanced (760 °C) steam cycles

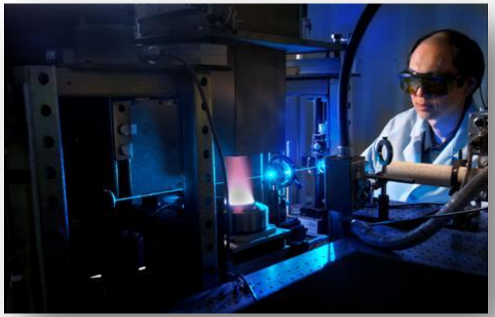
Status

- Grey-gas radiation model and particle model under development
- Fireside corrosion test: exposure tests with ash and flue gas; oxide fluxing behavior in ash and flue gas
- Integrated Pollutant Removal (IPR) licensed
- Flame emissions and heat transfer measurements in boilers









Post-combustion CO_2 Capture

- Amine-based scrubbing
- Advanced CO_2 Solvents
- Ionic Liquids
- Designing IL's via Molecular Simulations
- Solvents: Potassium Carbonate
- Phase Transitional Absorption
- Solid Sorbents: Metal Organic Framework
- Solid Sorbents: Pilot-scale development
- Reactors for CO_2 Dry Sorbents
- Advanced Flue Gas CO_2 Membranes

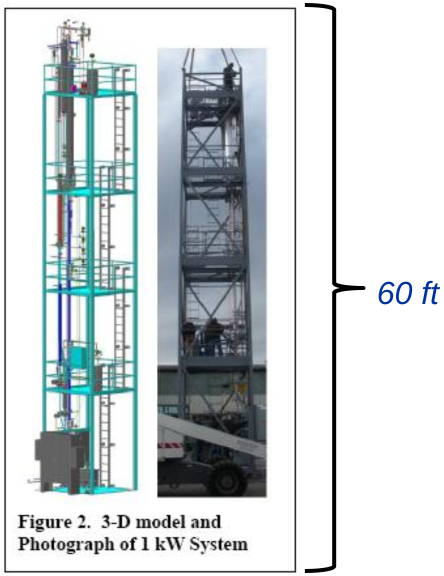
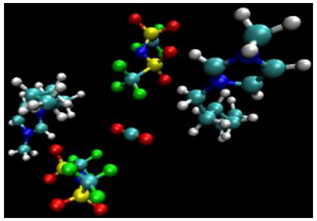
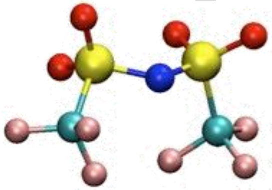
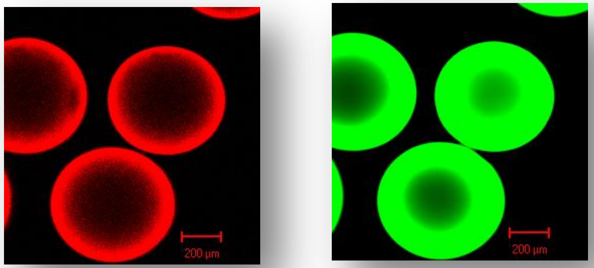


Figure 2. 3-D model and Photograph of 1 kW System





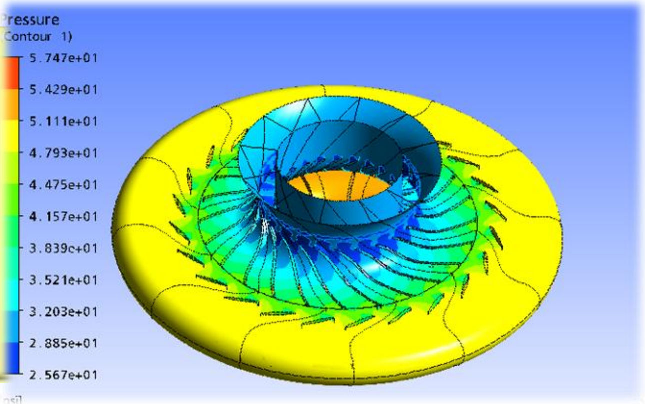
1-n-hexyl-3,5-dimethylpyridinum bis(trifluoromethane-sulfonyl)amide



Schematic shows how layers (red/green & black) are deposited. Experimental deposition on 600 micron porous spheres showing "tagged" red/green adsorbent Deposition via confocal fluorescence microscopy.

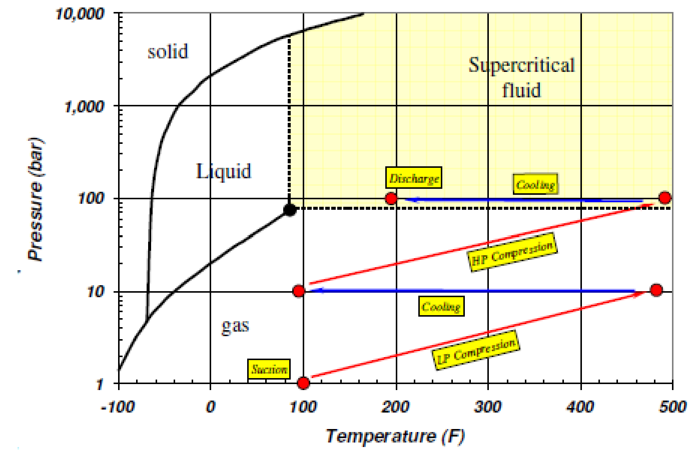
Advanced CO_2 Compression

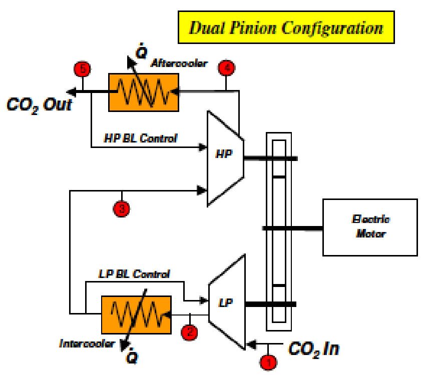
- **R&D Focus**
  - *Reduce capital costs*
  - *Increase efficiency*
  - *Integration with CO_2 capture process*
  - *Modeling*
  - *Heat recovery*
  - *Reduced footprint*



Approach:

- ***Compression process transitions from superheated to supercritical phase***
- ***Avoids liquid (sub-cooled) phase***





- ***PR ~ 100:1 (suction pressure ~15 psia)***
- ***Two stages***
- ***Stage efficiency ~85%***

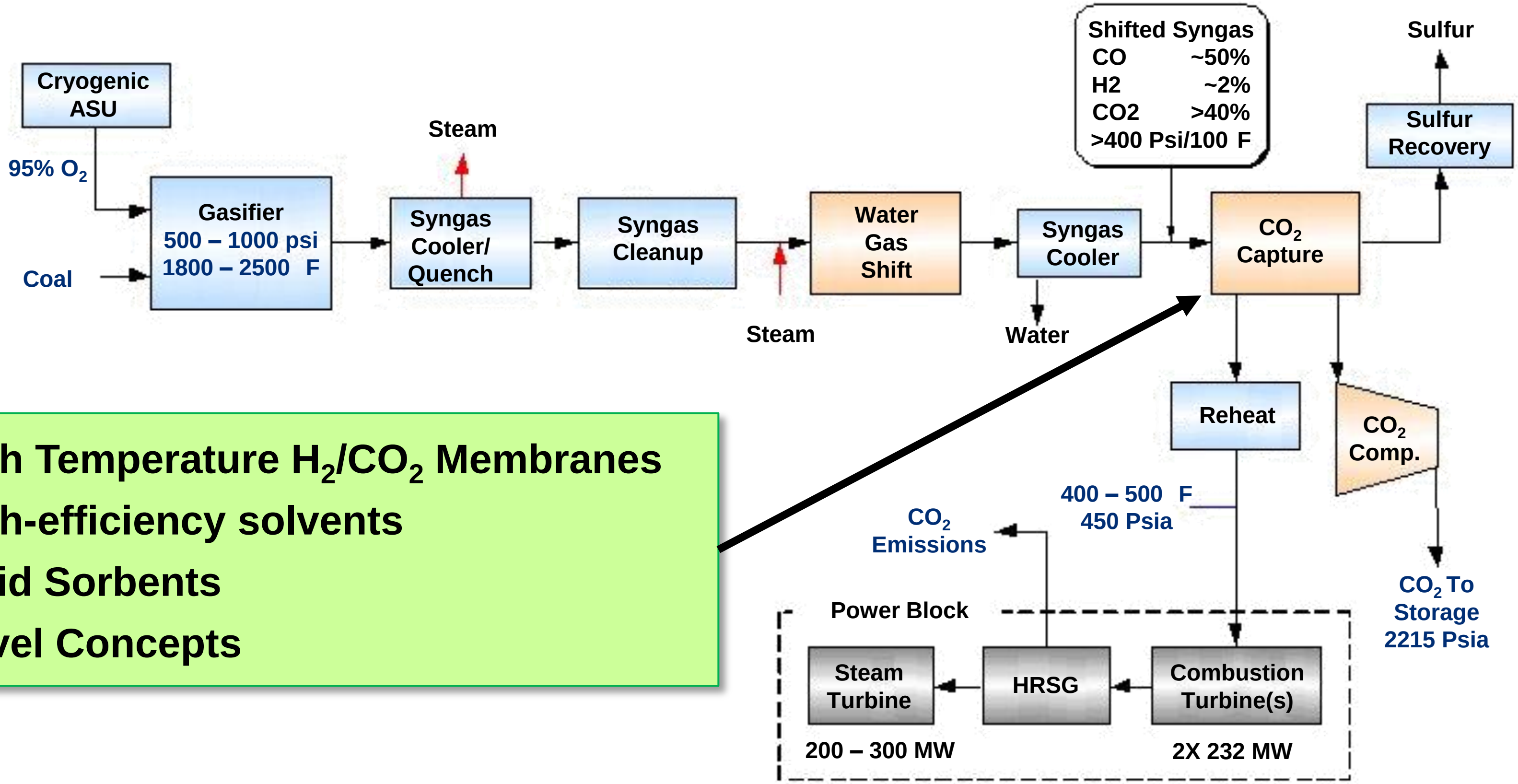
National Carbon Capture Center (NCCC) at Power Systems Development Facility (PSDF)

Wilsonville, AL

NCCC Mission: Develop technologies that will lead to the commercialization of cost-effective, advanced coal fueled power plants with CO_2 capture

- 6 Mwe Transport Gasifier
- 3 Mwe Post-Combustion Slipstream
- Southern Company
  - Peabody Energy
  - American Electric Power
  - Luminant
  - Arch Coal
  - RioTinto
  - Electric Power Research Institute

IGCC Pre-combustion CO_2 Capture Technologies



High Temperature H_2/CO_2 Membranes
High-efficiency solvents
Solid Sorbents
Novel Concepts

Advantages:

1. High P_{CO2}
2. Low Volume Syngas Stream

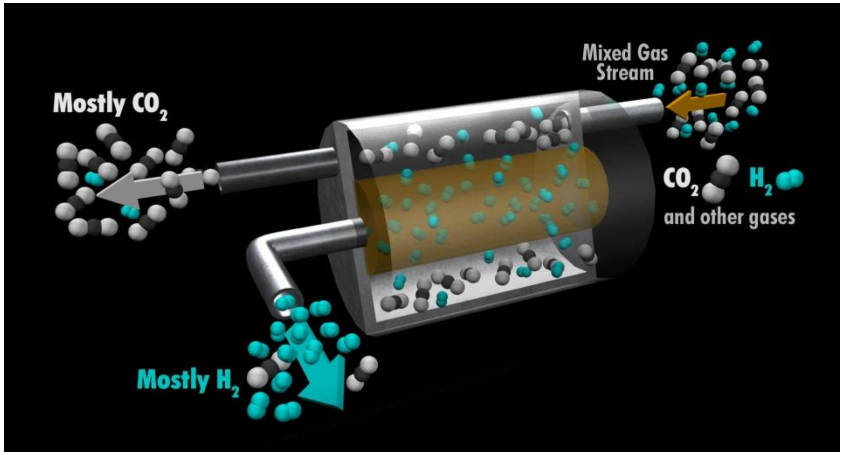
Challenges:

1. IGCC—system complexity
2. Additional water-gas-shift process

IGCC Pre-Combustion Polymer-Based High Temperature Membrane

R&D Focus

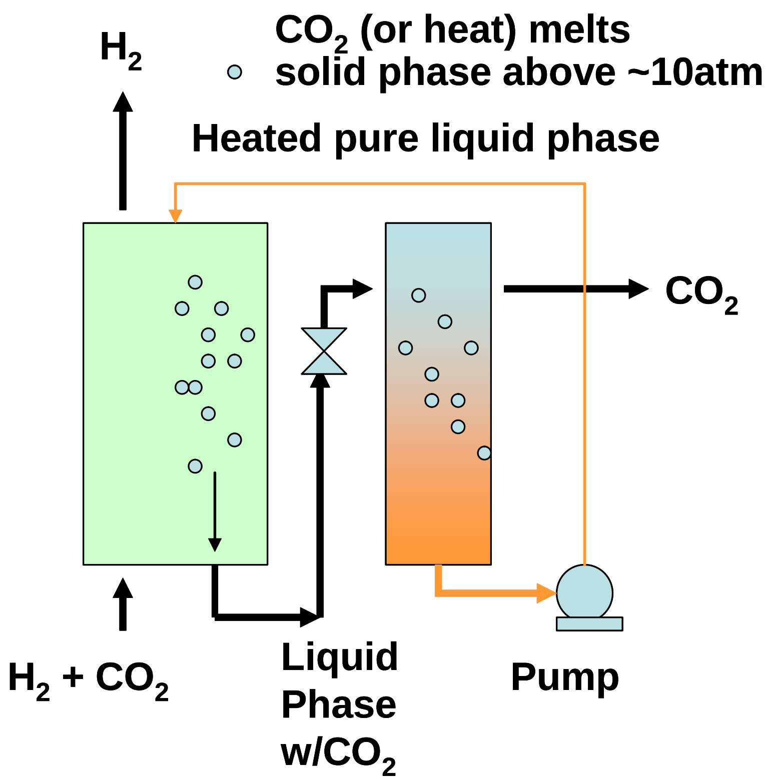
Developing a high temperature polymer-based membrane and full-scale module development for pre-combustion capture



Accomplishments:

- Developed polybenzimidazole (PBI) – based membrane exhibits the *highest* **operating temperature (400 °C)** of a polymer-based membrane.
- **Over 400 days** of testing in simulated synthesis gas environments at temperatures exceeding 250 °C conducted while demonstrating:
  – permeabilities and selectivities of commercial interest
  – operation temperatures well matched to process temperatures
  – chemical stability to primary synthesis gas components
  – mechanical stability in the presence of process cycling and simulated upset conditions

IGCC Carbon Capture: Phase Change Polymer



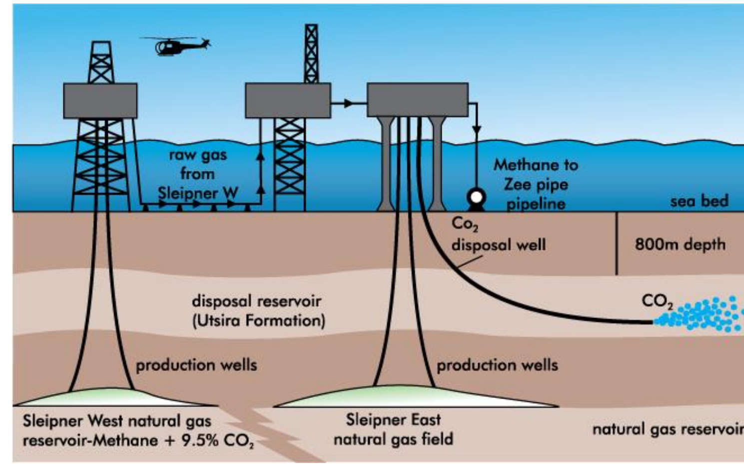
Concept for syngas CO_2 Capture w/phase change polymer

- Vessel on left is a fixed bed of solids (some polymer based)
- High pressure CO_2 is introduced (IGCC applications)
- Solids transform into homogeneous liquid phase, and extracted from bottom of vessel
- Pressure is decreased (only a small amount) in regeneration vessel, CO_2 is generated and the solids reform
- Heat is added to reliquify polymer and pump back to absorption column

Global Collaborations
Technology Transfer and Lessons Learned

Examples of Current Collaborations:

- **Sleipner (Norway, Europe)**
  - 1 Mt CO_2/y <Commercial 1996>
  - StatoilHydro
- **In Salah (Algeria, Africa)**
  - 1 Mt CO_2/y <Commercial 2004>
  - BP, Sonatrach,StatoilHydro
- **Weyburn-Midale (Saskatchewan, Canada)**
  - 1.8 Mt CO_2/y <Commercial 2000>
  - Encana, Apache
- **Fort Nelson (British Columbia, Canada)**
  - >1 Mt CO_2/y , 1.8 MT acid gas/yr <Demo Scale>
  - Spectra Energy



Sleipner Project Schematic

In Salah Gas Field, Algeria

DOE's Global CCS Project Involvement

Location	*Operations*	*U.S. Invol.*	*Reservoir*	*Operator /Lead*	*Int'l Recognition*
North America, Canada Saskatchewan **Weyburn-Midale**	**1.8 Mt CO_2/yr commercial 2000**	**2000-2011**	**oil field carbonate EOR**	**Encana, Apache**	**IEA GHG R&D Programme, CSLF**
North America, Canada, Alberta **Zama oil field**	**250,000 tons CO_2, 90,000 tons H_2S demo**	**2005-2009**	**oil field carbonate EOR**	**Apache (Reg. Part.)**	**CSLF**
North America, Canada, British Columbia **Fort Nelson**	**> 1 Mt CO_2/yr, 1.8 Mt acid gas/yr large-scale demo**	**2009-2015**	**saline formation**	**Spectra Energy (Reg. Part.)**	**CSLF**
Europe, North Sea, Norway **Sleipner**	**1 Mt CO_2/yr commercial 1996**	**2002-2011**	**marine sandstone**	**StatoilHydro**	**IEA GHG R&D Programme, CSLF, European Com.**
Europe, North Sea, Norway **Snovhit CO2 Storage**	**700,000 tonnes CO_2 commercial 2008**	**2009-TBD**	**marine sandstone**	**StatoilHydro**	
Europe, Germany **CO2SINK, Ketzin**	**60,000 tonnes CO_2 demo 2008**	**2007-2010**	**saline sandstone**	**GeoForsch-ungsZentrum, Potsdam(GFZ)**	**CSLF, European Commission, IEA GHG R&D Prog**
Australia, Victoria **Otway Basin**	**100,000 tonnes CO_2 demo 2008**	**2005-2010**	**gas field sandstone**	**CO2CRC**	**CSLF**
Africa, Algeria **In Salah gas**	**1 Mt CO_2/yr commercial 2004**	**2005-2010**	**gas field sandstone**	**BP, Sonatrach, StatoilHydro**	**CSLF, European Commission**
Asia, China, **Ordos Basin**	**assessment phase CCS**	**2008-TBD**	**Ordos Basin**	**Shenhua Coal**	

Final Observations

- **CCS technology is available today, however:**
  - It is very expensive, energy intensive, and not fully proven
- **Sequestration needs to be more widely demonstrated, especially in deep saline reservoirs with large-volume CO_2 injection**
- **DOE RD&D program is targeting the key issues**
- **Regulatory certainty is a prerequisite for commercial action.**

Virtual Power Plant Retrofit for Carbon Management

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