Overview of Recent Accomplishments and Work in Progress

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National Energy Technology Laboratory
April 2, 2001
Outline of Today’s Presentation

- Brief History of the Project
- Recent Accomplishments
  - IECM technologies
  - Toward Vision 21
- Work in Progress
- Future Plans
- Open Discussion
Project History

- “Development of the Integrated Environmental Control Model”
  - CORs: C. Drummond, L. Gould, P. Rawls, T. Feeley, G. Gibbon
  - September 1992 - April 2000

- “Development and Application of Optimal Design Capability for Coal Gasification Systems”
  - CORs: K. Williams, G. Gibbon
  - September 1992 - present
Because of the... 

- Increasing complexity of advanced processes
- Multiple options for component design & selection
- Strong interactions among system components
- Significant performance and cost uncertainties
Objectives

- Develop a comprehensive modeling framework to estimate the performance, environmental emissions, and cost of coal-based power generation technologies.

- Develop a method for comparing alternative options on a systematic basis, including the effects of uncertainty.
Approach

- Process Technology Models
- Engineering Economic Models
- Advanced Software Capabilities
- Systems Analysis Framework
Integrated Environmental Control Model (IECM)

Coal Cleaning

Combustion Controls

Flue Gas Cleanup & Waste Management

- NOx Removal
- Particulate Removal
- SO2 Removal

- Combined SOx/NOx Removal
- Advanced Particulate Removal
Process Performance Models

- Calculate detailed mass and energy flows
- Employ empirical relationships and models based on available data
- Predict component and system efficiency
- Predict multi-media environmental emissions
Process Cost Models

- Direct capital cost of major process areas
- Total system capital cost
- Fixed operating costs
- Variable operating costs
- Total cost of electricity
- Linked to process performance models
Probabilistic Software Capability

- Can specify parameter values as distribution functions to reflect uncertainty or variability in model input data

- Explicitly quantifies the effects of uncertainty on predicted performance, emissions, and cost, yielding confidence intervals for uncertain results
IECM Software Package

Fuel Properties
- Heating Value
- Composition
- Delivered Cost

Plant Design
- Furnace Type
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

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

Power Plant Model

Graphical User Interface

Plant and Fuel Databases

Plant & Process Performance
- Efficiency
- Resource Use

Environmental Emissions
- Air, Land

Plant & Process Costs
- Capital
- O&M
- COE
The IECM is Publicly Available

- Web Access:
Preliminary IECM User Group

- ABB Power Plant Control
- American Electric Power
- Consol, Inc.
- Energy & Env. Research Corp.
- Exportech Company, Inc.
- FirstEnergy Corp.
- FLS Miljo A/S
- Foster Wheeler Development Corp.
- Lehigh University
- Lower Colorado River Authority
- McDermott Technology, Inc.
- Mitsui Babcock Energy LTD.
- National Power Plc.
- Niksa Energy Associates
- Pacific Corp.
- Pennsylvania Electric Association
- Potomac Electric Power Co.
- Savvy Engineering
- Sierra Pacific Power Co.
- Southern Company Services, Inc.
- Stone & Webster Engineering Corp.
- Tampa Electric Co.
- University of California, Berkeley
- US Environmental Protection Agency
Overview of Recent Accomplishments

- Combustion NO$_x$ controls (v 3.3)
- Mercury control technologies (v 3.4)
- IGCC systems (current and advanced)
- Solid oxide fuel cells
- CO$_2$ capture and sequestration systems
- Flexible fuel options
- Enhanced software capabilities
Newest Versions of the IECM...
New IECM Modules for Combustion NO\textsubscript{x} Controls

*Version 3.3*

- Selective Non-Catalytic Reduction (SNCR)
- Low NO\textsubscript{x} Burners (LNB)
- LNB + Overfire air
- LNB + SNCR
- Natural Gas Reburn
- Tangential, Wall & Cyclone Firing
New IECM Modules for Mercury Controls

Version 3.4

- Carbon injection systems
- Flue gas humidification option
- Effects of coal type (eastern vs. western)
- Effects of control technology selection
  - Particulate collector
  - FGD system
  - SCR system
Multi-Pollutant Interactions

Criteria Air Pollutants

PM
SO₂
NOₓ

Hazardous Air Pollutants

Hg
HCl
H₂SO₄
A Special Announcement
Welcome to the DOE Integrated Environmental Control Model

IECM 3.3 © 2000, Carnegie Mellon University
IECM Interface 3.3 © 2000, Carnegie Mellon University
Model Applications

- Process design
- Technology evaluation
- Cost estimation
- R&D management

- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning
Current Activities and Plans (PC plants)

- Refine existing models for mercury control and other pollutants as new data become available
- Couple the IECM to a database of U.S. power plant and fuel characteristics
- Analyze options, costs and emission reductions associated with use of control technologies for criteria pollutants and air toxics
- Explore IECM applications to the DOE Power Plant Improvement Initiative
Toward Vision 21 ...
Model Software Improvements

- Increased Flexibility
  - Multiple fuel types (coal, oil, gas)
  - Multiple plant types (combustion, IGCC, fuel cells, gas turbines, etc)
  - Easy and fast integration of new modules

- Additional Features
  - Plant configurations
  - Results tools
User Interface Improvements

- Increased Flexibility
  - Configuration of flowsheets
  - Two-dimensional flowsheets
  - Interface database compiler

- Additional Features
  - Multiple technology navigation menu
  - Multiple session results
    - Comparisons of up to six sessions
    - Differences between two cases
Comparisons of Competing Options

Cumulative Probability

Technology A

Technology B

Total Cost Savings Relative to Baseline Technology ($/MWh)
Select Gasification Combined Cycle (IGCC) Options

Choose Power System

Please Choose a Power System:

- Conventional Combustion
- Gasification Comb. Cycle
- Advanced Combustion
- Fuel Cells
- Vision 21 Plant
Select Oxygen Plant

Configure Plant

Set Parameters

Get Results

Gasification Options
- Gasifier: KRW
- Oxidant: Oxygen
- Gas Cleanup: Air, Oxygen

Post-Combustion Controls
- NOx Control: None

Solids Management
- Slag: Landfill
- Sulfur: Landfill

Plant Diagram
Select Gas Cleanup System

Gasification Options
- Gasifier: KRW
- Oxidant: Oxygen
- Gas Cleanup: Cold

Post-Combustion
- NOx Control: SCR, None, SCR

Solids Management
- Slag: Landfill
- Sulfur: Landfill
Current Status of IGCC Models

- Response surface model of advanced IGCC system (KRW gasifier + hot gas cleanup) is completed; implementation in the IECM framework is nearing completion.

- Response surface model of baseline IGCC system (Texaco gasifier + cold gas cleanup) is under development; expected completion in June.
### Set IGCC Process Parameters

The image shows a software interface for setting IGCC (Integrated Gasification Combined Cycle) process parameters. The interface allows the configuration and management of various parameters related to the plant setup and process control.

#### Table of Parameters:

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Units</th>
<th>Unc</th>
<th>Value</th>
<th>Calc</th>
<th>Min</th>
<th>Max</th>
<th>Default</th>
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<td>mol O2 / mol C</td>
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<td>Calcium to Sulfur Ratio</td>
<td>mol Ca / mol C</td>
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</table>
IGCC Process Areas

- Coal Handling
- Limestone Handling
- Oxidant Feed
- Gasification
- Sulfation
- Zinc Ferrite

- Boiler Feedwater System
- Gas Turbine
- Heat Recovery Steam Generation
- Selective Catalytic Reduction
- Steam Turbine
- General Facilities
IGCC Fixed O&M Costs

- **Fuels**
  - Coal Cost
  - Fuel Oil Cost
  - LPG - Flare Cost

- **Reagents**
  - Sulfuric Acid Cost
  - NaOH Cost
  - Hydrazine Cost
  - Morpholine Cost
  - Limestone Cost
  - Lime Cost
  - Soda Ash Cost

- **SCR System**
  - SCR Catalyst Cost
  - Ammonia Cost

- **Zinc Ferrite System**
  - Zinc Ferrite Sorbent Cost
  - Plant Air Adsorbent Cost

- **Waste Water System**
  - Corrosion Inhibitor Cost
  - Surfactant Cost
  - Chlorine Cost
  - Biocide Cost
  - Waste Water Cost
  - Raw Water Cost

- **Byproducts**
  - Sulfur Byproduct Cost
  - Sulfuric Acid Byproduct Cost
ASPEN Model of an IGCC System
Response Surface Model Development

Range of Parameter Inputs, $I_i$

Detailed Performance Model

Performance Outputs ($O_j$)

Performance Outputs ($O_j$)

Response Surface Model

Regression Analysis

$O_j = f(I_i)$
Response Surface Model for an IGCC System
Desktop Model of a Process

Input Assumptions

Response Surface Model (RSM)

Cost Model

Performance
Emissions
Cost
Additional Fuel and Technology Options

Choose Power System

Please Choose a Power System:

- Conventional Combustion
- Gasification Comb. Cycle
- Advanced Combustion
- Fuel Cells
- Vision 21 Plant
Simple Cycle Gas Plant

Gasification Options
- Plant Type: Simple Cycle

Post-Combustion Controls
- NOx Control: None
- CO2 Control: None

Solids Management
- Slag: Landfill
- Sulfur: Landfill
Open Vision 21 Plant Options

Choose Power System

Please Choose a Power System:
- Conventional Combustion
- Gasification Comb. Cycle
- Advanced Combustion
- Fuel Cells
- Vision 21 Plant
Vision 21 Workbench
Select Existing Flowsheet - 2

Vision 21 Plant:
- FETC - Combustion Based
- FETC - Gasifier Based
- FETC - Combustion Based
- User Specified

Plant Diagram:
- PFBC
- ASU
- CB
- HRSG
- GTST
- FC
- GC
- TC
- ST
- GT
- Air
- Water
- Chemical
- Solid
- Liquid
- Gas
New Modules Under Development ...
Tubular SOFC Design

- Fuel
- Air
- Electrolyte
- Cathode
- Anode
- Interconnect
CO₂ Capture Technologies

CO₂ Separation and Capture

Absorption
- Chemical
  - MEA
  - Caustic
  - Other
- Physical
  - Selexol
  - Rectisol
  - Other

Adsorption
- Adsorber Beds
  - Alumina
  - Zeolite
  - Activated C
- Regeneration Method
  - Pressure Swing
  - Temperature Swing
  - Washing

Cryogenics

Membranes
- Gas Separation
  - Polyphenyleneoxide
  - Polydimethylsiloxane
- Gas Absorption
  - Polypropylene
- Ceramic Based Systems

Microbial/Algal Systems
CO₂ Capture Using Amine-Based System

Absorber

Exhaust Gas

Blower

MEA makeup

Flue Gas

Pump

Cooler

rich-cool

lean-cool

H-Ex*

rich-hot

Lean-hot

MEA Storage

Flash

CO₂ product

Cooler

Regenerator

Reboiler

Spent Sorbent

Pump
### Combustion Controls

- **Furnace Type:** Tangential
- **NOx Control:** Low NOx Burners

### Post-Combustion Controls

- **NOx Control:** Hot-Side SCR
- **Particulates:** Cold-Side ESP
- **SO2 Control:** Wet FGD
- **SO2/NOx:** None
- **CO2 Control:** Absorption - MEA

### By-Product Management

- **Recovery:** None
- **Fly Ash Disposal:** mixed w/ Landfill
- **CO2 Storage:** Depleted Oil Wells

---

**Plant Diagram**

[Diagram showing the process flow of a plant with various stages and routes labeled.]
Cost of CO₂ Avoided

![Cost of CO₂ Avoided](image)

- Mitigation cost ($/ton CO₂ avoided)
- Cumulative probability

- Deterministic
- Probabilistic
Application to Major Power Generation Options

Power Generation Technologies

Fuel
- Coal
  - Combustion-based
  - Gasification-based
- Natural Gas
  - Direct Combustion
  - Gas Reforming

Oxidant
- Air
- Oxygen

Technology
- Simple Cycle
  - Pulverized Coal Gas Turbines
- Combined Cycle
  - Gas Turbines
  - Coal Gasification
  - Fuel Cells
  - Other
IGCC Plant with CO$_2$ Capture

Configure Plant

Set Parameters

Get Results

Gasification Options

Gasifier: KRW
Oxidant: Oxygen
Gas Cleanup: Hot

Post-Combustion Controls

NOx Control: SCR

Solids Management

Slag: Landfill
Sulfur: Sulfur, Landfill, Sulfuric Acid

Plant Diagram
NGCC Plant with CO$_2$ Capture
To Succeed We Need ...
Recipe for Success

- Talented Researchers
- DOE Collaboration
- Continuity of Funding

*(blend in equal parts)*
Comments and Discussion
Configure Base Plant

**Combustion Controls**
- Furnace Type: Tangential
- NOx Control: Low NOx Burners

**Post-Combustion Controls**
- NOx Control: None
- Particulates: None
- SO2 Control: None
- SO2/NOx: None

**Solids Management**
- Recovery: None
- Fly Ash Disposal: mixed w/ Landfill

**Plant Diagram**
Select SO₂ Controls

**Combustion Controls**
- Furnace Type: Tangential
- NOx Control: Low NOx Burners

**Post-Combustion Controls**
- NOx Control: Hot-Side SCR
- Particulates: Cold-Side ESP
- SO₂ Control: Wet FGD
- SO₂/NOx: None

**Solids Management**
- Recovery: None
- Fly Ash Disposal: mixed w/ Landfill
Set Coal Properties

Current Coal
Name: Appalachian Medium Sulfur
Rank: Bituminous
Source: Model Default Coals

Composition (wt% as fired) and Higher Heating Value (Btu/lb)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Save As User-Defined</th>
<th>Add to Favorites</th>
<th>Use Default Ash Properties</th>
<th>Edit Ash Properties</th>
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<td>2 Carbon</td>
<td>73.31</td>
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<td>3 Hydrogen</td>
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<tr>
<td>5 Chlorine</td>
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<td>6 Sulfur</td>
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<td>7 Nitrogen</td>
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<td>8 Ash</td>
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<td>9 Moisture</td>
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<td>10 Cost ($/ton)</td>
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</table>

Favorite Coals
Name: Wyoming Powder River Basin
Rank: Sub-Bituminous

Browse All Coals
Use This Coal
Remove From Favorites
View Ash Properties
## Set Base Plant Parameters

### Configure Plant
- Overall Plant
- Coal Properties
- Base Plant

### Set Parameters
- Furnace Factors
- Emission Constraints
- NOx Control
- Particulate Control
- SO2 Control
- Solid Waste Mgmt

### Get Results

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<tr>
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<th>Units</th>
<th>Unc</th>
<th>Value</th>
<th>Calc</th>
<th>Min</th>
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<tr>
<td>Cooling System</td>
<td>% MWg</td>
<td></td>
<td>1.8</td>
<td></td>
<td>0</td>
<td>2</td>
<td>1.8</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>% MWg</td>
<td></td>
<td>1.3</td>
<td></td>
<td>0</td>
<td>4</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Specify Input Uncertainties

**Uncertainty Editor**

<table>
<thead>
<tr>
<th>Plant Parameter</th>
<th>Units</th>
<th>Value</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum SO2 Removal Efficiency</td>
<td>%</td>
<td>95</td>
<td>90</td>
<td>99</td>
</tr>
</tbody>
</table>

**Distribution:**
- Triangular
- Normal
- Uniform
- Fractiles

**Description:**
Triangular(a,b,c) describes a triangular-shaped distribution where the values a, b, and c represent the minimum, most likely and maximum values, respectively.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Min</th>
<th>Mode</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.9000</td>
<td>1.000</td>
<td>1.023</td>
</tr>
<tr>
<td>Triangular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniform</td>
<td>85.50</td>
<td>95.00</td>
<td>97.18</td>
</tr>
</tbody>
</table>

**Uncertainty Tools: Untitled**

**Uncertainty Areas**
- Base Plant
- Air Preheater
- Solid Waste Mgmt.
- NOx Control
- Particulate Control
- SO2 Control
- SO2/NOx Control

- Select All
- Select None

**Sample Size:** 50

**Sampling Method:** Median LHS
## Results: Plant Mass Flows

### Stack Gas Component

<table>
<thead>
<tr>
<th>Stack Gas Component</th>
<th>Flow Rate (ton/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>1771</td>
</tr>
<tr>
<td>O2</td>
<td>149.0</td>
</tr>
<tr>
<td>H2O</td>
<td>252.7</td>
</tr>
<tr>
<td>CO2</td>
<td>454.3</td>
</tr>
<tr>
<td>CO</td>
<td>0.0</td>
</tr>
<tr>
<td>HCl</td>
<td>2.395e-02</td>
</tr>
<tr>
<td>SO2</td>
<td>1.300</td>
</tr>
<tr>
<td>SO3</td>
<td>3.137e-02</td>
</tr>
<tr>
<td>NO</td>
<td>0.2053</td>
</tr>
<tr>
<td>NC2</td>
<td>1.656e-02</td>
</tr>
<tr>
<td>Ash</td>
<td>3.313e-02</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2629</strong></td>
</tr>
</tbody>
</table>

### Overall Flow Component

<table>
<thead>
<tr>
<th>Overall Flow Component</th>
<th>Flow Rate (ton/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>166.5</td>
</tr>
<tr>
<td>Lime/Limestone</td>
<td>9.729</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.3460</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>176.6</strong></td>
</tr>
<tr>
<td>Bottom Ash</td>
<td>3.997</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>9.638</td>
</tr>
<tr>
<td>FGD Waste</td>
<td>17.82</td>
</tr>
<tr>
<td>By-Product Ash</td>
<td>0.0</td>
</tr>
<tr>
<td>By-Product Gypsum</td>
<td>0.0</td>
</tr>
<tr>
<td>By-Product Sulfur</td>
<td>0.0</td>
</tr>
<tr>
<td>By-Product Acid</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>31.45</strong></td>
</tr>
</tbody>
</table>
## Results: Plant Cost Summary

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capital Cost (M$)</th>
<th>Capital Cost ($/kW)</th>
<th>O&amp;M Cost (M$/yr)</th>
<th>Revenue Required (M$/yr)</th>
<th>Revenue Required (mills/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 NOx Control</td>
<td>24.04</td>
<td>52.97</td>
<td>3.160</td>
<td>5.645</td>
<td>1.892</td>
</tr>
<tr>
<td>2 TSP Control</td>
<td>19.67</td>
<td>43.34</td>
<td>1.739</td>
<td>3.565</td>
<td>1.194</td>
</tr>
<tr>
<td>3 SO2 Control</td>
<td>64.13</td>
<td>141.3</td>
<td>10.13</td>
<td>17.66</td>
<td>5.817</td>
</tr>
<tr>
<td>4 Comb. SOx/NOx</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5 Subtotal</td>
<td>107.8</td>
<td>237.6</td>
<td>15.03</td>
<td>26.87</td>
<td>9.003</td>
</tr>
<tr>
<td>6 Base Plant</td>
<td>437.7</td>
<td>964.2</td>
<td>58.29</td>
<td>99.73</td>
<td>34.69</td>
</tr>
<tr>
<td>7 Total</td>
<td>545.5</td>
<td>1202</td>
<td>73.32</td>
<td>126.6</td>
<td>43.70</td>
</tr>
</tbody>
</table>

Costs are in constant 1996 dollars.
Probabilistic Results
IECM Capabilities

- A comprehensive modeling framework to estimate the performance, emissions, and cost of coal-based power plants
- A tool for comparing alternative options on a systematic basis, including the effects of uncertainty in performance and cost
A Hierarchy of Models for Technical and Policy Analysis

- Detailed (mechanistic) models or codes for specific processes or components
- Design options for a single facility (tech. feasibility, cost, efficiency, emissions)
- Multi-facility (or multi-sector) optimization or simulation (dynamic)
- Integrated assessment models (including measures of impacts)
Conventional Process Modeling
(Deterministic Simulation)
Parameter Uncertainty
Distributions

NORMAL

UNIFORM

LOGNORMAL

TRIANGULAR

BETA

FRACTILE
Stochastic Simulation

Parameter Uncertainty Distributions → Stochastic Modeler → Process Model → SAMPLING LOOP → Results
Example of a Probabilistic Result

Cumulative Probability

Total Capital Requirement ($/kW)

Probabilistic Result
Expert Judgments on Key Model Parameters

Sorbent Sulfur Loading

Gasifier Fines Carryover

Carbon Retention in Bottom Ash

Sorbent Sulfur Loading, wt-%

Fines Carryover, % of coal feed

Carbon Retention in Bottom Ash, % of coal feed carbon
Calculated Plant Efficiency

Cumulative Probability

Net Plant Efficiency (%, HHV basis)

- Probabilistic
- Deterministic
Total Plant Capital Cost

Total Plant Capital Cost

Cumulative Probability

Total Capital Requirement ($1994/kW)

DOE (1989)

Probabilistic

524 MW net

524 MW net
Value of Targeted Research

Input Uncertainty Assumptions
- Base Case Uncertainties
- Reduced Uncertainties in Selected Performance and Cost Parameters

Levelized Cost of Electricity, Constant 1989 mills/kWh
NETL 2001 Award Ceremony

March 28, 2001

Silver Award

to
Mercury Control Performance and Cost Model Team

- Developed a model that evaluated mercury control options for 12 different coal-fired plant configurations which EPA used in their final determination to regulate mercury.