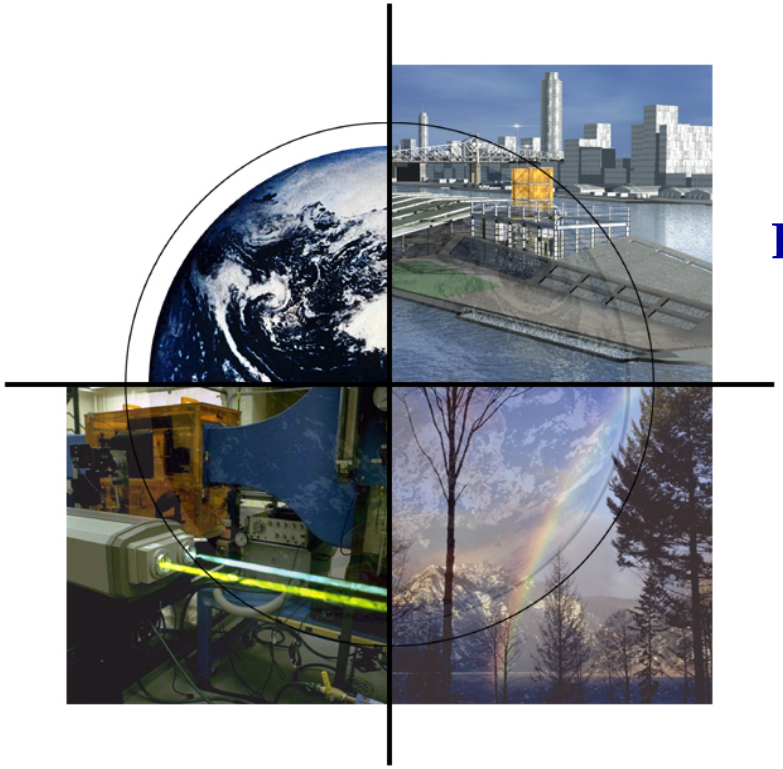
Virtual Engineering for Power Plant Design



Stephen E. Zitney

Director, Collaboratory for
Process & Dynamic Systems Research

stephen.zitney@netl.doe.gov

Virtual Environments, Virtual Worlds, and Applications

November 1, 2007

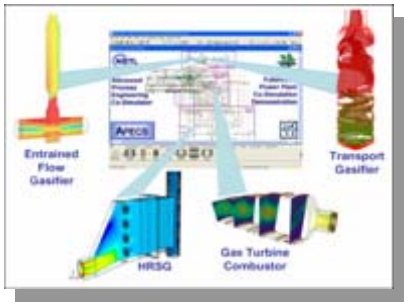
Iowa State University

Ames, IA

National Energy Technology Laboratory
Morgantown, WV

Outline of Presentation

- **Introduction**
  - Fossil Energy Outlook
  - DOE's *FutureGen* Plant
- **Power Plant Design Tools and Challenges**
- **Virtual Engineering**
  - Goals and Objectives
  - Workflow Example
  - Software Requirements
- **APECS/VE-Suite Integration**
  - Current Status
  - *FutureGen* Application
- **Future R&D Efforts**
- **Concluding Remarks**

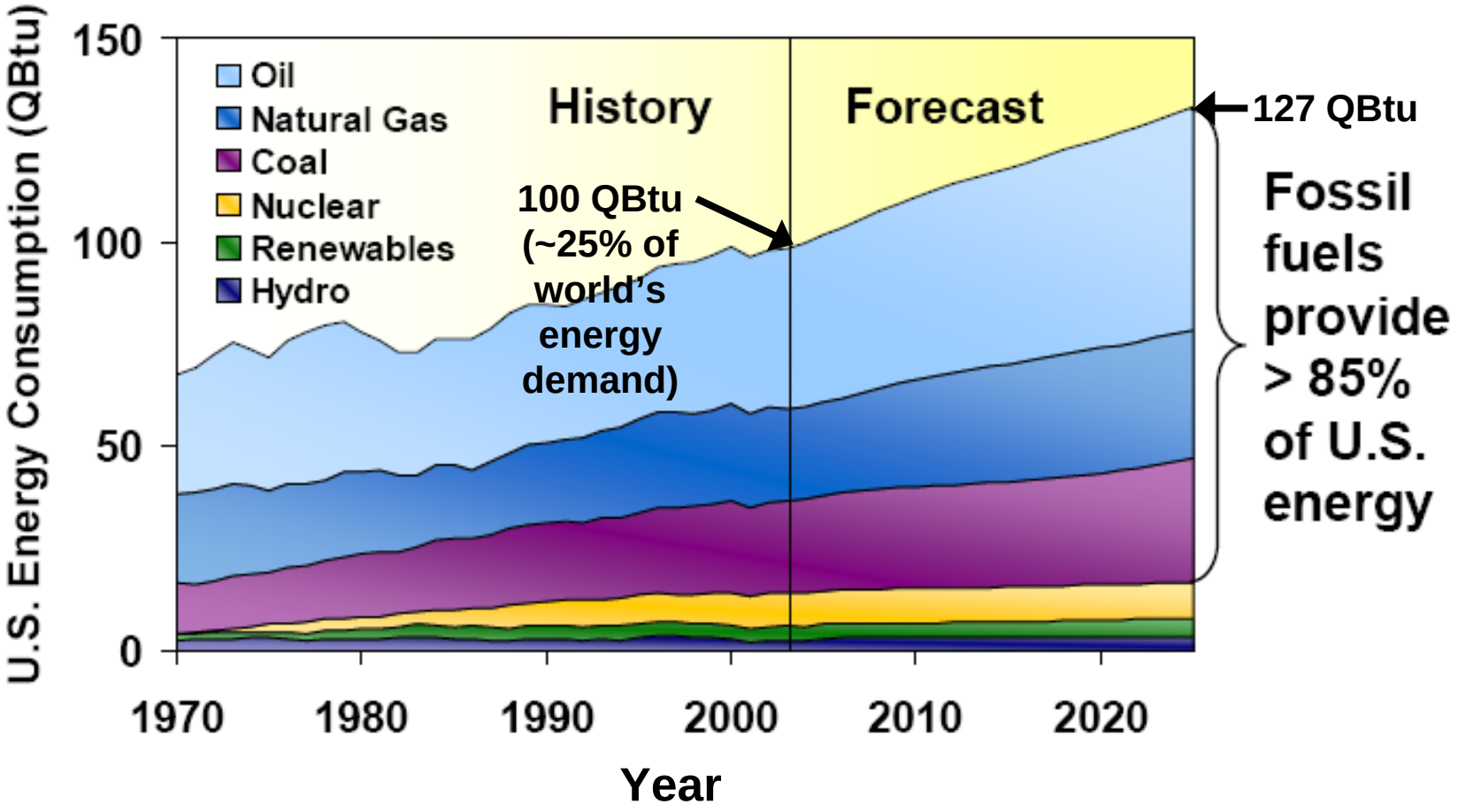


APECS Co-Simulation

APECS/VE Collaboration

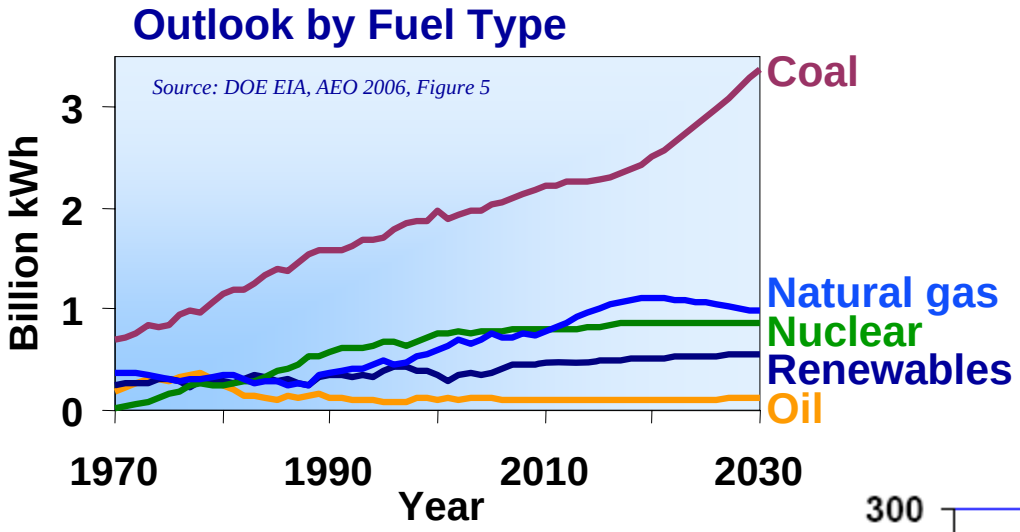
***FutureGen* Plant**

Growing U.S. Energy Demand
Fossil Fuels Dominate Energy Consumption



DOE EIA, Annual Energy Outlook 2005, Figure 3

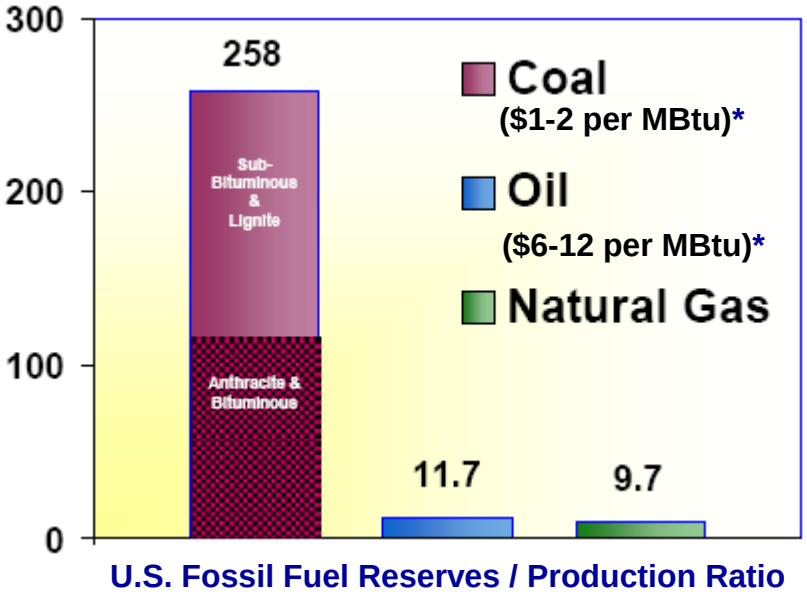
U.S. Electricity Generation



Coal dominates electricity generation

Over 50% of U.S. electricity from coal

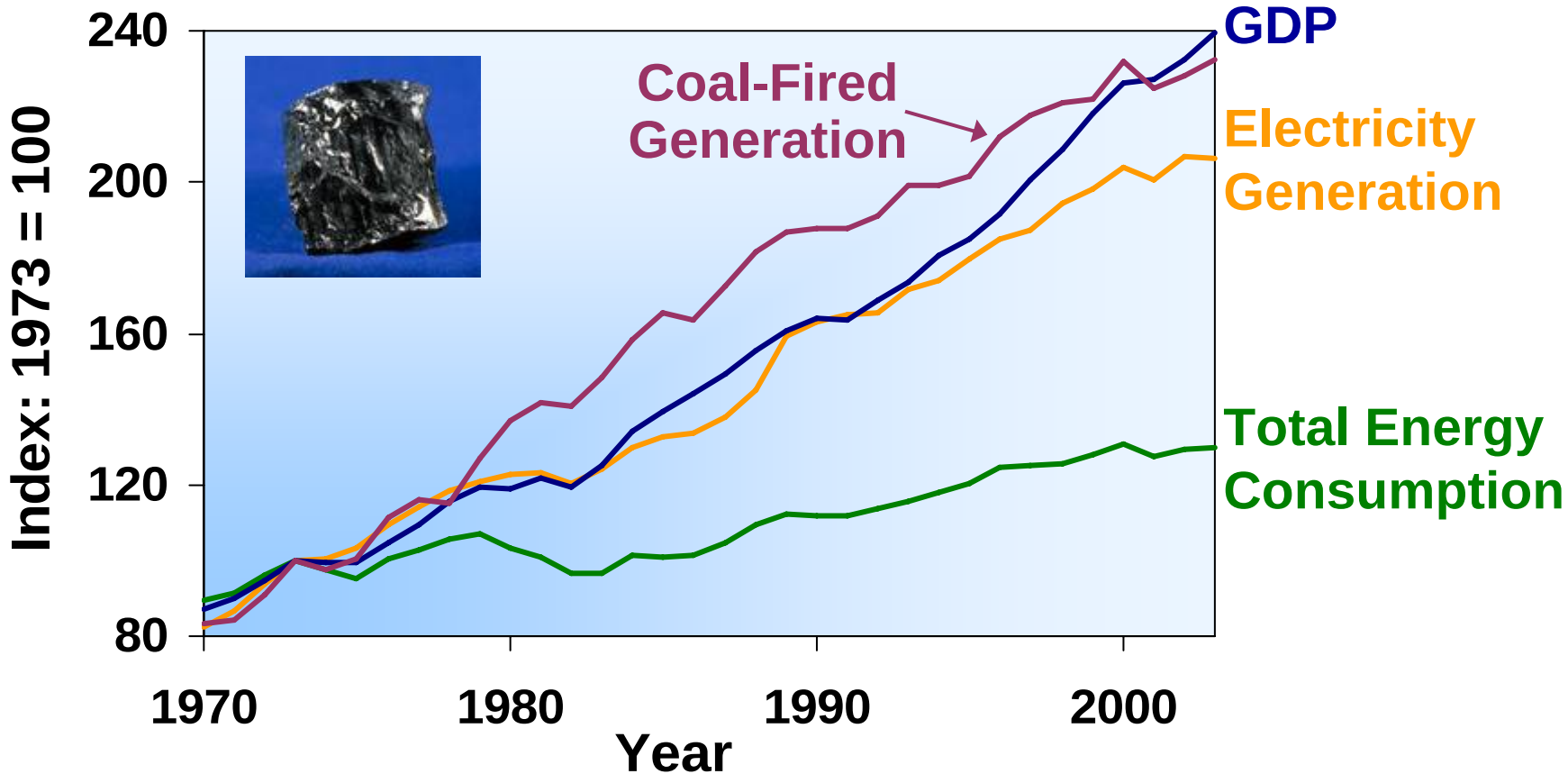
Over 250 year supply of coal at current demand levels



Sources: BP Statistical Review, June 2004, - for coal reserves data - World Energy Council; EIA, Advance Summary U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, September 22, 2004 - for oil and gas reserves data

**Source – The Future of Coal, MIT, 2007*

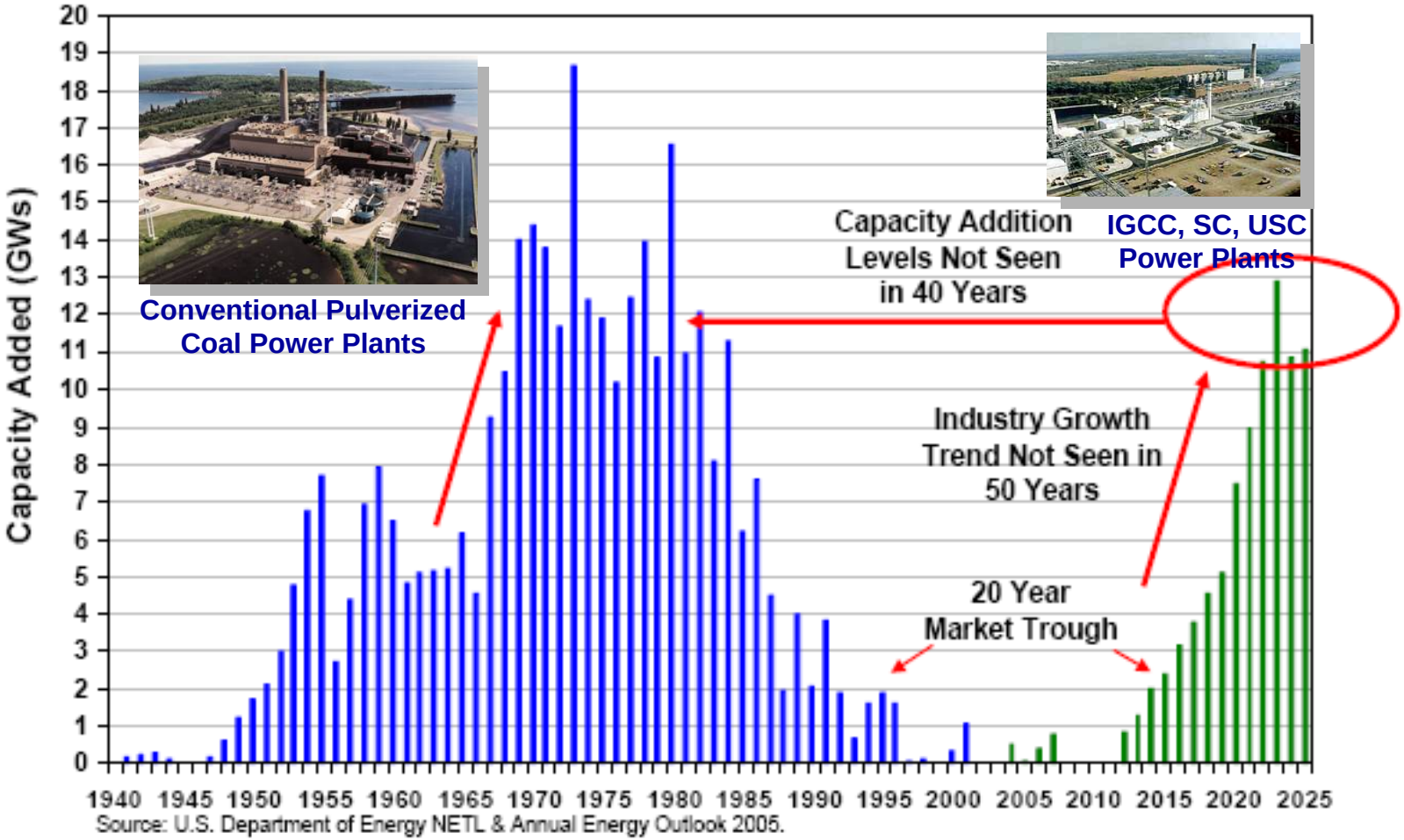
U.S. Coal Use Linked to Economic Growth



Coal-fired generation and GDP have grown at nearly the exact same pace over last 30 years

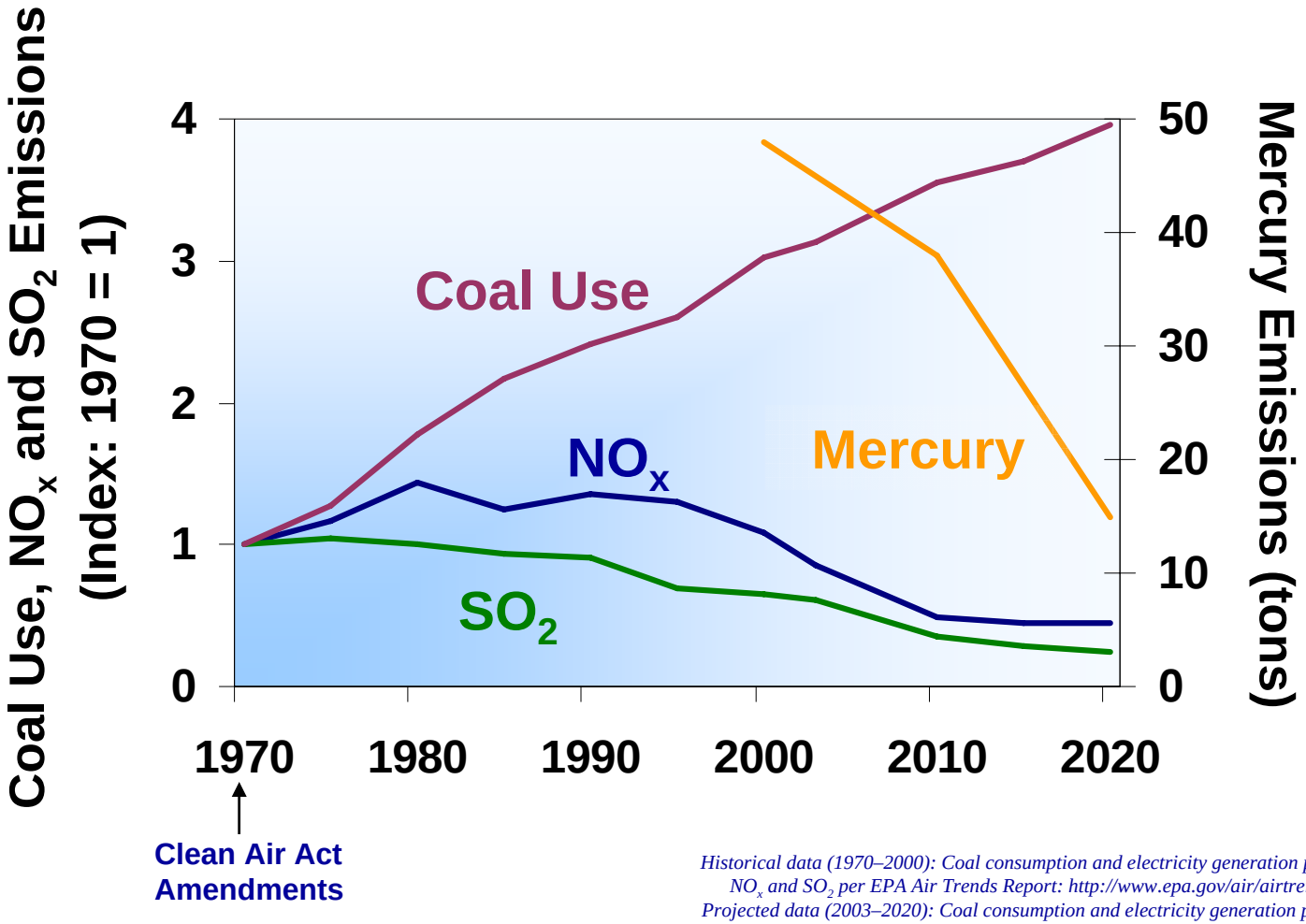
GDP: U.S. DOC, Bureau of Economic Analysis
Energy & Electricity: EIA, Annual Energy Review 2003

U.S. Coal-Fired Power Generation
Capacity Additions, 1940-2025



Air Emission Trends and Projections

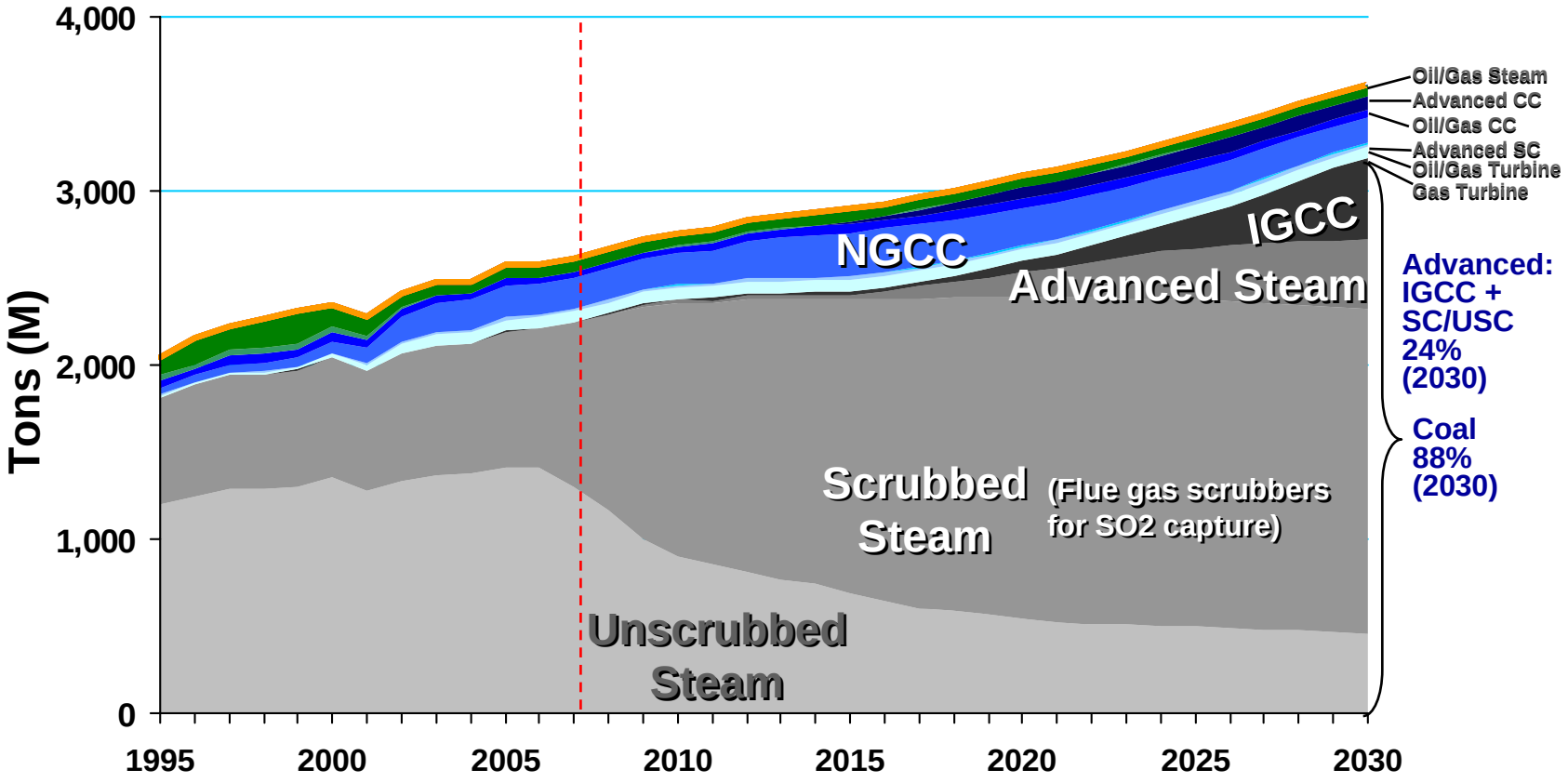
Annual U.S. Air Emissions and Coal Use



Historical data (1970–2000): Coal consumption and electricity generation per DOE EIA, AER 2003
NO_x and SO_2 per EPA Air Trends Report: http://www.epa.gov/air/airtrenda/econ-emissions.html
Projected data (2003–2020): Coal consumption and electricity generation per DOE EIA, AEO 2005
NO_x and SO_2 per EPA projections under CAIR: http://www.epa.gov/interstateairquality/charts.html
Mercury per EPA Clean Air Mercury Rule

U.S. CO_2 Emissions from Fossil Power Generation

Forecast - Annual Energy Outlook 2006



Need for CO_2 Capture and Storage (CCS) as Coal Dominates CO_2 Emissions from Fossil Power Generation

Annual Energy Outlook 2006, reference case

Fossil Energy Power Generation
Industry Challenges

- ***Short-term:*** **Manage existing fleet of combustion power plants**
  - Plant optimization and control
  - Improve efficiency and economics
  - Reduce carbon emissions

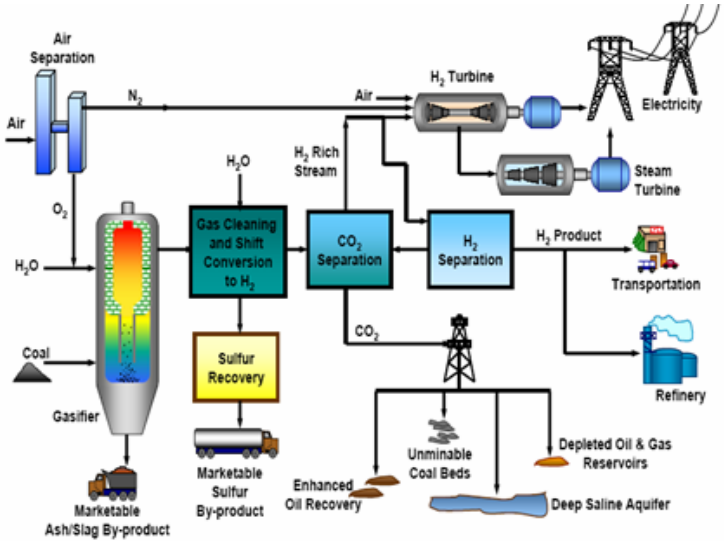
Combustion Power Plant

- ***Long-term:*** **Design next generation of advanced power plants**
  - High-efficiency, zero-emission
  - CO_2 capture and storage (CCS)
  - Gasification-based
    - Integrated gasification combined cycles (IGCC)
    - Polygeneration systems
      - Power, steam, H_2, chemicals

IGCC Power Plant

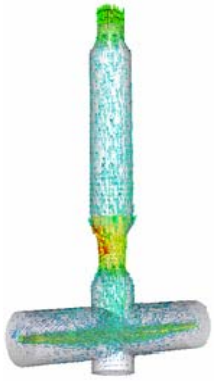
U.S. DOE *FutureGen* Power Plant

- 10-year, $1B DOE project
- Design, build, and operate commercial-scale, coal-fired, gasification-based plant
- Co-produce hydrogen and electricity (275MWe) with near-zero emissions:
  - Near-zero levels of NOx, SOx, PM, and Hg
  - Capture >90% CO_2
  - Store permanently more than 1M metric tons of CO_2 per year in a deep saline aquifer
- Provide "R&D laboratory" for cutting-edge technologies
- Bring facility on-line by 2012

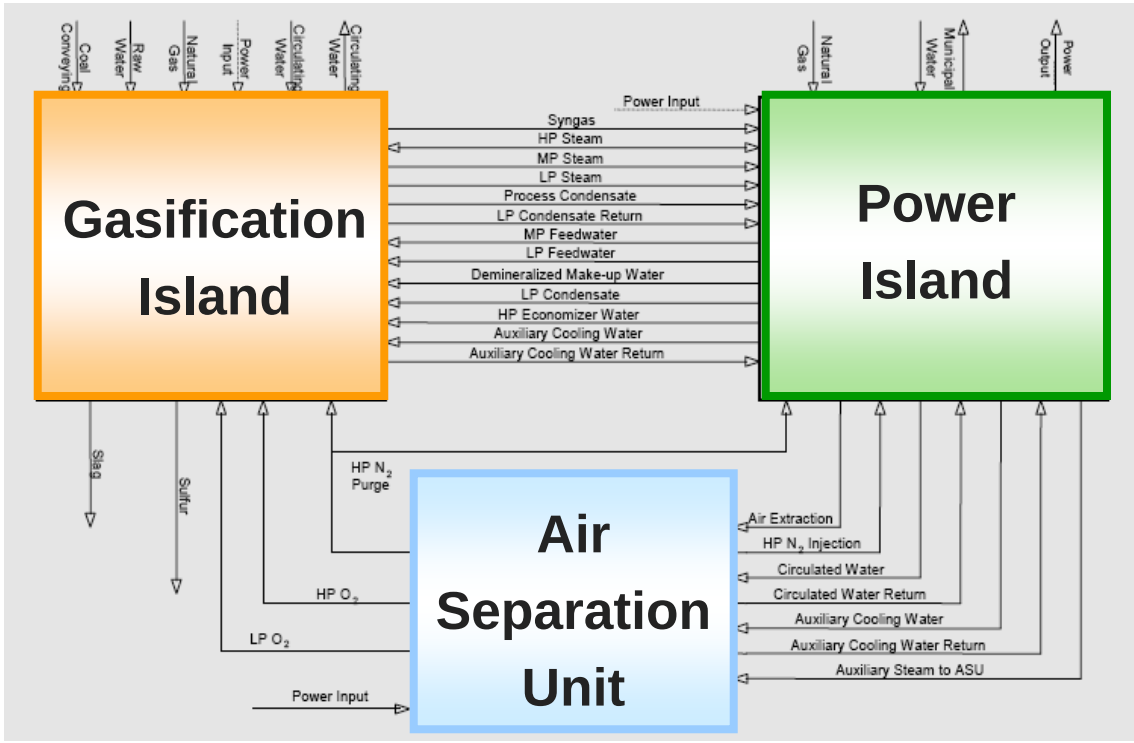


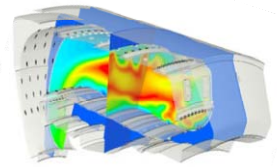
FutureGen Process

FutureGen Power/Hydrogen Production Plant



Gasifier





Syngas-fired Turbine Combustor

Large polygeneration plant with high degree of systems integration, complex components, and no pilot/demo-scale facilities

Excellent candidate for Virtual Engineering!

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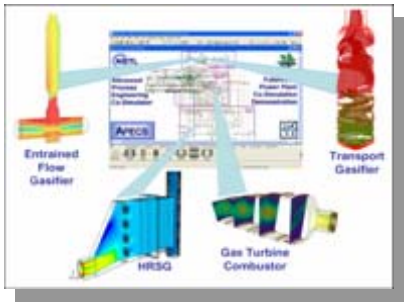


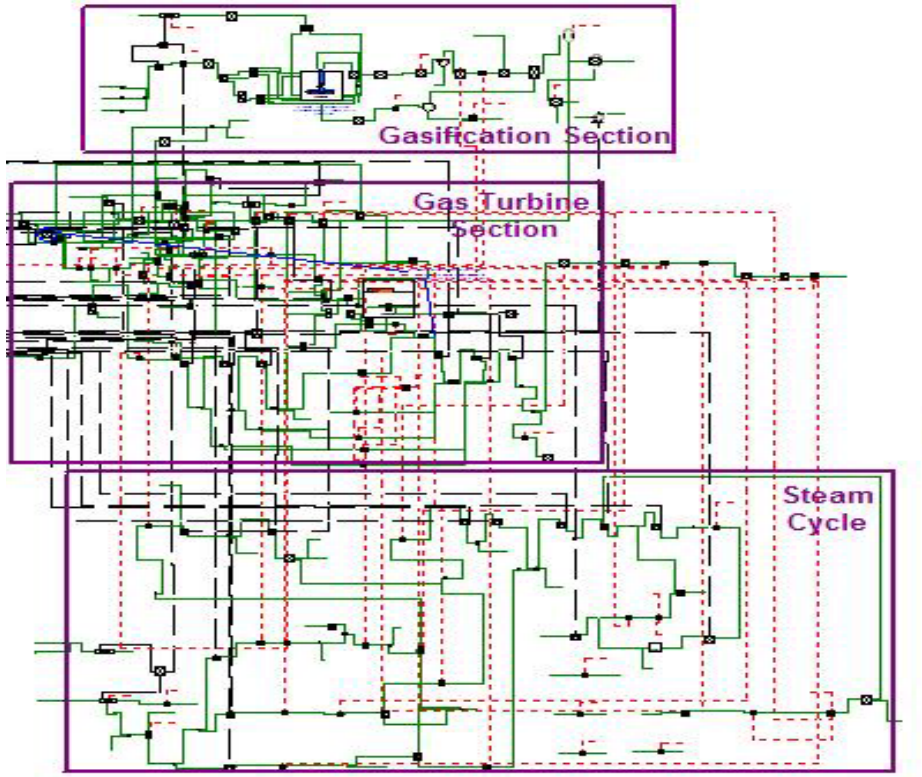
APECS Co-Simulation

APECS/VE Collaboration

***FutureGen* Plant**

Power Plant Design Tools
Process Simulation

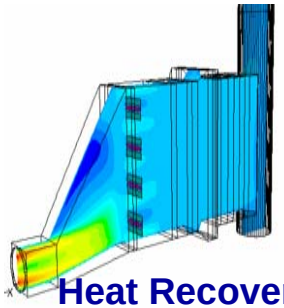
- Power output, overall efficiency, environmental performance
- Hundreds of process units and streams
- Mass and energy balances only
- Lumped-parameter equipment models
- Extensive physical properties database, including solids (coal)
- Recycles, heat and water integration



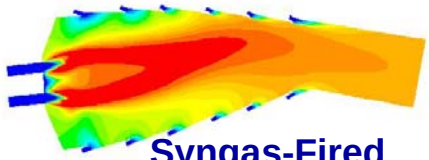
Aspen Plus® process simulation of the *FutureGen* plant

Power Plant Design Tools
Equipment Simulation

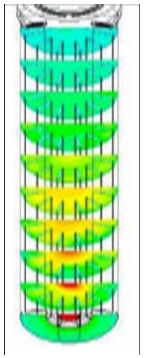
- Equipment design, analysis, and optimization
- Detailed engineering
- Complex geometries
- 2D/3D distributed-parameter models
- Coupled multiphysics: fluid flow, heat/mass transfer, and reactions
- Many physical sub-models: turbulence, combustion, mixing
- Flow field visualization



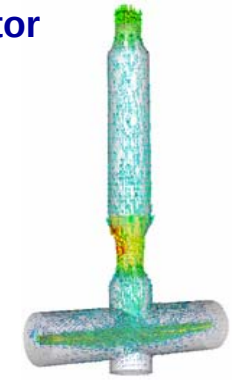
Heat Recovery Steam Generator



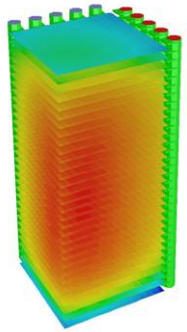
Syngas-Fired Turbine Combustor



Syngas Cooler



Entrained-Flow Gasifier



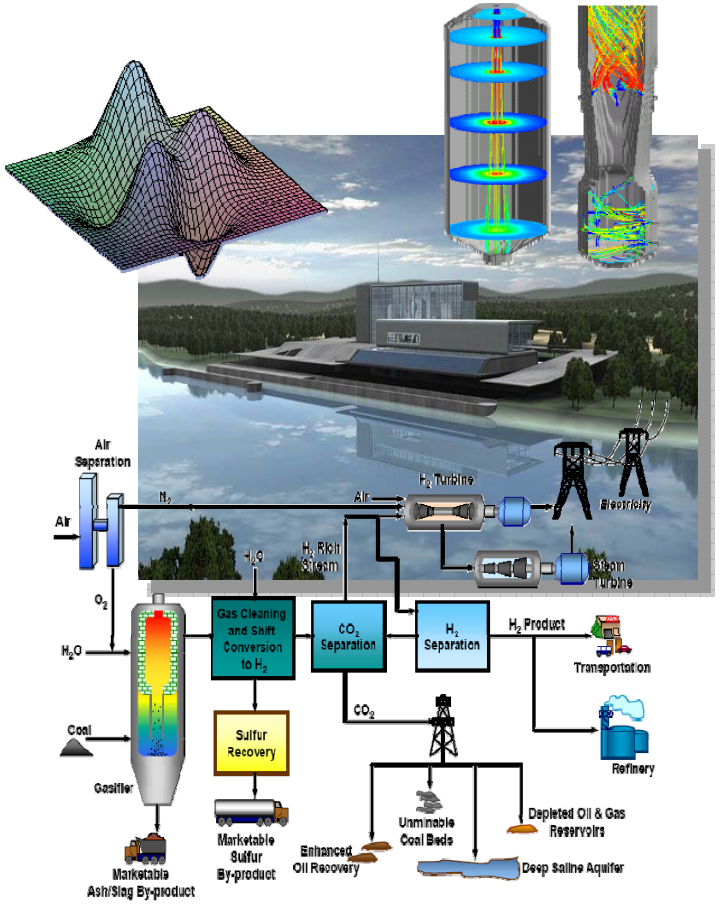
Solid Oxide Fuel Cell Stack

<u>*FutureGen* Equipment Simulations</u>

- **Computational Fluid Dynamics (CFD)**
- **FLUENT® (ANSYS), MFIX (NETL)**

Next-Generation Power Plant Design Challenges

- Large, highly-integrated, and multipurpose systems with heat and water network management
- Wide variety of advanced devices with complex multiphysics and geometries
- Aggressive design goals
  - Zero emissions
  - Unprecedented efficiency
- Limited number of demo plants
- Need to make informed decisions that impact plant performance, cost, and risk



***FutureGen* Power/Hydrogen Generation Plant with CCS**

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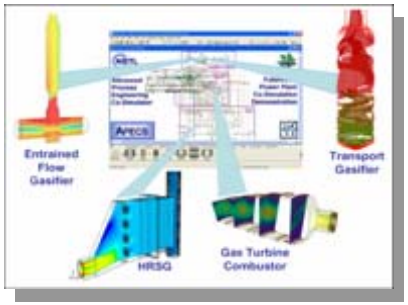


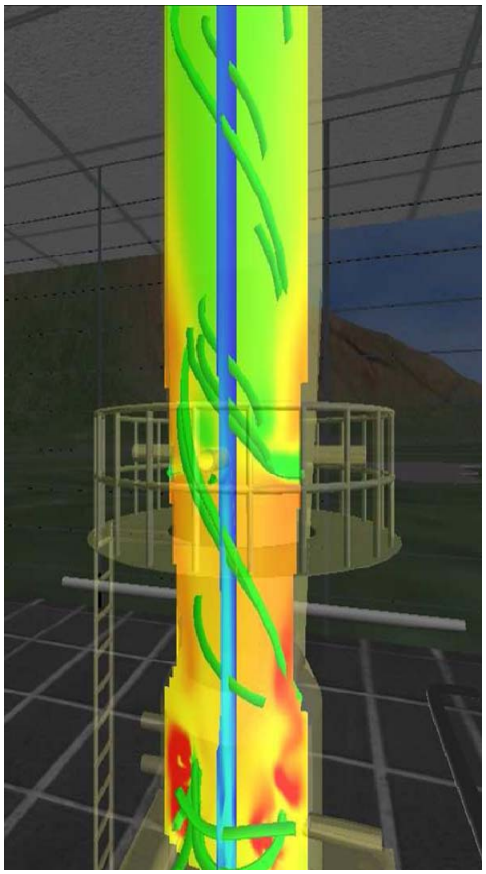
APECS Co-Simulation

APECS/VE Collaboration

***FutureGen* Plant**

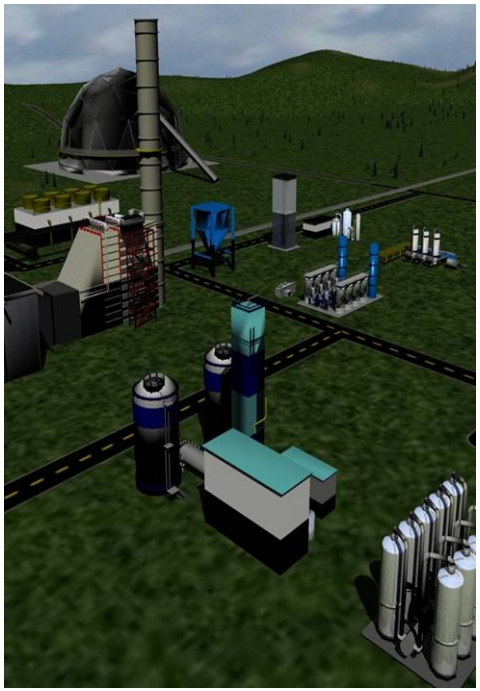
Virtual Engineering for Power Plant Design
Goals

- Provide real-time exploration of proposed designs from a first-person perspective
- Promote collaborative design, as well as communication of advanced power plant concepts to other key stakeholders
- Enable power plant designers to test and develop cutting-edge technologies before they create a pilot plant
- Shorten the design cycle time and allow new technologies to reach production and operation more quickly
- Reduce the cost and risk to develop high-efficiency, zero-emission power generation systems, such as *FutureGen*

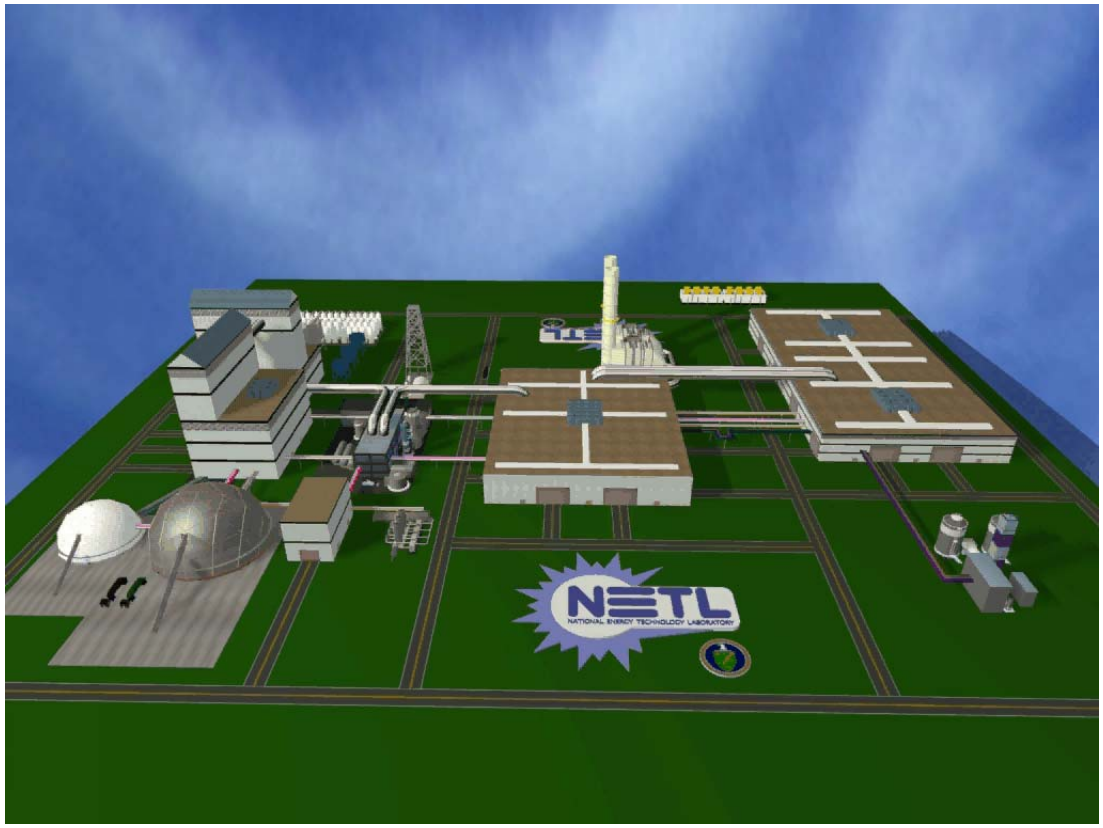


Virtual Engineering for Power Plant Design
Technical Objectives

- Deploy process/equipment co-simulations in a 3D, immersive and interactive, virtual plant walkthrough environment
- Provide a visual interface that is as familiar and engineer-friendly as the real plant
- Let an engineering team alter equipment design parameters (e.g., shape, size) and operating conditions (e.g., pressure) and see effect of changes throughout the plant
- Automate complex virtual engineering workflow across the plant lifecycle, from design to operations



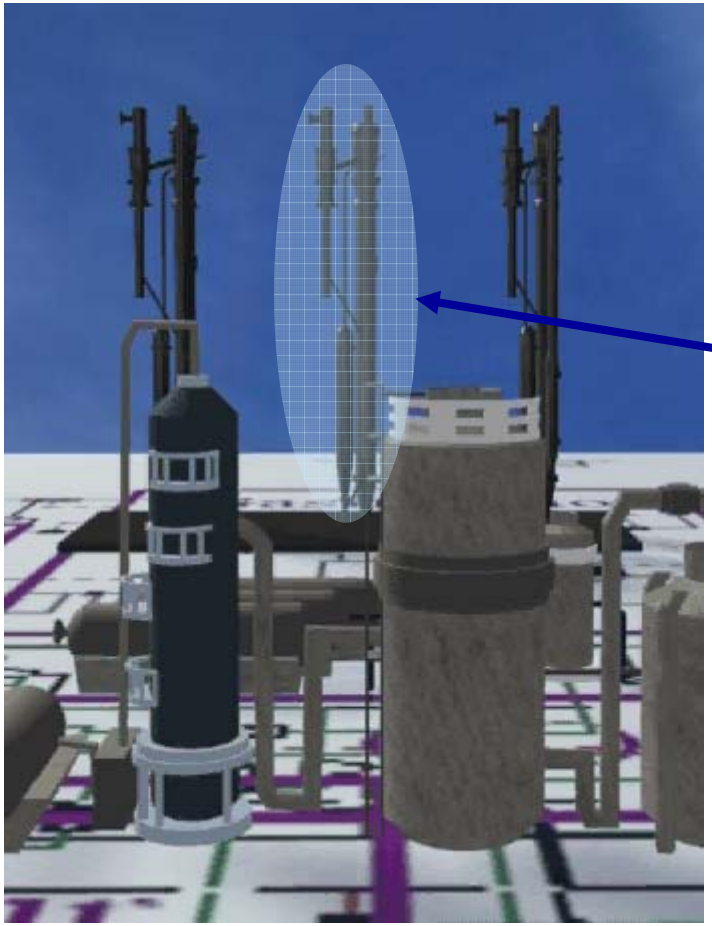
Virtual Engineering for Power Plant Design
Workflow Example



FutureGen **power and hydrogen generation plant with carbon capture and storage**

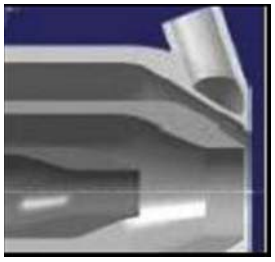
Start with an immersive, interactive, 3D virtual plant walk-through environment that represents the real power plant

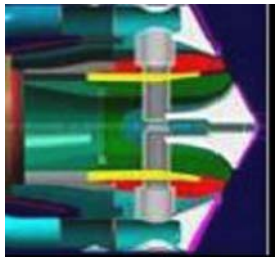
Virtual Engineering for Power Plant Design
Workflow Example



Gasifier

- Navigate through the power plant to focus in on a equipment object representing a key equipment item, such as the coal gasifier
- Adjust feed injector parameters (e.g., angle, diameter, length)

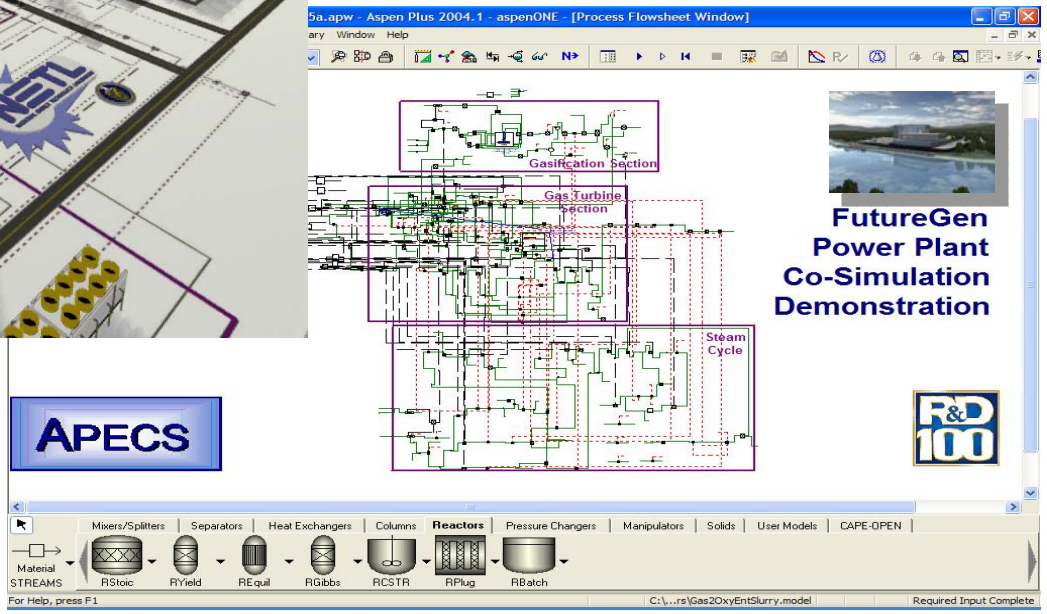




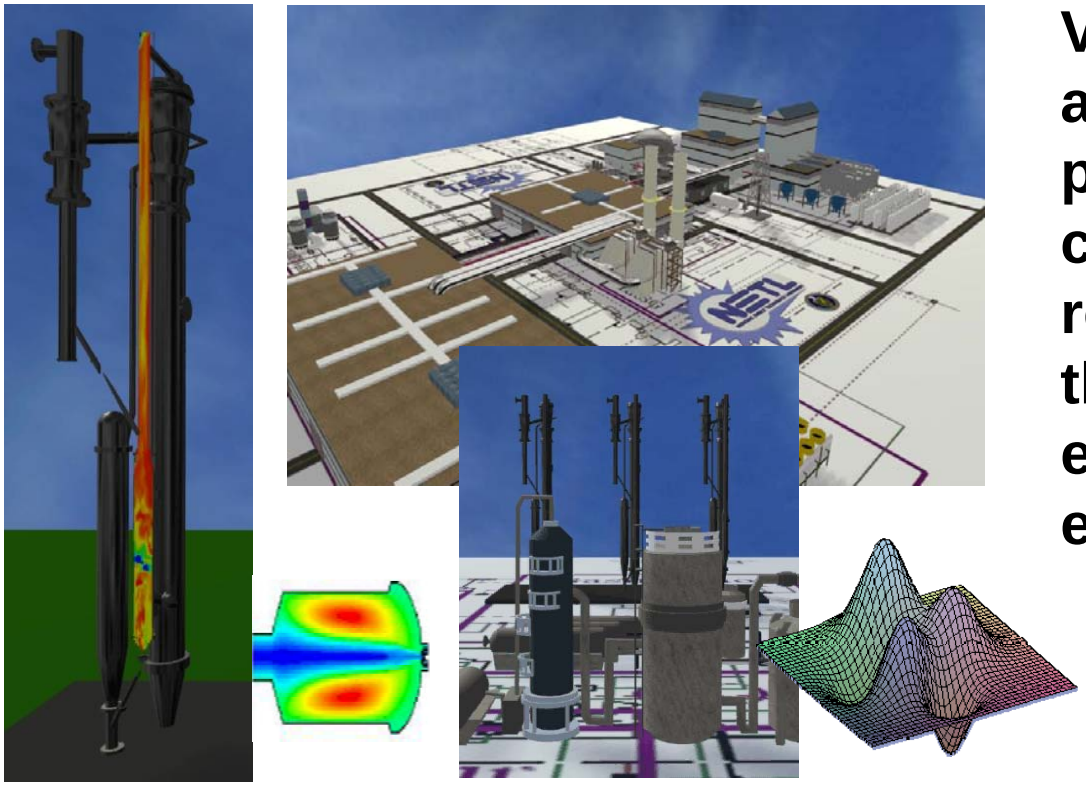
Feed Injector

Virtual Engineering for Power Plant Design
Workflow Example

Run process/CFD co-simulation for the power plant from the VE environment



Virtual Engineering for Power Plant Design
Workflow Example

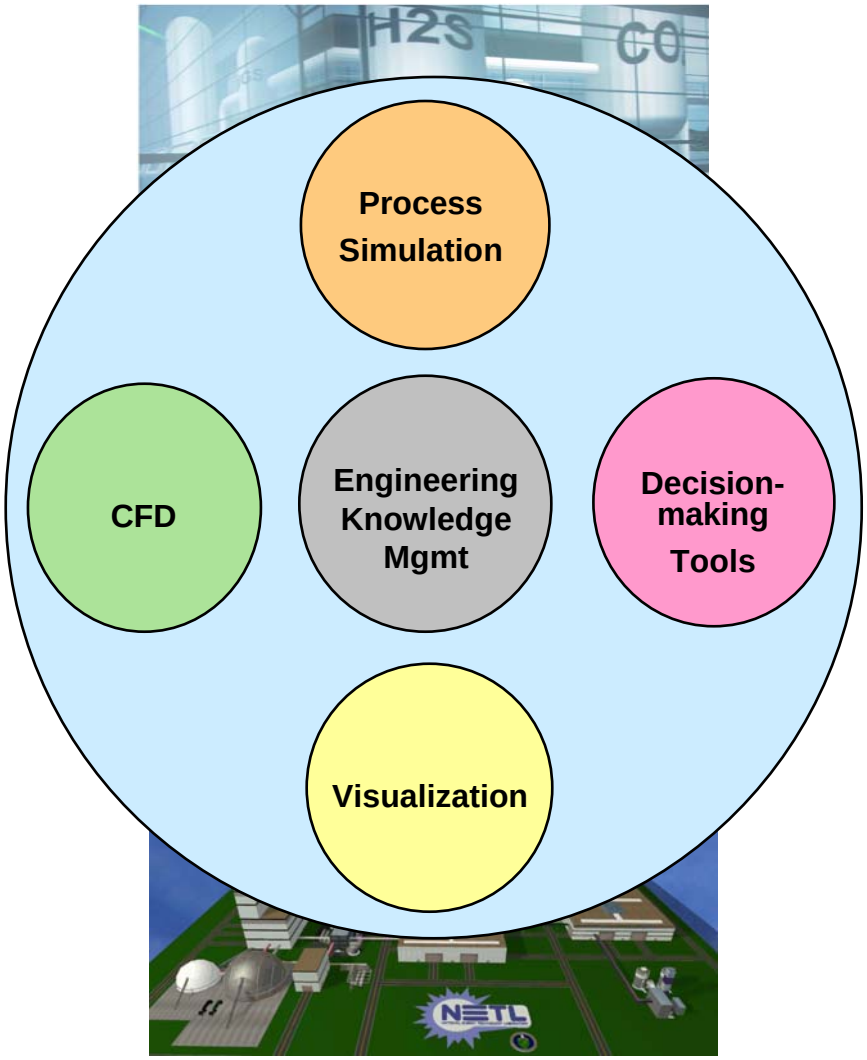


View, analyze, and optimize process/CFD co-simulation results within the virtual engineering environment

Determine what effects the feed injection nozzle changes have on the composition of the syngas produced by the gasifier, as well as the change in overall efficiency and cost of the plant

Virtual Engineering for Power Plant Design
Software Requirements

- Integration of process and equipment simulation tools
- Complexity and knowledge management tools
- Visualization and interaction technology
- Design, analysis, and optimization capabilities
- Costing and decision-making tools



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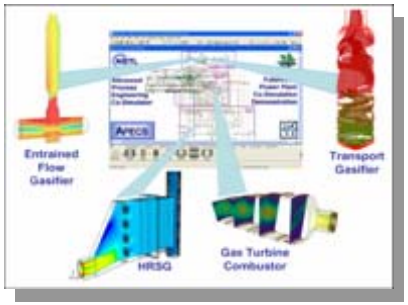


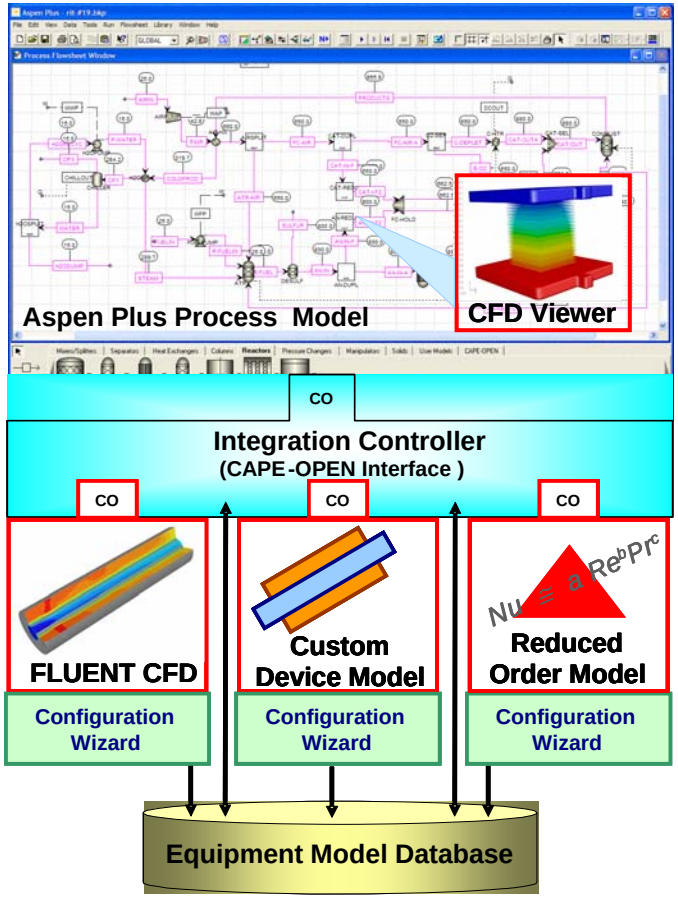
APECS Co-Simulation

APECS/VE Collaboration

***FutureGen* Plant**

Advanced Process Engineering Co-Simulator (APECS)

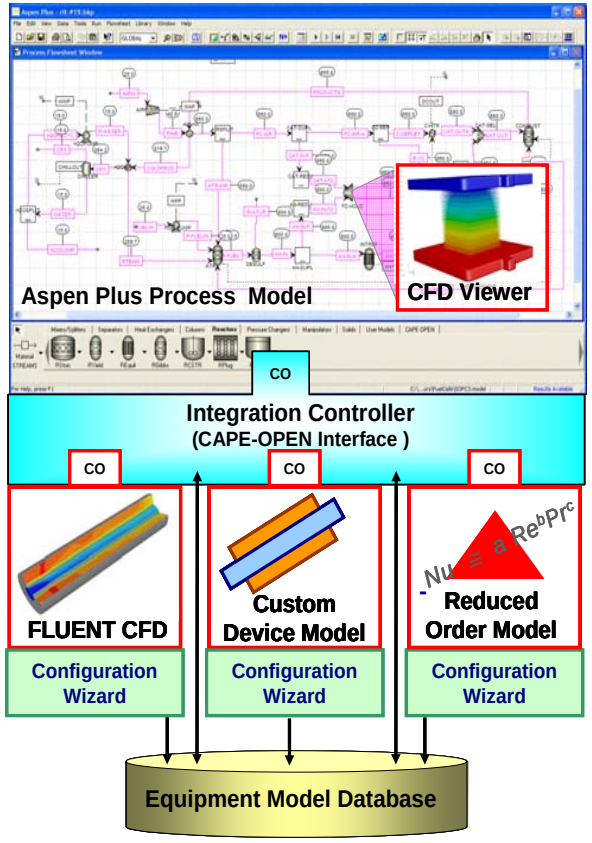
- Co-simulation software framework for integration of:
  - Process simulation
  - Equipment simulations
    - Computational fluid dynamics (CFD)
    - Custom engineering models (CEMs)
    - Reduced-order models (ROMs)
- Enables analysis and optimization of overall plant performance with respect to complex thermal and fluid flow phenomena



APECS Software Integration Framework

APECS Software Components and Features

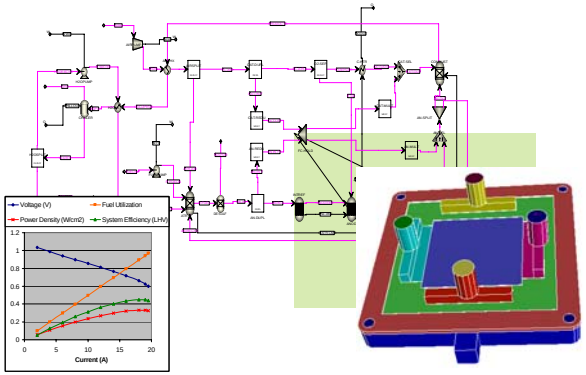
- **Process Simulators**
  - CAPE-OPEN compliant
  - Aspen Plus®, HYSYS®, gPROMS®
- **Equipment Models and Database**
  - CAPE-OPEN compliant
  - CFD: FLUENT®
  - Custom Models: e.g., INDVU
  - ROMs: LR, NN, PCA, POD
- **Integration Controller**
  - CAPE-OPEN v1.0 Interfaces
  - Unit Ops, Phys Props, Reactions
- **Configuration Wizards**
  - FLUENT®, Custom Model, and ROM
- **Solution/Analysis Tools**
  - CAPE-OPEN compliant
  - Hybrid: Speed (ROM), Accuracy (CFD)
  - Stochastic, Multi-objective Optimization
- **Distributed Execution**
  - CAPE-OPEN COM/Corba Bridge
  - Windows/Linux, Serial/Parallel
- **Visualization**
  - CFD Viewer (2D), Paraview (3D)



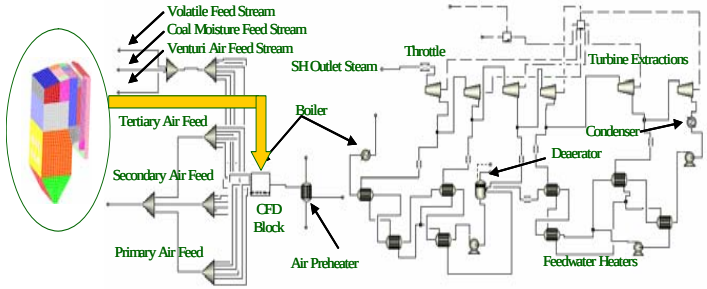
APECS

APECS Power Generation Applications

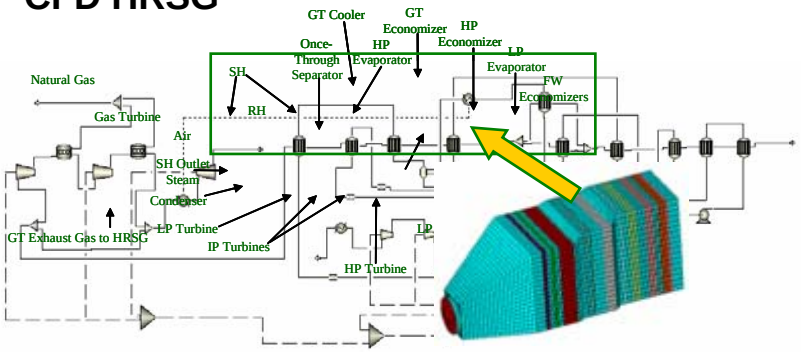
- **Fuel Cell Auxiliary Power Unit (APU) with 3D CFD SOFC**



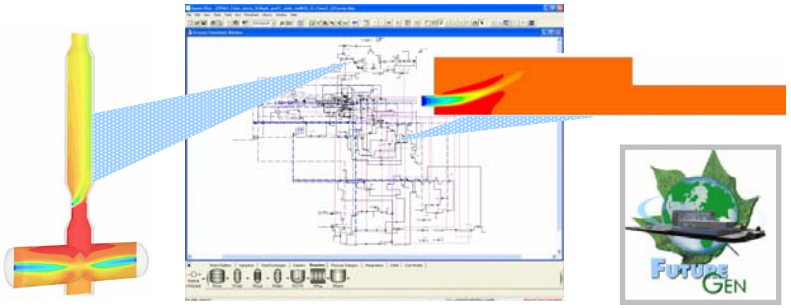
- **ALSTOM Conventional Steam Plant (250MWe) with 3D CFD Boiler**



- **ALSTOM NGCC (250MWe) with 3D CFD HRSG**

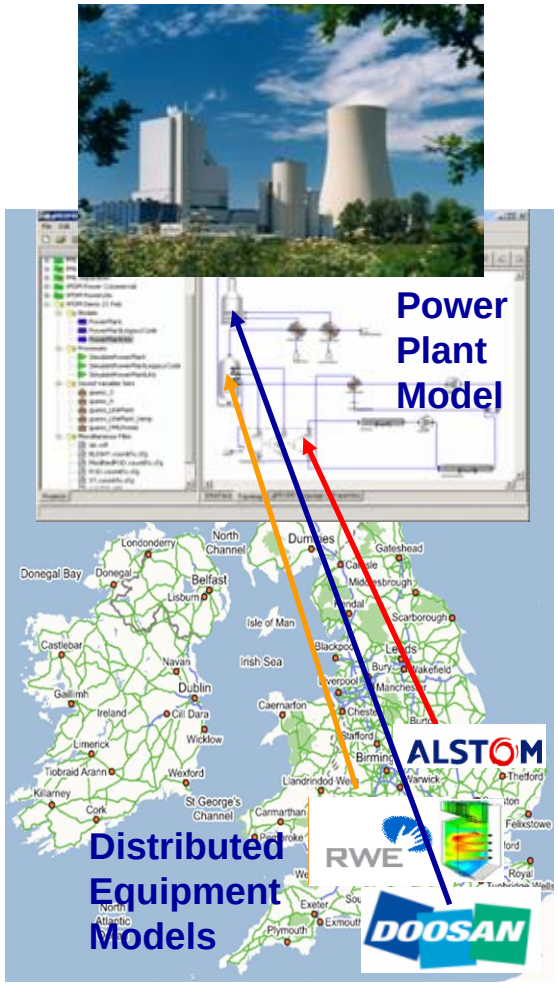


- **FutureGen Plant (250MWe) with 3D CFD Gasifier and 2D CFD Turbine Combustor**



US-UK Collaboration on Virtual Plant Simulation
Fossil Energy R&D

- **Major Goal**
  - Develop compatible process/CFD co-simulation software platforms for application to advanced FE systems
- **Leverages On-Going R&D Projects**
  - US DOE/NETL APECS
  - UK Virtual Plant Demonstration Model (VPDM)
  - CAPE-OPEN Software Standard
- **Didcot A coal-fired power station**
  - Plant: PSE (gPROMS)
  - Equipment Items:
    - Furnace – RWE; APECS for CFD (FLUENT) / ROM (ANN)
    - Boiler – MBEL; Turbine – ALSTOM

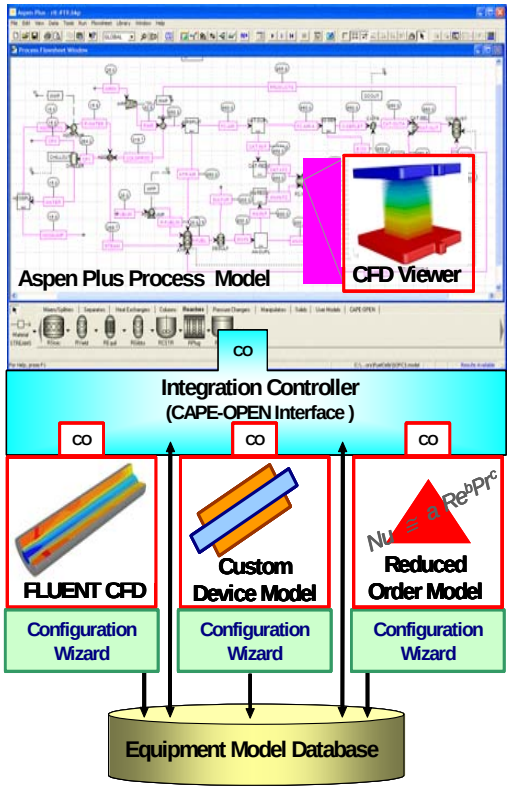


VPDM/APECS Co-Simulation

United States Department of Energy

United Kingdom DEPARTMENT FOR BUSINESS ENTERPRISE & REGULATORY REFORM

Virtual Engineering for Power Plant Design
APECS/VE-Suite Integration



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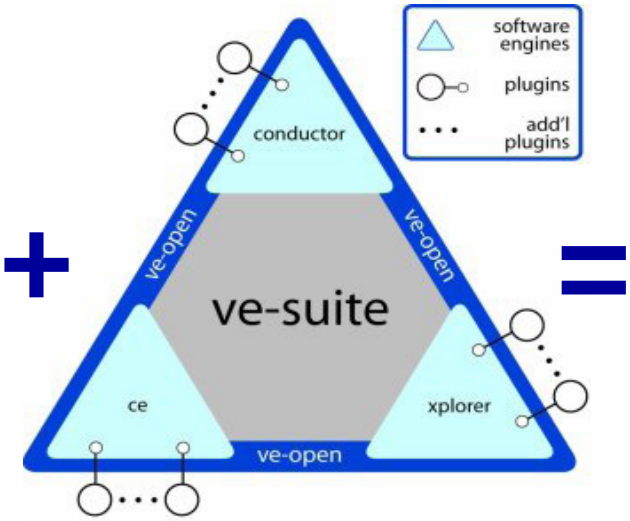

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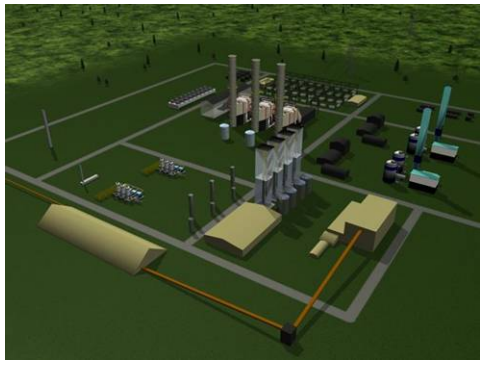
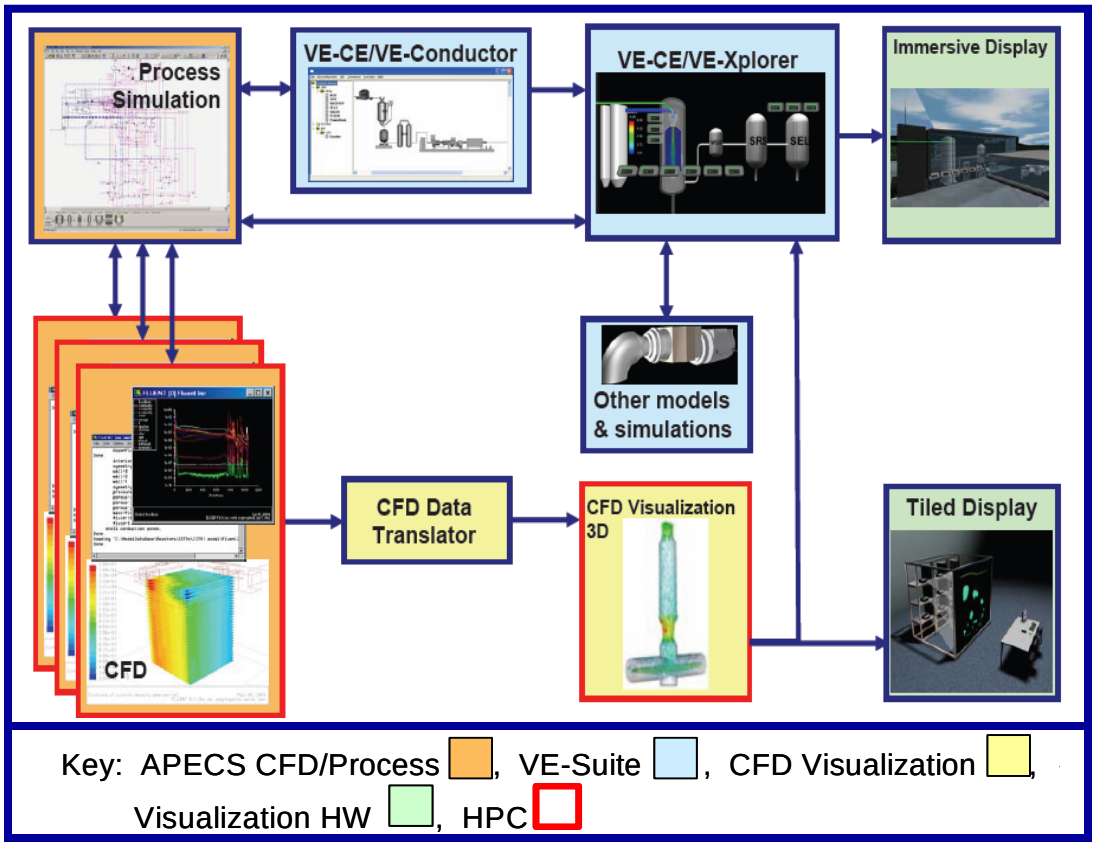


Virtual Plant
Simulation

VE-Suite

Virtual Engineering for Power Plant Design
APECS/VE-Suite Integration – Current Capabilities

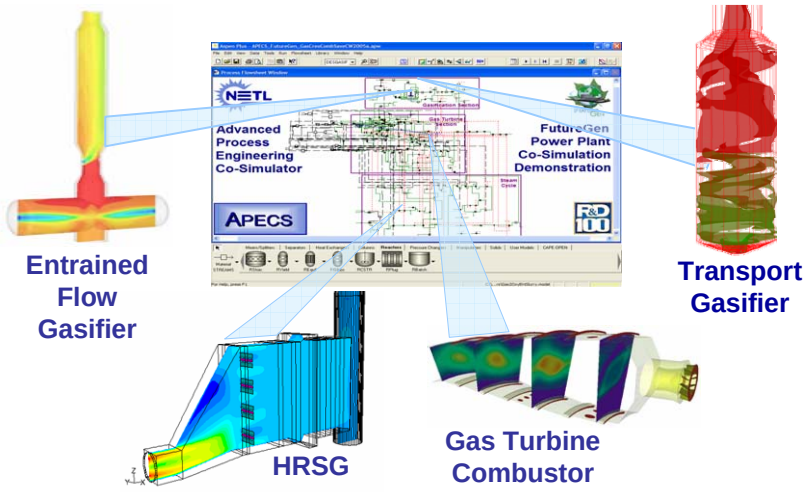
- Blocks/streams in process flowsheet automatically mapped to VE-Conductor
- Default 2D/3D graphical plug-ins of process library models available in VE-Conductor and VE-Xplorer, respectively
- CAD plug-ins used to replace default model icons
- Process simulation and CFD parameters accessible for use in VE-Suite
- Process simulation run-time control provided in VE-Suite
  - Open, Start, Step, Reinitialize, Save



- Process simulation used as single operation in VE-CE
- Process simulation results available in VE-Conductor
- CFD results overlaid on CAD in VE-Xplorer

Virtual Engineering for Power Plant Design
APECS/VE-Suite FutureGen Application

- Plant-wide Aspen Plus® process simulation model
- High-fidelity FLUENT® CFD models for key equipment items (e.g., gasifier)
- NETL's APECS system for process/CFD co-simulation
- VE-Suite for an interactive, user-centered, 3D computer generated VE environment
- APECS/VE-Suite integration for collaborative analysis and optimization of *FutureGen* plant design and operation



Virtual Engineering for Power Plant Design

APECS/VE-Suite FutureGen Application

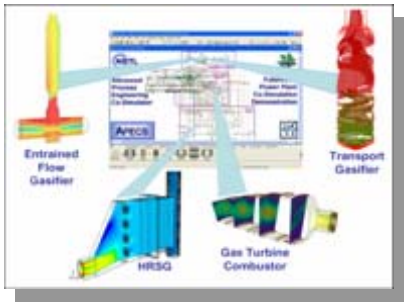
Virtual Engineering for Power Plant Design
APECS/VE-Suite FutureGen Application

- ***FutureGen* will use virtual engineering to:**
  - Understand interactions between individual component technologies and overall plant performance
  - Automate workflow between the detailed and process engineering phases of plant design
  - Aid in engineering decision making including design, construction, operation, and maintenance
  - Explain to the public and other nations how this next-generation technology works

All with very limited demonstration-scale data and physical prototypes

Outline of Presentation

- **Introduction**
  - Fossil Energy Outlook
  - DOE's *FutureGen* Plant
- **Power Plant Design Tools and Challenges**
- **Virtual Engineering**
  - Goals and Objectives
  - Workflow Example
  - Software Requirements
- **APECS/VE-Suite Integration**
  - Current Status
  - *FutureGen* Application
- **Future R&D Efforts**
- **Concluding Remarks**



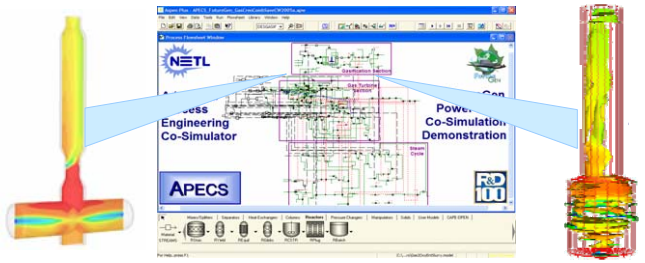
APECS Co-Simulation

APECS/VE Collaboration

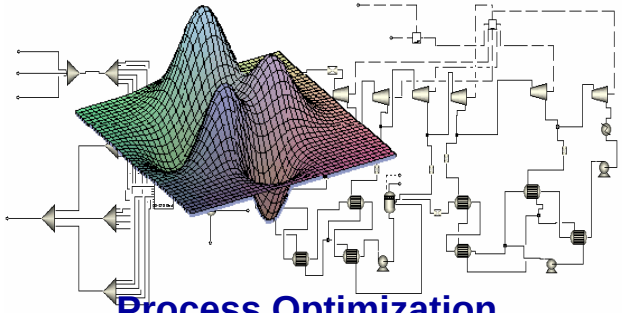
***FutureGen* Plant**

Virtual Engineering for Power Plant Design
Future R&D Efforts

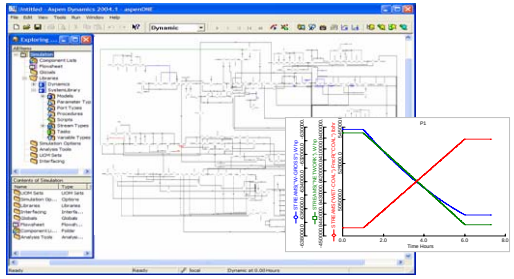
- **Virtual Process/CFD Co-Simulation**
  - Reduced order models (ROMs)
    - Regression, ANN, PCA, POD
    - Network of zones
  - Parallel/distributed computing
- **Optimization**
  - Design optimization
  - Plant-wide, multi-objective optimization
  - Cost estimation
  - Stochastic simulation for risk/uncertainty analysis
- **Dynamic Simulation**
  - Process control
  - Real-time applications



APECS FutureGen



Process Optimization



Dynamic Simulation

IGCC Dynamic Simulator & Research Center
Project Overview

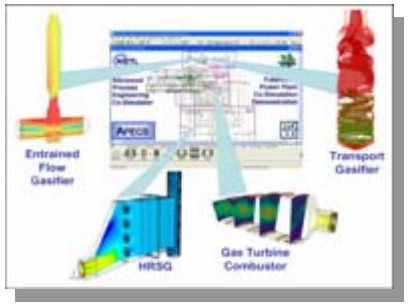
- Full-scope, real-time dynamic simulator for generic IGCC plant
- Dynamic Simulator & Research (DS&R) Center
- WVU's National Research Center for Coal & Energy
- Industry participation and custom, site-specific IGCC dynamic simulators
- Extend to FutureGen and other advanced systems
- Opportunity to incorporate virtual engineering concepts

IGCC DS&R Center

WVU's NRCCE

Concluding Remarks

- U.S. energy challenges are daunting
- Fossil fuels will continue to play a major role for decades
- *FutureGen* is on the pathway to zero-emission, coal-fired power generation
- Continued R&D on APECS/VE-Suite integration is aimed at reducing the time, cost, and risk of developing next-generation power plants
- Optimization challenges exist across the power plant lifecycle and offer considerable potential benefits for collaborative virtual engineering



APECS Co-Simulation

APECS/VE Collaboration

***FutureGen* Plant**

Thank You

Questions?

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