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New Developments with IECM

February 27, 2014

Outline of Talk

- Overview of the IECM
- Recent & planned work: Pre-combustion capture
- Recent & planned work: Post-combustion capture
- Recent & planned work: Oxy-combustion capture
- Recent & planned work: Other activities

IECM Overview

IECM: A Tool for Analyzing Power Plant Design Options

- A desktop/laptop computer simulation model developed for DOE/NETL
- Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  - PC, IGCC and NGCC plants
  - All flue/fuel gas treatment systems
  - CO_2 capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
- Free and publicly available at: www.iecm-online.com

IECM Modeling Approach

- Systems Analysis Approach
- Process Performance Models
- Engineering Economic Models
- Advanced Software Capabilities
  - User-friendly graphical interface
  - Probabilistic analysis capability
  - Versatile input/output features

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IECM Software Package

Fuel Properties
- Heating Value
- Composition
- Delivered Cost

Plant Design
- Conversion Process
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

Cost Factors
- O&M Costs
- Capital Costs
- Financial Factors

Power Plant Models

Graphical User Interface

Plant and Fuel Databases

Plant & Process Performance
- Efficiency
- Resource use

Environmental Emissions
- Air, water, land

Plant & Process Costs
- Capital
- O&M
- COE

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IECM Technologies for PC Plants

(excluding CO_2 capture, transport and sequestration)

Boiler/Turbine Types
- Subcritical
- Supercritical
- Ultra-supercritical

Furnace Firing Types
- Tangential
- Wall
- Cyclone

Furnace NO_x Controls
- LNB
- SNCR
- SNCR + LNB
- Gas reburn

Flue Gas NO_x Removal
- Hot-side SCR

Mercury Removal
- Carbon/sorbent injection

Particulate Removal
- Cold-side ESP
- Fabric filter
  - Reverse Air, Pulse Jet

SO_2 Removal
- Wet limestone
  - Conventional, Forced oxidation
  - Additives
- Wet lime
- Lime spray dryer

Solids Management
- Ash pond, Landfill, Co-mixing
- Byproducts (for export)

Cooling and Wastewater Systems
- Once-through cooling
- Wet cooling tower
- Dry cooling tower
- Chemical treatment
- Mechanical treatment

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Technologies for IGCC and NGCC Plants

(excluding CO_2 capture, transport and sequestration)

Air Separation Unit
- Cryogenic

Slurry Preparation

Coal Pretreatment

Gasification
- Slurry-feed gasifier (GE-Q)
- Dry-feed gasifier (Shell)

Syngas Cooling and Particulate Removal System

Mercury Removal
- Activated carbon

H_2S Removal System
- Selexol
- Sulfinol

Sulfur Recovery System
- Claus Plant
- Beavon-Stretford Unit

FOR BOTH IGCC and NGCC:

Gas Turbine
- GE 7FA
- GE 7FB

Heat Recovery Steam Generator

Steam Turbine

Boiler Feedwater System

Process Condensate Treatment

Auxiliary Equipment

Cooling Water System
- Once-through
- Wet cooling tower
- Air cooled condenser

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IECM Technologies for CCS

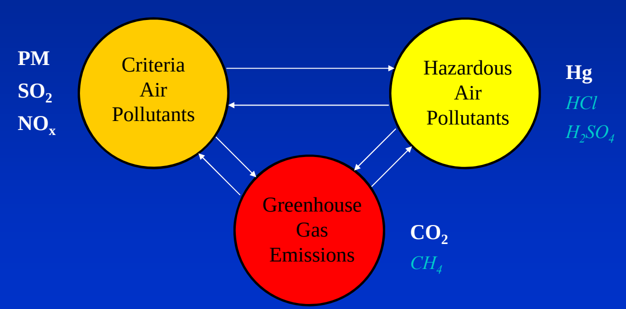
(version 8.0.2)

- CO_2 Capture Options
  - *Pre-Combustion (IGCC):*
    - Water gas shift + Selexol
    - Chemical looping
  - *Oxy-Combustion (PC)*
  - *Post-Combustion (PC, NGCC):*
    - Amine systems (MEA, FG+)
    - Chilled ammonia
    - Membrane systems
    - Auxiliary NG boiler or power plant (optional)
- CO_2 Transport Options
  - Pipelines (six U.S. regions)
- CO_2 Sequestration Options
  - Geologic: Deep Saline or Other Formations
  - Geologic: Enhanced Oil Recovery (EOR)

Process Performance Models

- Detailed mass and energy balances for each major component and overall plant
- For components with complex chemistry and/or heat integration schemes, multi-variate regression or other reduced-order models are derived from experimental data and detailed process models
- Approximately 10-20 performance parameters for each component technology

Performance Models Account for Multi-Pollutant Interactions



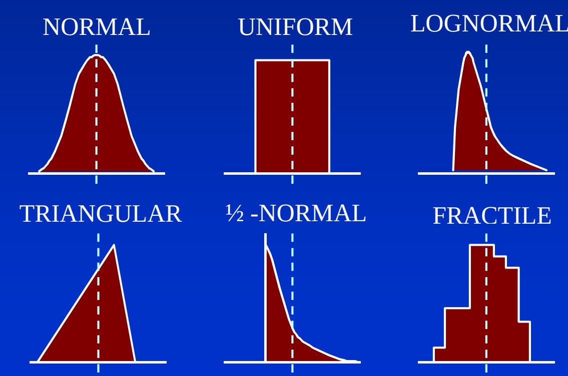
Technology Cost Models

- Direct cost models for each major process area (typically 5-10 areas per technology) based on detailed engineering design studies
- Explicit links to process performance models via key parameters (e.g., flow rate, temp., pressure, etc.)
- Calculate total capital cost, variable O&M costs, fixed O&M costs and annualized cost of electricity
- Approximately 20-30 cost elements per technology

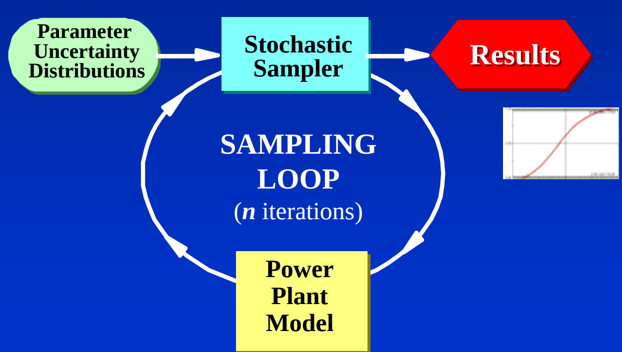
Probabilistic Capability

- Allows users to explicitly model and quantify the effects of uncertainty and/or variability on component and system performance, emissions and cost
- Values for user-selected parameters are specified as a probability distribution function, which is sampled using a selected method and sample size (default = median latin hypercube sampling, LHS)
- Results are displayed as a cumulative distribution function, yielding confidence intervals and probability of different outcomes for selected parameters

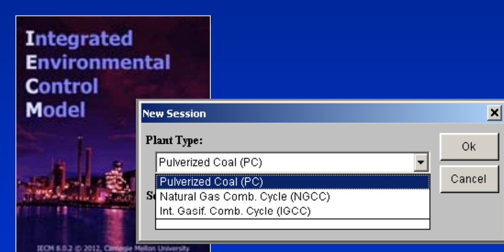
Examples of IECM Parameter Uncertainty Distributions



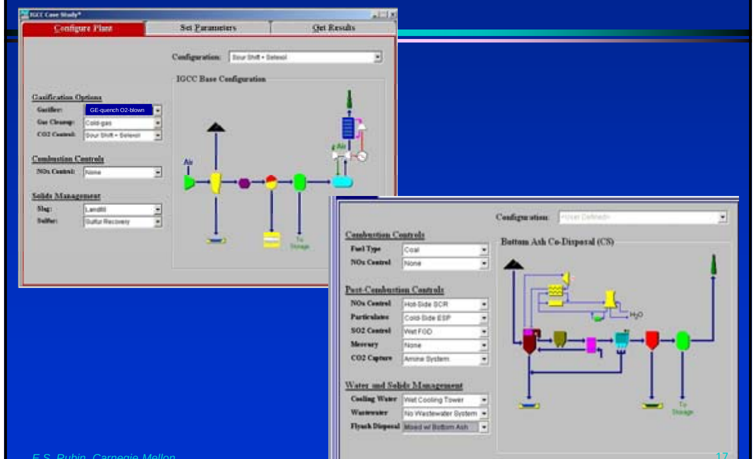
Stochastic Simulation



Graphical User Interface



Configure Plant Screens



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Set Parameters Screens: Plant Components

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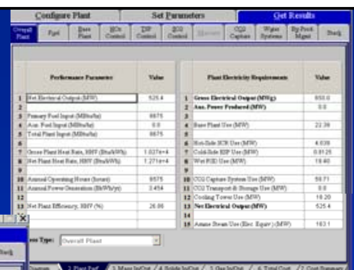
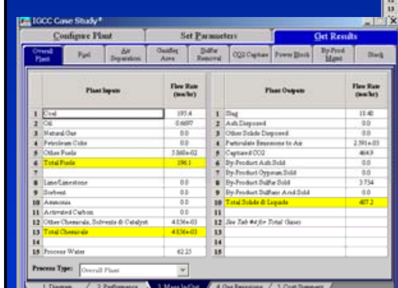
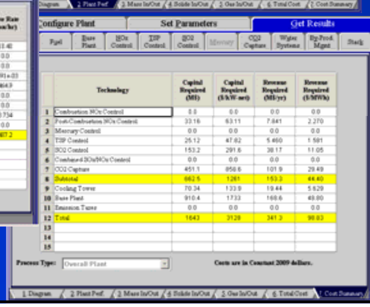
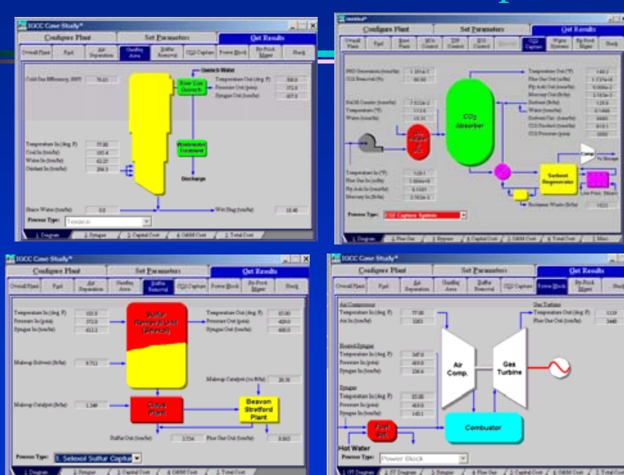
Get Results Screens: Overall Plant







Get Results Screens: Components



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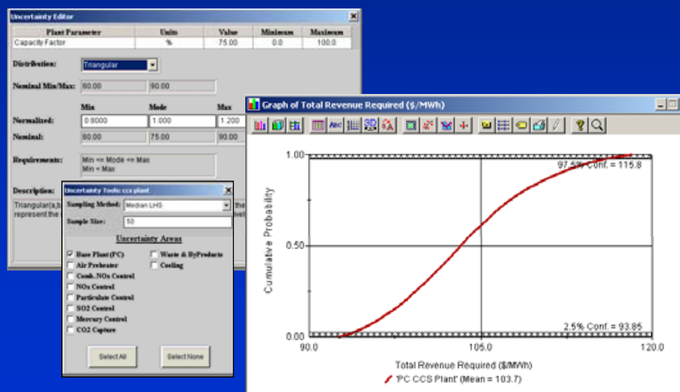
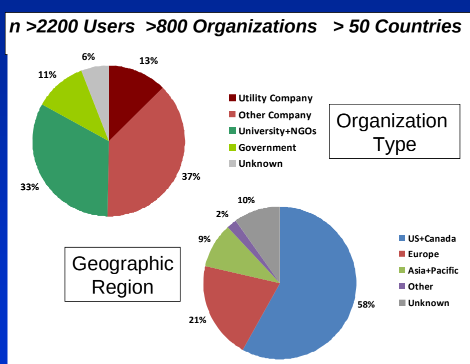
Probabilistic Results: *Uncertainty in COE*



Some Questions of Interest

- What technologies are available to control emissions from a given power plant system? What levels of pollution reduction are possible?
- What are the associated impacts and uncertainties on:
  - – resource requirements
  - – efficiency
  - – cost?
- How *likely* is it that a given advanced technology can:
  - Achieve lower cost and/or better performance than current systems?
  - Meet DOE goals for "high risk, high payoff" technology?

IECM Users and Uses

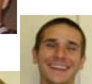


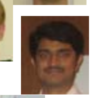
IECM IS USED FOR:

- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning
- Teaching/Education

The IECM Project Team

- Performance and Cost Models of Advanced CO_2 Capture Systems
  - Membrane capture systems *(Haibo Zhai)*
  - Solid sorbent systems *(Justin Glier)*
  - Advanced oxy-combustion *(Kyle Borgert)*
  - Chemical looping combustion *(Hari Mantripragada)*
- Software Development & Dist. *(Karen Kietzke)*

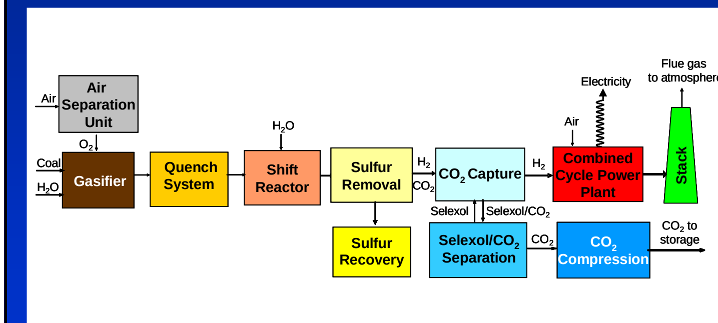






Recent and planned activities:

Pre-combustion capture

Current IGCC Power Plant with Pre-Combustion CO_2 Capture



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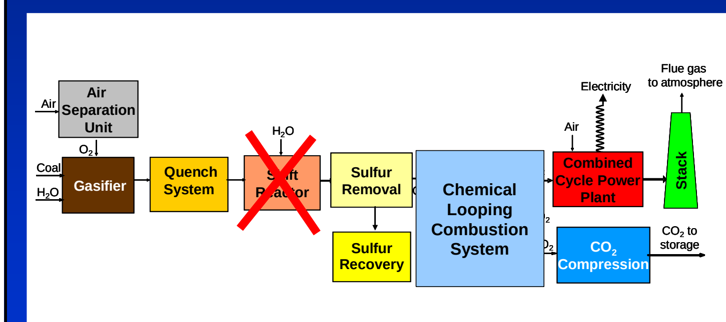
Chemical Looping Combustion System for CO_2 Capture



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CLC System Reactions

- $CH_4 + 4NiO \Leftrightarrow CO_2 + 2H_2O + 4Ni$ ($\Delta H = 134$ kJ/mol)
- $CH_4 + 3NiO \Leftrightarrow CO + 2H_2O + 3Ni$
- $CO + NiO \Leftrightarrow CO_2 + Ni$ ($\Delta H = -43.3$ kJ/mol)
- $H_2 + NiO \Leftrightarrow H_2O + Ni$ ($\Delta H = -2.1$kJ/mol)
- $CO + H_2O \Leftrightarrow CO_2 + H_2$

Overall Reaction:

$(xCO + yH_2 + zCH_4) + (x+y+4z)NiO \Leftrightarrow$

$(x+z)CO_2 + (y+2z)H_2O + (x+y+4z)Ni$

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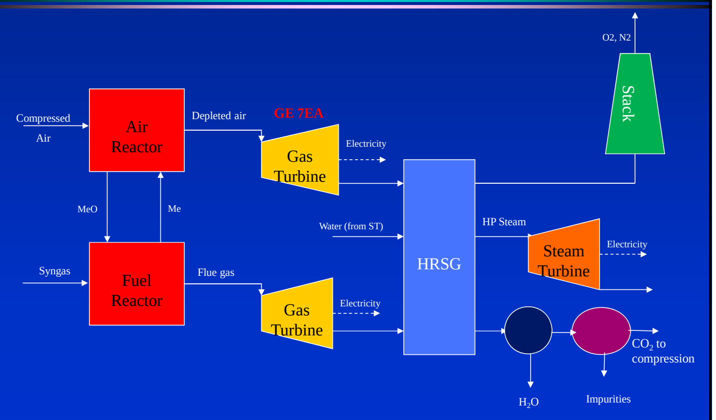
Schematic of CLC Combined Cycle Power Plant



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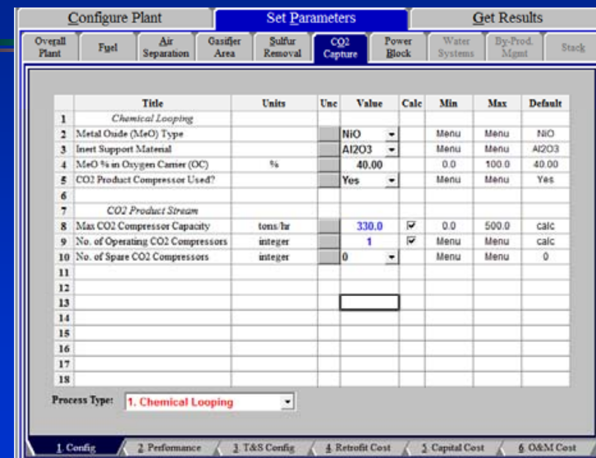
CLC Model in IECM (v 8.0.2)



Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel | Air Separation | Gasifier Area | Sulfur Removal | CO2 Capture | Power Block | Water Systems | By-Prod. Mgmt | Stack

	Title	Units	Unc	Value	Calc	Min	Max	Default
1	*Chemical Looping*							
2	Metal Oxide (MeO) Type			NiO		Menu	Menu	NiO
3	Inert Support Material			Al2O3		Menu	Menu	Al2O3
4	MeO % in Oxygen Carrier (OC)	%		40.00		0.0	100.0	40.00
5	CO2 Product Compressor Used?			Yes		Menu	Menu	Yes
6								
7	*CO2 Product Stream*							
8	Max CO2 Compressor Capacity	tons/hr		330.0	☑	0.0	500.0	calc
9	No. of Operating CO2 Compressors	integer		1	☑	Menu	Menu	calc
10	No. of Spare CO2 Compressors	integer		0		Menu	Menu	0
11								
12								
13								
14								
15								
16								
17								
18								

Process Type: 1. Chemical Looping

1. Config | 2. Performance | 3. T&S Config | 4. Retrofit Cost | 5. Capital Cost | 6. O&M Cost

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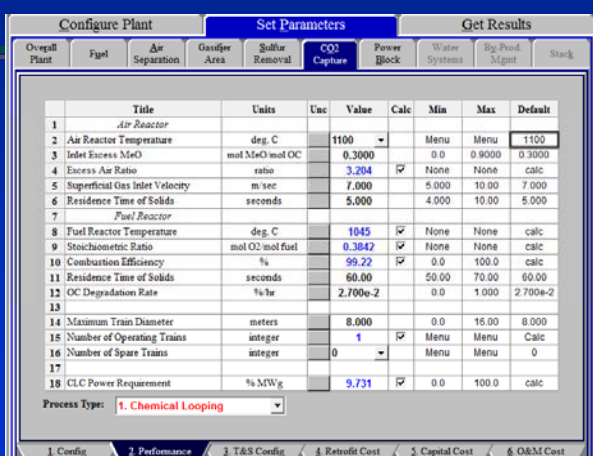
CLC Model in IECM (v 8.0.2)



Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel | Air Separation | Gasifier Area | Sulfur Removal | CO2 Capture | Power Block | Water Systems | By-Prod. Mgmt | Stack

	Title	Units	Unc	Value	Calc	Min	Max	Default
1	*Air Reactor*							
2	Air Reactor Temperature	deg. C		1100		Menu	Menu	1100
3	Inlet Excess MeO	mol MeO/mol OC		0.3000		0.0	0.9000	0.3000
4	Excess Air Ratio	ratio		3.204	☑	None	None	calc
5	Superficial Gas Inlet Velocity	m/sec		7.000		5.000	10.00	7.000
6	Residence Time of Solids	seconds		5.000		4.000	10.00	5.000
7	*Fuel Reactor*							
8	Fuel Reactor Temperature	deg. C		1045	☑	None	None	calc
9	Stoichiometric Ratio	mol O2/mol fuel		0.3842	☑	None	None	calc
10	Combustion Efficiency	%		99.22	☑	0.0	100.0	calc
11	Residence Time of Solids	seconds		60.00		50.00	70.00	60.00
12	OC Degradation Rate	%/hr		2.700e-2		0.0	1.000	2.700e-2
13								
14	Maximum Train Diameter	meters		8.000		0.0	16.00	8.000
15	Number of Operating Trains	integer		1	☑	Menu	Menu	Calc
16	Number of Spare Trains	integer		0		Menu	Menu	0
17								
18	CLC Power Requirement	% MWg		9.731	☑	0.0	100.0	calc

Process Type: 1. Chemical Looping

1. Config | 2. Performance | 3. T&S Config | 4. Retrofit Cost | 5. Capital Cost | 6. O&M Cost

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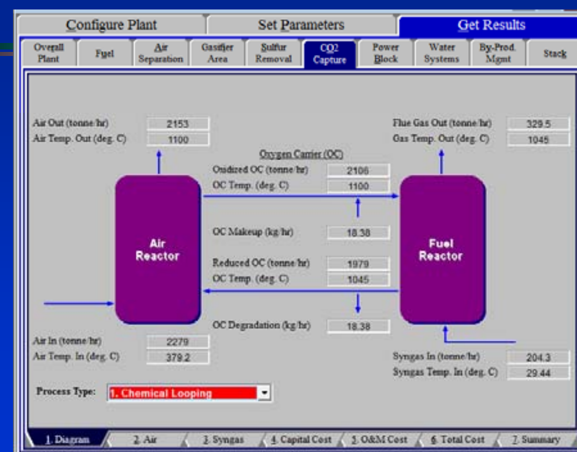
CLC Model in IECM (v 8.0.2)



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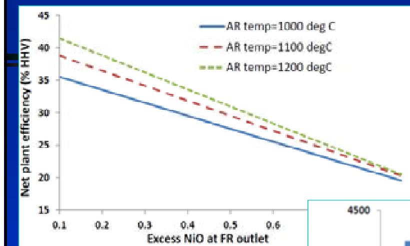
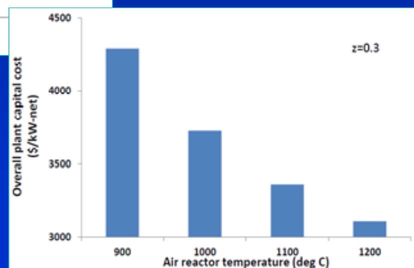
Illustrative Results for CLC System



Plant Efficiency



Plant Cost

IECM Work Plan for FY2014

- New pre-combustion system and capture technologies
  - Chemical looping systems using low-cost metal oxygen carriers
  - The GE-radiant gasification system
  - Sorbent-enhanced water gas shift reactor system
- New post-combustion capture technologies
  - Air-sweep membrane system
  - Calcium looping system
  - Solid sorbent system
  - Ionic liquid-based system
- New oxy-combustion system and capture technologies
  - ASU, DCC, CPU and other new or enhanced components
- Develop and test a new IECM release (v9.0) with the added technologies and capabilities above

New Pre-Combustion Tasks *(1)*

- Building on the current CLC model we will:
  - Model two new low-cost oxygen carriers, copper and iron
  - Develop performance models for air and fuel reactors
  - Develop new performance model for GE 7EA gas turbine
  - Develop performance model for CO_2 purification system
  - Develop cost models for all the above
  - Implement and test in the IECM
  - Prepare technical documentation for all the above

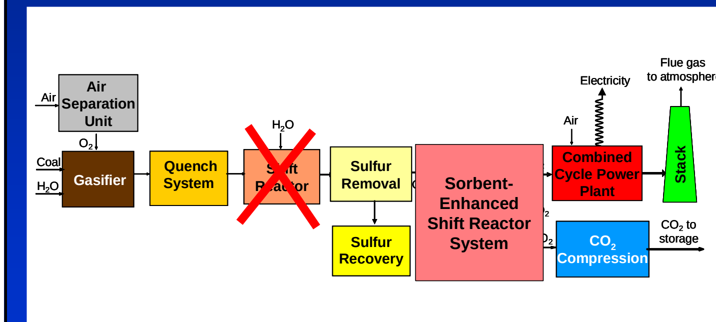
New Pre-Combustion Tasks *(2)*

- Implement model of a GE-Radiant gasification system (based on NETL Baseline studies)
  - Develop performance model for gasifier
  - Modified IGCC power block model
  - Develop cost models for the above
  - Implement and test in the IECM
  - Prepare technical documentation for all the above

New Pre-Combustion Tasks *(3)*

- Develop and implement new model of a sorbent-enhanced WGS reactor system:
  - Performance models
  - Cost models
  - Implement and test in the IECM
  - Prepare technical documentation

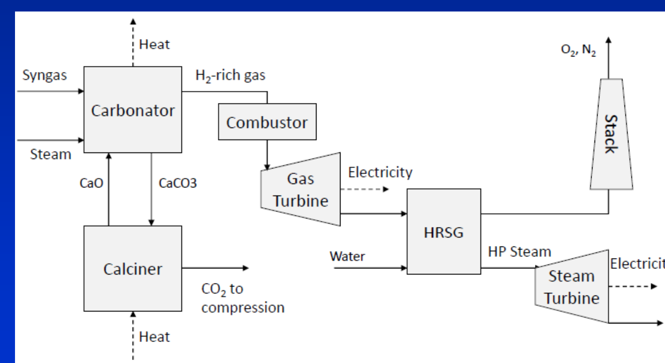
Sorbent Enhanced Shift Reactor System for CO_2 Capture



Performance Characteristics for Sorbent-Enhanced WGS

- Chemical Reactions
  - *Shift reaction*: $CO + H_2O \rightarrow CO_2 + H_2$
  - *Carbonation*: $CaO + CO_2 \rightarrow CaCO_3$
  - *Overall reaction*: $CaO + CO + H_2O \rightarrow CaCO_3 + H_2$
  - *Calcination*: $CaCO_3 \rightarrow CaO + CO_2$ (to storage)
- Carbonator temperature: 650°C
- Calciner temperature: 950°C
- Variable H_2O/CO ratio

Schematic of Sorbent-Enhanced Shift Reactor System



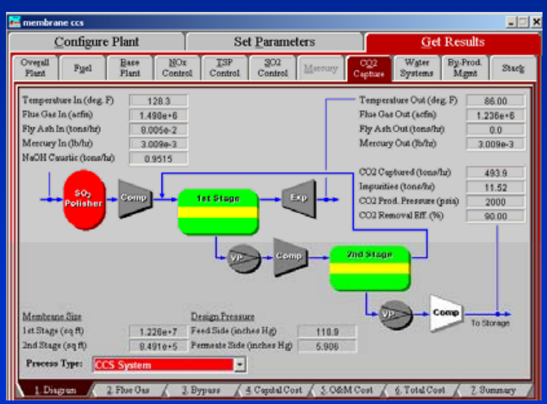
Recent and planned work:

Post-combustion capture

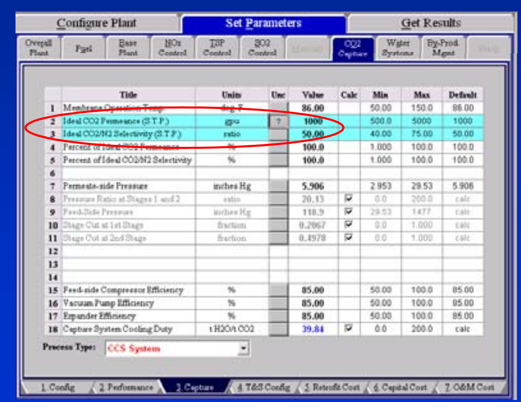
IECM Work Plan for FY2014

- New pre-combustion system and capture technologies
  - The GE-radiant gasification system
  - Chemical looping systems using low-cost metal oxygen carriers
  - Sorbent-enhanced water gas shift reactor system
- New post-combustion capture technologies
  - Air-sweep membrane system
  - Calcium looping system
  - Solid sorbent system
  - Ionic liquid-based system
- New oxy-combustion system and capture technologies
  - ASU, DCC, CPU and other new or enhanced components
- Develop and test a new IECM release (v9.0) with the added technologies and capabilities above

2-Stage Membrane System Model in IECM (v. 8.0.2)

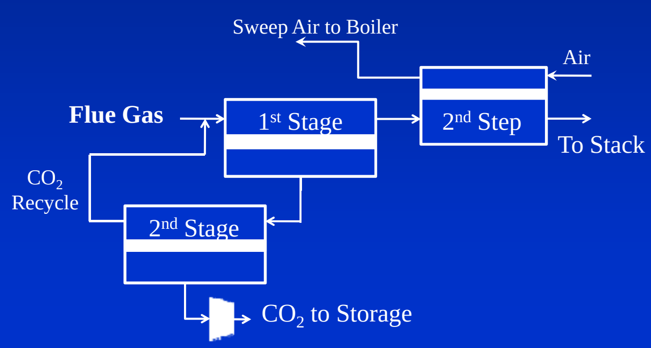


Performance Parameters for the Membrane Capture System Model

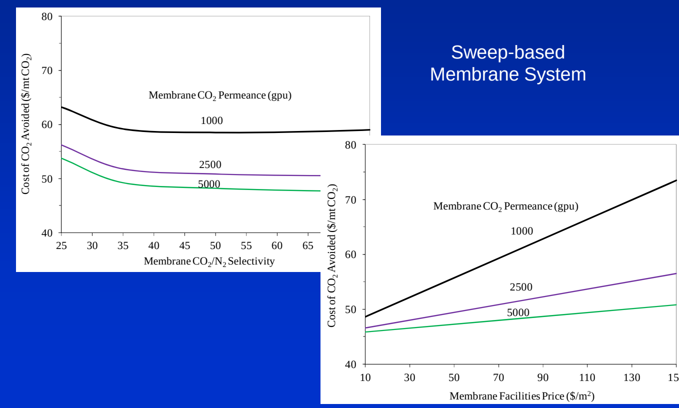


Sweep-based 2-Stage, 2-Step Membrane System Model

(Model developed but not yet implemented in IECM)

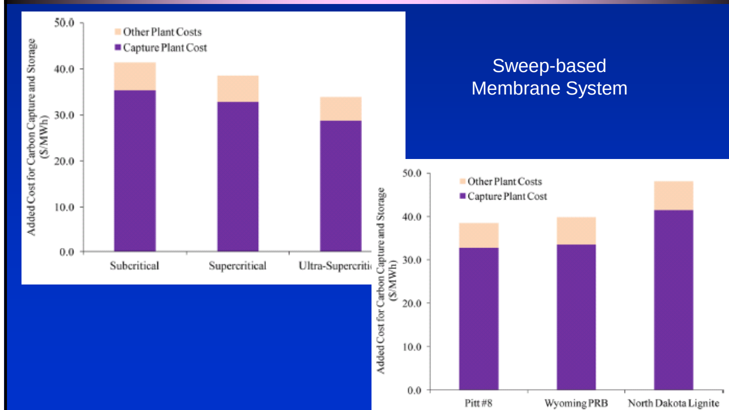


Effects of Membrane Properties and Price on Cost of CO_2 Avoided



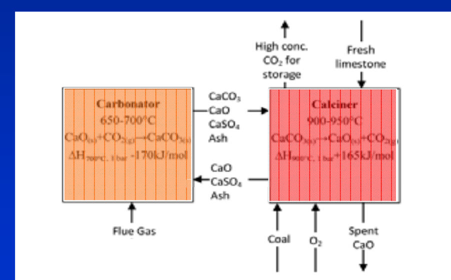
Sweep-based Membrane System

Effects of Power Plant and Coal Type on Membrane System Cost



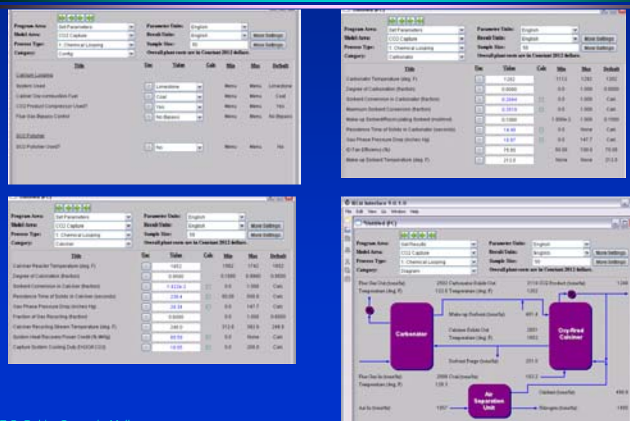
Sweep-based Membrane System

Under Development: Post-Combustion Chemical Looping

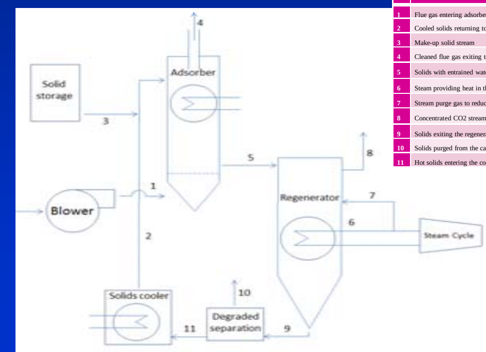


Source: Dean, et al., 2011

New Calcium-based Chemical Looping Module (in IECM v9.0 dev)



Also Under Development: Solid Sorbent Capture System



No	Description
1	Flue gas entering adsorber
2	Cooled solids returning to adsorber
3	Make-up solid stream
4	Cleaned flue gas exiting to stack
5	Solids with entrained water leaving adsorber
6	Steam providing heat in the regenerator
7	Stream purge gas to reduce the partial pressure of steam
8	Concentrated CO2 stream to dehydration and compression
9	Solids exiting the regenerator
10	Solids purged from the capture system
11	Hot solids entering the cooling unit

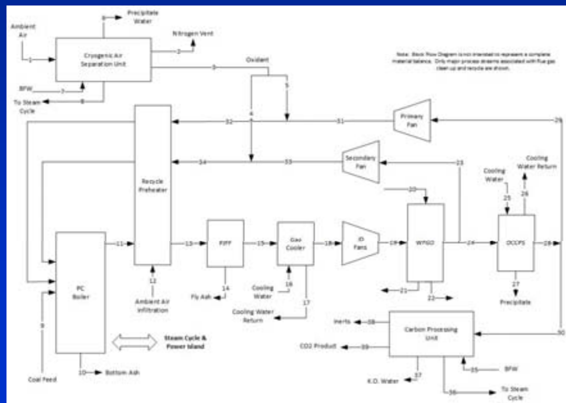
Recent and planned work:

Oxy-combustion capture

IECM Work Plan for FY2014

- New pre-combustion system and capture technologies
  - The GE-radiant gasification system
  - Chemical looping systems using low-cost metal oxygen carriers
  - Sorbent-enhanced water gas shift reactor system
- New post-combustion capture technologies
  - Air-sweep membrane system
  - Calcium looping system
  - Solid sorbent system
  - Ionic liquid-based system
- New oxy-combustion system and capture technologies
  - ASU, DCC, CPU and other new or enhanced components
- Develop and test a new IECM release (v9.0) with the added technologies and capabilities above

PC Oxyfuel Combustion Model



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Air Separation Unit

- Updated performance and cost models:
  - Are functions of oxidant flow rate, purity, and delivery pressure
  - Include cooling water consumption for main air compressor
  - Include main air compressor water generation from ambient humidity removal prior to cold box

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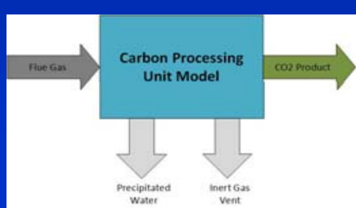
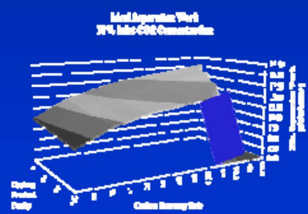
Carbon Processing Unit

- New generalized model to handle a wide variety of inlet flue gas compositions
- Second law calculations used to determine the minimum separation energy as performance baseline





E.S. Rubin, Carnegie Mellon

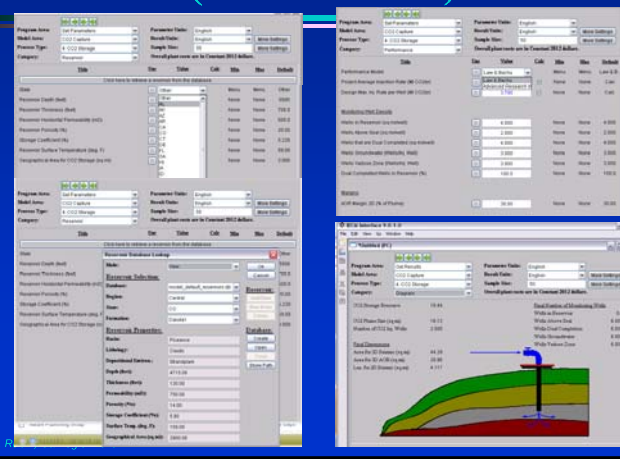
Recent and planned work:

Other activities

IECM Work Plan for FY2014

- New pre-combustion system and capture technologies
  - The GE-radiant gasification system
  - Chemical looping systems using low-cost metal oxygen carriers
  - Sorbent-enhanced water gas shift reactor system
- New post-combustion capture technologies
  - Air-sweep membrane system
  - Calcium looping system
  - Solid sorbent system
  - Ionic liquid-based system
- New oxy-combustion system and capture technologies
  - ASU, DCC, CPU and other new or enhanced components
- Develop and test a new IECM release (v9.0) with the added technologies above plus other new capabilities

New CO_2 Storage Cost Module (IECM v.9.0 dev)



2013 IECM-Related Publications

- Borgert, K.J., & Rubin, E. S. (2013). Oxyfuel combustion: technical and economic considerations for the development of carbon capture from pulverized coal power plants. *Energy Procedia*, 37:1291–1300.
- Glier, J.C. & Rubin, E. S. (2013). Assessment of solid sorbents as a competitive post-combustion CO2 capture technology. *Energy Procedia*, 37:65-72.
- Mantripragada, H.C. & Rubin, E. S. (2013). Chemical Looping for Pre-combustion CO2 Capture - Performance and Cost Analysis*. Energy Procedia*, 37:618–625.
- Versteeg, P., Oates, D.L., Hittinger, E. & Rubin, E.S. (2013). Cycling coal and natural gas-fired power plants with CCS. *Energy Procedia*, 37:618–625.
- Versteeg,P. , Zhai, H. and Rubin, E.S., Comparative Assessments of Advanced Amine and Ammonia Systems for Post-combustion CO_2 Capture*. 2013 Carbon Capture Utilization & Sequestration*, May, 2013, Pittsburgh, PA.
- Zhai, H., & Rubin, E. S. (2013). The Effects of Membrane-based CO2 Capture System on Pulverized Coal Power Plant Performance and Cost . *Energy Procedia*, 37:1117–1124.
- Zhai, H., & Rubin, E. S. (2013). Techno-Economic Assessment of Polymer Membrane Systems for Postcombustion Carbon Capture at Coal-Fired Power Plants. *Environmental Science & Technology, 47*(6), 3006-3014.
- Zhai, H., & Rubin, E. S. (2013). Comparative Performance and Cost Assessments of Coal- and Natural-Gas-Fired Power Plants under a CO2 Emission Performance Standard Regulation. *Energy & Fuels*. 27(8):4290-4301.

Thank You

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