Multi-Pollutant Interactions at Coal-Fired Power Plants

Edward S. Rubin
Carnegie Mellon University
Pittsburgh, Pennsylvania

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Outline of Talk

- Overview of multi-pollutant controls
- Methods to evaluate options
- Effects of multi-pollutant interactions
  - On plant performance
  - On emission control costs
- Conclusions and future work

Emissions of Primary Concern

Acid deposition	SO_2, NO_x
Urban ozone	NO_x
Fine particles	SO_2, NO_x
Air toxics	Hg
Greenhouse gases	CO_2

The Current Policy Context

- *As of 2000* — SO_2 and NO_x reduced to control acid rain
- *By 2004* — NO_x further reduced to control summer ozone
- *By 2007?* — New controls on mercury
- *By 20??* — Likely new reductions of SO_2 and NO_x (for $PM_{2.5}$)
- *By 20??* — CO_2 reductions to control global warming

Recent U.S. Policy Proposals

Proposer	Proposed Emissions Cap			
	SO_2 (million tons)	NO_x (million tons)	Hg (tons)	CO_2
Jeffords Bill (2007)	2.5	1.75	4	1990 Value
Bush/Clear Skies (2018)	3.0	1.7	15	18% red.[a]

[a] Target GHG/GDP by 2012

Some Key Questions

- What technologies are available to reduce these emissions individually? Jointly?
- What interactions affect the feasibility, performance, and cost of multi-pollutant controls?
- Are there any advantages to multi-pollutant control strategies?

Modeling Tools for Technical and Policy Analysis

Detailed models or data for a specific process or component

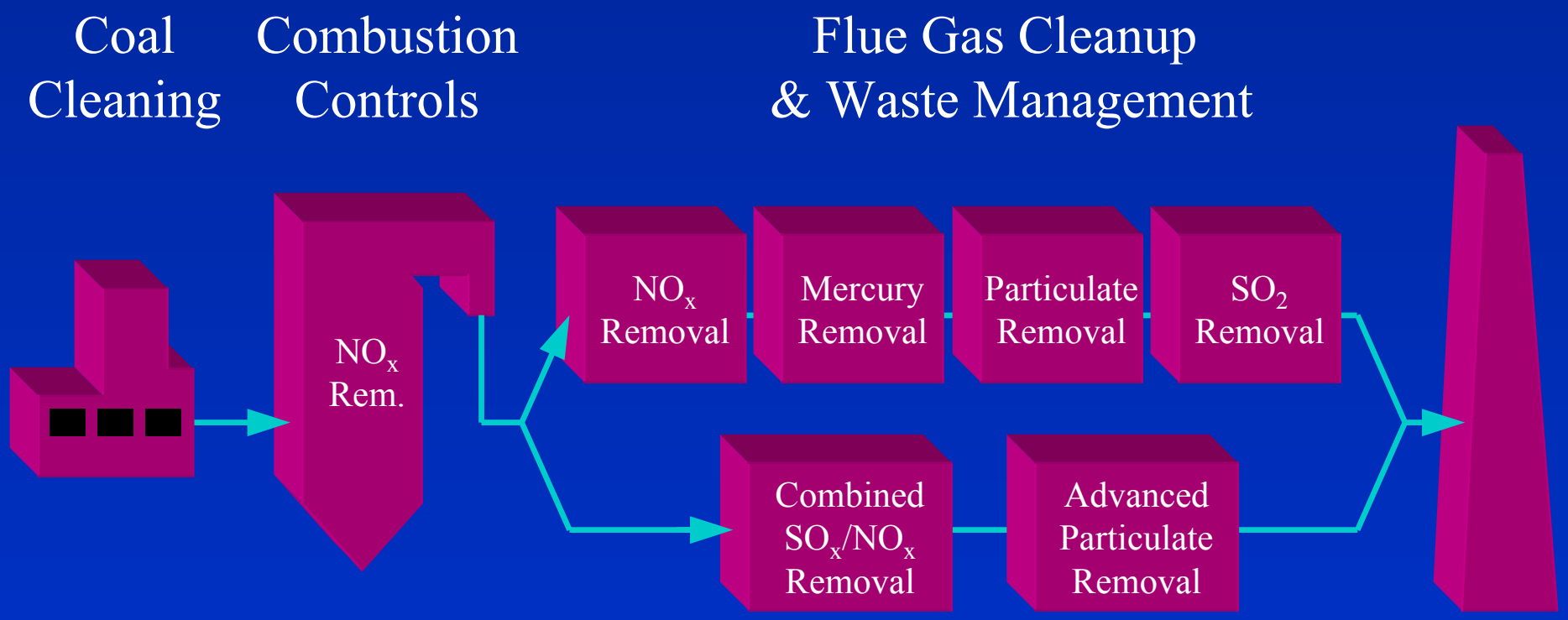
Design options for a single facility (performance, emissions, cost)

National (multi-facility) optimization or simulation (dynamic)

CMU Modeling Approach

- Plant-level Analysis
- Process Technology Models
- Engineering Economic Models
- Systems Analysis Framework
- Advanced Software Capabilities
  - Probabilistic analysis capability
  - User-friendly graphical interface
  - Easy to add or update models

Integrated Environmental Control Model (IECM) Framework



Current IECM Technologies

Furnace Types
- Tangential
- Wall
- Cyclone

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

NO_x Removal
- Hot-side SCR

Mercury Removal
- Carbon injection
- Carbon + water

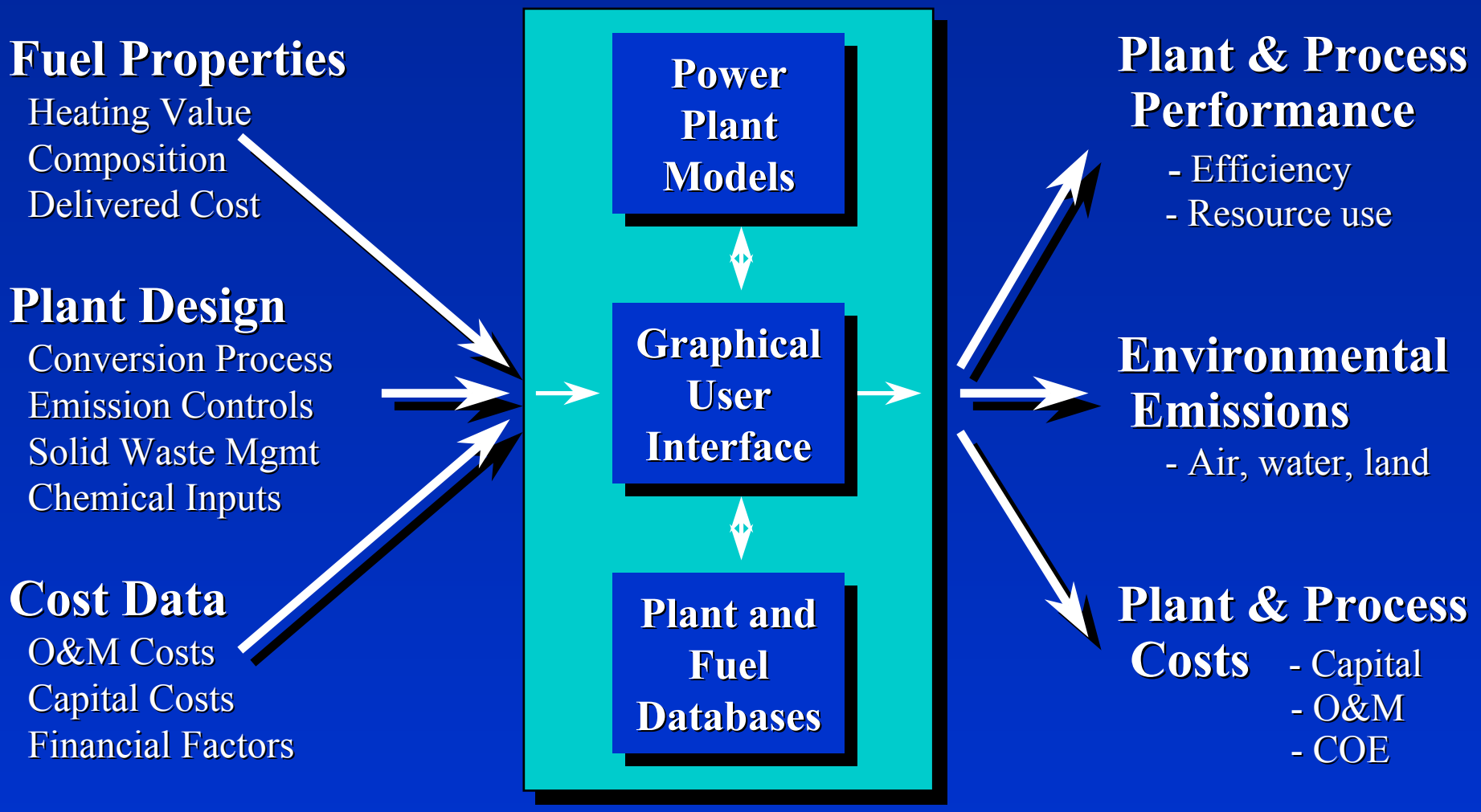
Particulate Removal
- Cold-side ESP
- Fabric filter
  - Reverse Air
  - Pulse Jet

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

Combined SO_2/NO_x Removal
- Copper oxide
- NOXSO

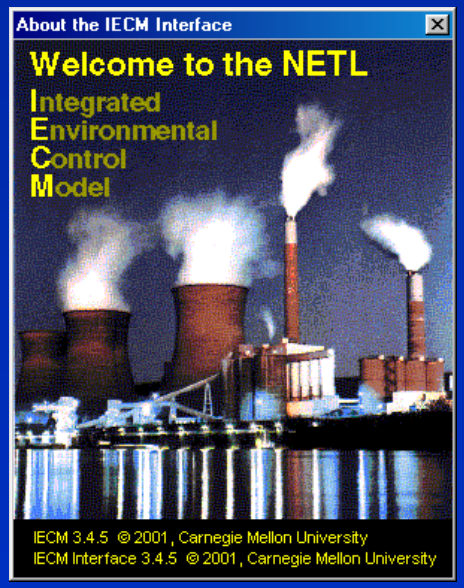
Solids Management
- Ash pond
- Landfill
- Stacking
- Co-mixing
- Byproducts
  - Ash
  - Gypsum
  - Sulfuric Acid

Model Software Package



The IECM is Publicly Available

- **Web Access:**
  - www.iecm-online.com
- **Technical Support:**
  - PED.modeling@netl.doe.gov



IECM User Group

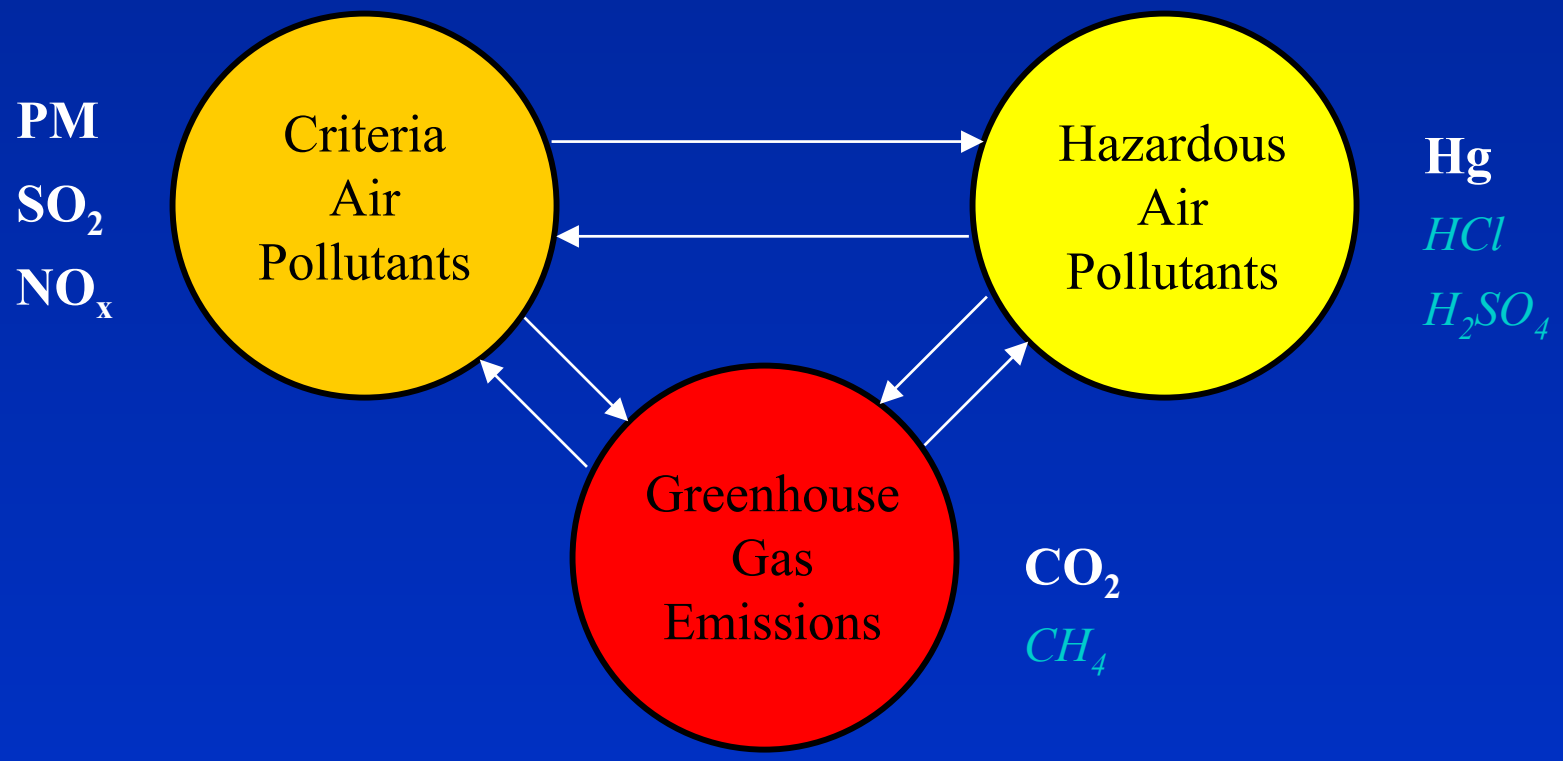
ABB
AEP-SCR Engineering
Airborne Technologies
Akzo Nobel Functional Chem
Alberta Economic Development
Alberta Environment
ALCOA Power Generating, Inc.
Allegheny Energy Supply
Alliant Energy
Alstom Power Inc.
American Electric Power
Apogee Scientific, Inc.
Applied Technology Services
Argonne National Laboratory
ATCO Power
Babcock Borsig Power, Inc.
Babcock & Wilcox Co.
Bechtel Power Corp.
Black & Veatch Corp.
BOC Gases
Boiler Systems Engineering
Canada Environment
Canada Natural Resources
Carnegie Mellon University
Cinergy Power Generation
Clean Energy Int.
Cogentrix Energy, Inc.
CONSOL Energy, Inc.
Consumers Energy
CP&L
CPG, Inc.
CQ, Inc.
Croll-Reynolds
Department of Environmental Prot
Detroit Edison Co.
Diamond Power Specialty Co
Doyen & Associates, Inc.
Duke Engineering & Services.
Duke Fluor Daniel
Dynegy Midwest Generation
Electric Energy, Inc. (EEI)
Electricte de France
Emera Inc.
Emery Recycling Corporation
Enel Produzione
EnerenUE
Energy & Environ Research Corp.
Energy & Environ Strategies
Energy Systems Associates
Energy Technology Enterprises
ENSR, Inc.
Environmental Defense
Envirol & Renewable Energy Syst
EPRI, Palo Alto
Exportech Company, Inc.
FirstEnergy Corp.
Florida Power & Light Co.
FLS Miljo A/S
Fortum Power and Heat Oy
Fossil Energy Research Corp.
Foster Wheeler Development
Foster Wheeler USA Corp.
Fuel Tech, Inc.
General Electric Company
Goodwin Environmental
Great River Energy
Gyeongsang National University
H&W Management Science
Hamon Research Cottrell, Inc.
Harza Engineering
Holland Board of Public Works
IEA Coal Research
Illinois Clean Coal Institute
Illinois Dept. of Natural Resources
Illinois EPA
Illinois Institute of Technology
Indiana Dept. of Env. Mgt.
Intermountain Power Service Corp.
Jack R. McDonald, Inc.
Kansas City Power & Light Co.
KEMA Nederland B.V.
Kinectrics
Korea Electric Power Corporation
Korea Institute of Energy Research
Korea Western Power Co.
Krupp Polysius Corp.
LAB SA
Lehigh University
Lower Colorado River Authority
Mail Station PAß358
McDermott Technology, Inc.
MidAmerican Energy Co.
Minnkota Power Cooperative, Inc.
Mitsubishi Heavy Industries, Ltd.
Mitsui Babcock Energy Ltd.
National Park Service
National Power Plc.
NESCAUM
New Hampshire Dept. of Env. Svc
New Jersey DEP
Nicholson Environmental, Inc.
Niksa Energy Associates
NIPSCO
Niro A/S
North Carolina DENR
North Carolina State Univ
Ontario Power Generation
Pacific Corp.
Parsons Technology
Pavillon Technologies, Inc.
Pennsylvania Electric Assoc
PEPCO
PG&E National Energy Group
Pinnacle West Energy
Potomac Electric Power Co.
PowerGen
PPL Generation, LLC
PPL Montana, LLC
Predict Maintenance Tech
Princeton University
Progress Materials, Inc.
PSEG Power LLC
Public Power Institute
Reaction Engineering Intl
Research Triangle Institute
Rheinbraun Brennstoff GmbH
Sargent & Lundy, LLC
SaskPower
Savvy Engineering, LLC
Scientech
Sierra Pacific Power Co.
Southern Company Services, Inc.
State of New Jersey
Stone & Webster Engineering Corp.
Superior Adsorbents, Inc.
Syncrude
Tampa Electric Co.
Tennessee Valley Authority
Texas Natural Resource Conv Comm
TNO Envit, Energy & Process Innov
TransAlta
TXU Electric
U.S. DOE
U.S. EPA
University of California
University of New Orleans
University of Pittsburgh
URS Corporation
Utah Dept. of Env. Quality
W.L. Gore & Associates, Inc.
Washington Power
Western Kentucky Energy Corp.
Wheelabrator Air PollControl
Wisconsin Dept. of Nat Resources
Wisconsin Electric Power Co.
Wisconsin Energy Corp.
Wisconsin Public Service Corp.
Wisvest-Connecticut, LLC

Model Applications

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

Case Studies of Multi-Pollutant Controls

Multi-Pollutant Interactions



Case Study Plant Parameters

Parameter	Value
Plant Size (gross)	500 MW_g
Heat Rate (gross)	8954 Btu/kWh
Coal Type	High-S Bitum.
Capacity Factor	67%

Base Case Plant Configuration

Configure Plant | Set Parameters | Get Results

Combustion Controls

Furnace Type: Tangential

NOx Control: None

Post-Combustion Controls

NOx Control: None

Mercury: None

Particulates: Cold-Side ESP

SO2 Control: None

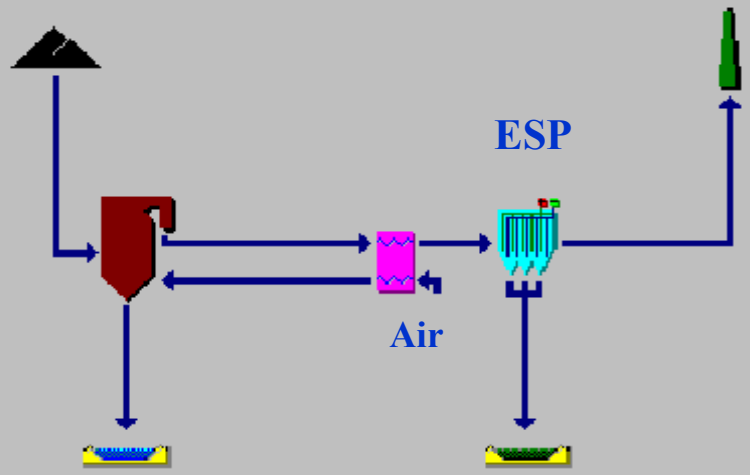
SO2/NOx: None

Solids Management

Recovery: None

Fly Ash Disposal: mixed w/ Landfill

Plant Diagram



Case 1

Reduce SO_2 by

switching to

low-sulfur coal

Coal Composition

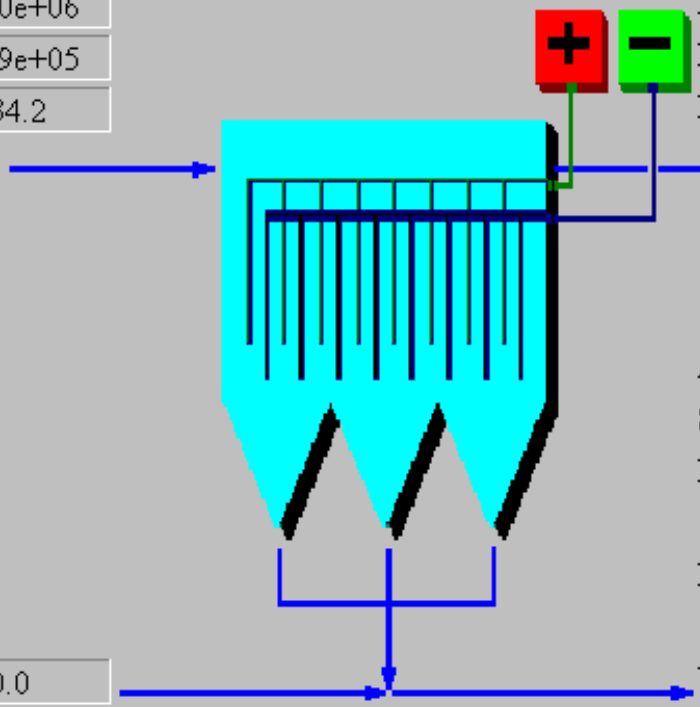
	Original (Ill.#6)	Low-S (PRB)
Carbon (wt%)	61.2	47.9
Hydrogen	4.20	3.40
Oxygen	6.02	10.8
Sulfur	**3.25**	**0.48**
Nitrogen	1.16	0.62
Chlorine	0.17	0.03
Ash	11.0	6.40
Moisture	13.0	30.4
Mercury (ppm,dry)	0.12	0.10
HHV (Btu/lb)	10,900	8,335

Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel (Coal) | Boiler | Air Preheater | NOx Control | Mercury Control | Particulate Control | SO2 Control | Solids Mgmt | Stack

Temperature In (deg. F)	300.0
Flue Gas In (acfm)	1.640e+06
Fly Ash In (ton/yr)	1.069e+05
Mercury In (lb/yr)	234.2

Temperature Out (deg. F)	300.0
Flue Gas Out (acfm)	1.640e+06
Fly Ash Out (ton/yr)	791.1
Mercury Out (lb/yr)	161.6



Ash Removal (%)	99.26
SO3 Removal (%)	25.00
Mercury Removal (%)	31.00
Dry Ash (ton/yr)	1.061e+05
Wet Ash (ton/yr)	1.061e+05
Sluice Water (ton/yr)	0.0

Process Type: Cold-Side ESP

1. Diagram | 2. Capital Cost | 3. O&M Cost | 4. Total Cost | 5. Cost Inputs | 6. Gas Summary

Effect of SO_2 Controls on ESP Performance

Coal Type	SCA (ft^2/acfm)	lb PM emitted/kWh
Original	.310	0.286
Low-S	.295	0.383

Multi-Pollutant Impacts of Emission Control Options (1)

Primary Emission Controlled			Multi-Pollutant Interactions	
Species	**Method**	**% Reduction**	**Pollutant**	**Effect**
SO_2	Low-S coal	83%	PM	34% increase
			Hg	36% increase
			NO_x	30% increase

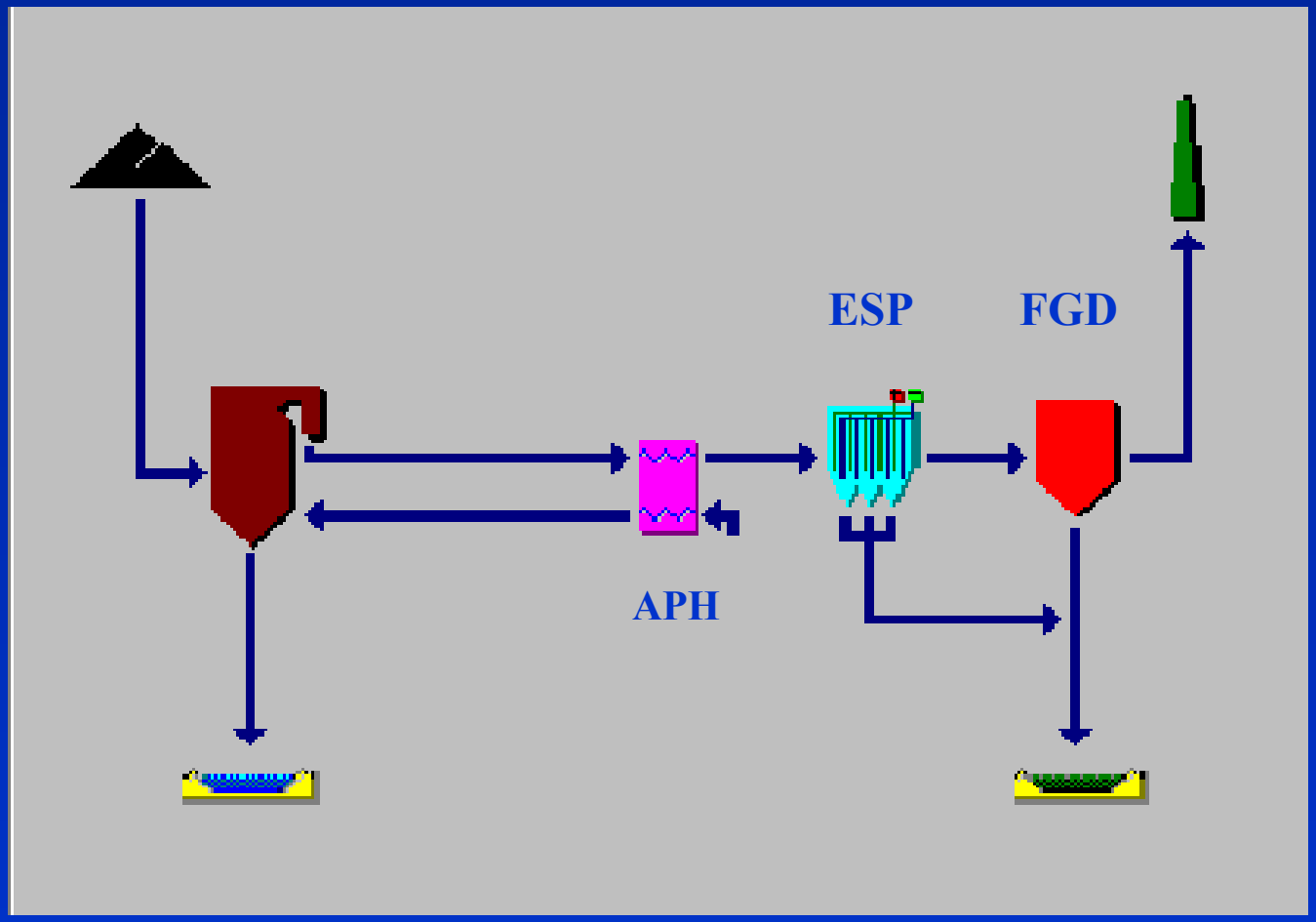
% change based on lbs/kWh (net)

Case 2

Reduce SO_2 using

a wet FGD system

Plant Configuration (2)



Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel (Coal) | Boiler | Air Preheater | NOx Control | Mercury Control | Particulate Control | SO2 Control | Solids Mgmt | Stack

Temperature (deg. F) 131.5

Temperature (deg. F) 314.0

Temperature In (deg. F) 300.0
Flue Gas In (acfm) 1.640e+06
Fly Ash In (ton/yr) 788.7
Mercury In (lb/yr) 161.6

Temperature Out (deg. F) 152.0
Flue Gas Out (acfm) 1.439e+06
Fly Ash Out (ton/yr) 394.4
Mercury Out (lb/yr) 48.48
Dry Reagent (ton/yr) 1.185e+05
Makeup Water (ton/yr) 8.481e+05

Dewatering System

Ash Removal (%) 50.00
SO2 Removal (%) 89.62
SO3 Removal (%) 50.00
Mercury Removal (%) 70.00

Wet FGD Solids (ton/yr) 2.155e+05

Process Type: Wet FGD

1. Diagram | 2. Capital Cost | 3. O&M Cost | 4. Total Cost | 5. Cost Inputs | 6. Gas Summary

Chemistry of SO_2 Capture

$$SO_2 + CaCO_3 + H_2O \longrightarrow$$

$$CaSO_4 \bullet 2H_2O + CO_2$$

Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel (Coal) | Boiler | Air Preheater | NOx Control | Mercury Control | Particulate Control | SO2 Control | Solids Mgmt | Stack

	Major Flue Gas Components	Flue Gas In (moles/hr)	Flue Gas Out (moles/hr)	Flue Gas In (lbs/kWh)	Flue Gas Out (lbs/kWh)
1	Nitrogen (N2)	1.300e+05	1.300e+05	7985	7985
2	Oxygen (O2)	9667	9504	678.4	667.0
3	Water Vapor (H2O)	1.623e+04	3.238e+04	641.1	1279
4	Carbon Dioxide (CO2)	2.093e+04	2.129e+04	2019	2054
5	Carbon Monoxide (CO)	0.0	0.0	0.0	0.0
6	Hydrochloric Acid (HCl)	19.70	1.970	1.574	0.1574
7	Sulfur Dioxide (SO2)	402.7	41.80	56.57	5.872
8	Sulfuric Acid (equivalent SO3)	1.218	0.6089	0.2138	0.1069
9	Nitric Oxide (NO)	63.60	63.60	4.185	4.185
10	Nitrogen Dioxide (NO2)	3.347	3.347	0.3377	0.3377
11	Total	1.773e+05	1.933e+05	1.139e+04	1.200e+04
12					
13					
14					
15					

Process Type: Wet FGD

1. Diagram | 2. Capital Cost | 3. O&M Cost | 4. Total Cost | 5. Cost Inputs | 6. Gas Summary

Multi-Pollutant Impacts of Emission Control Options (2)

Primary Emission Controlled			Multi-Pollutant Interactions	
Species	**Method**	**% Reduction**	**Pollutant**	**Effect**
SO_2	Wet FGD	89%	PM	50% decrease
			Hg	70% decrease
			CO_2	2% increase
			Solids	150% increase

% change based on lbs/kWh (net)

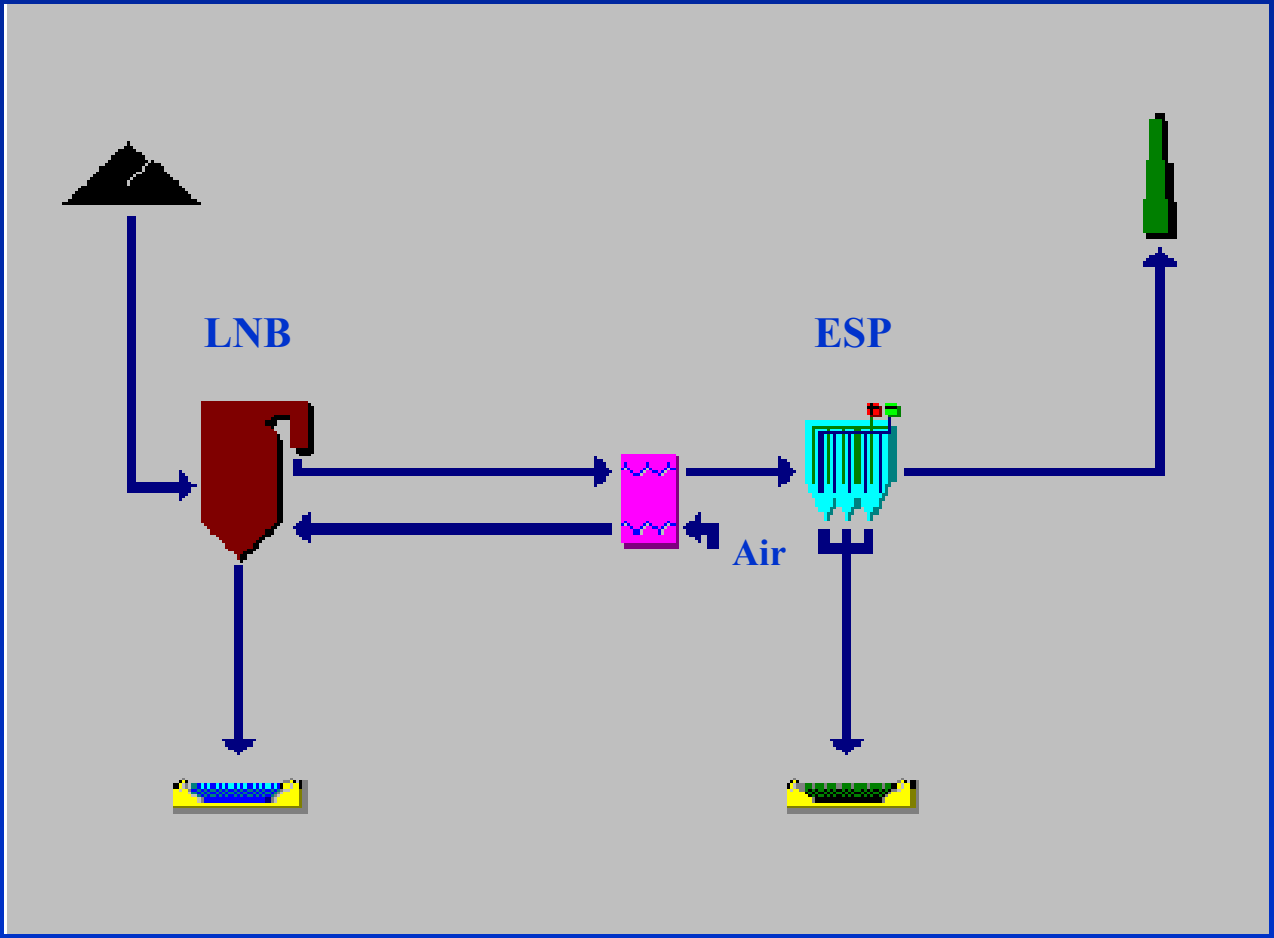
Case 3

Reduce NO_x using

low- NO_x burners

(LNB)

Plant Configuration (3)



Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel (Coal) | Boiler | Air Preheater | NOx Control | Mercury Control | Particulate Control | SO2 Control | Solids Mgmt | Stack

(No Reagent)

(No Overfire Air)

(No Reburn)

Temperature Out (deg. F) 700.0

Flue Gas Out (acfm) 2.067e+06

Fly Ash Out (ton/yr) 8.383e+04

Mercury Out (lb/yr) 247.3

Wet Coal In (ton/yr) 1.143e+06

Mercury In (lb/yr) 265.9

Temperature (deg. F) 502.6

Heated Air (acfm) 1.645e+06

Convective Zone

Temperature (deg. F) 700.0

Flue Gas (acfm) 2.067e+06

Fly Ash (ton/yr) 8.383e+04

Mercury (lb/yr) 247.3

Boiler NOx Removal (%) 33.97

Process Type: In-Furnace Controls

1. Diagram | 2. Capital Cost | 3. O&M Cost | 4. Total Cost | 5. Cost Inputs | 6. Gas Summary

Multi-Pollutant Impacts of Emission Control Options (3)

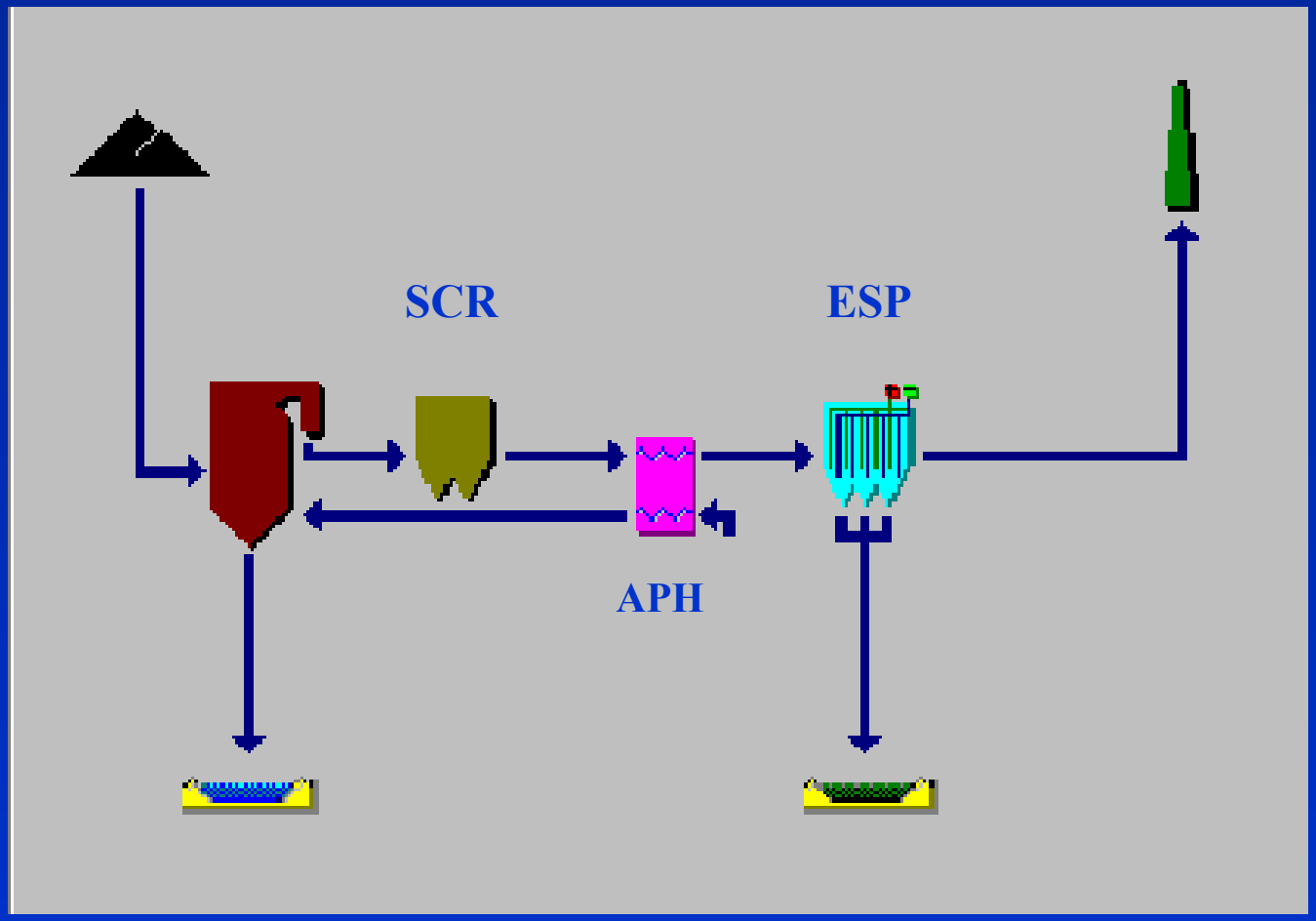
Primary Emission Controlled			Multi-Pollutant Interactions	
Species	**Method**	**% Reduction**	**Pollutant**	**Effect**
NO_x	LNB	34%	Unburned Carbon	Increases offset by boiler tuning

% change based on lbs/kWh (net)

Case 4

Reduce NO_x using selective catalytic reduction (SCR)

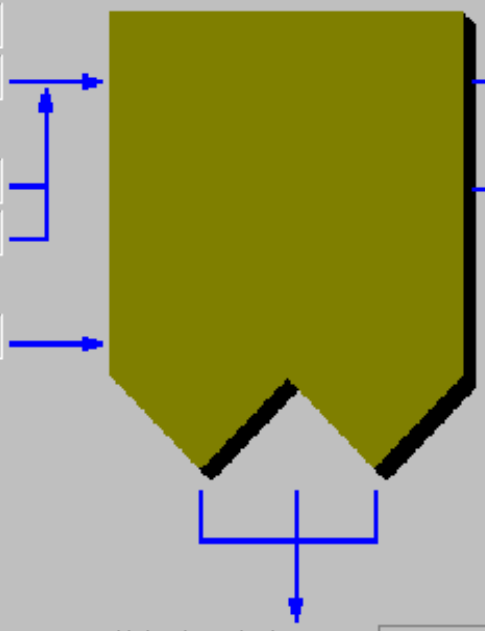
Plant Configuration (4)



Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel (Coal) | Boiler | Air Preheater | NOx Control | Mercury Control | Particulate Control | SO2 Control | Solids Mgmt | Stack

Temperature In (deg. F)	700.0
Flue Gas In (acfm)	2.176e+06
Fly Ash In (ton/yr)	1.069e+05
Mercury In (lb/yr)	234.2
Ammonia Injection	2657
Steam for Injection	5.341e+04
Steam for Soot (ton/yr)	2354



Temperature Out (deg. F)	700.0
Flue Gas Out (acfm)	2.206e+06
Fly Ash Out (ton/yr)	1.069e+05
Mercury Out (lb/yr)	234.2
Ammonia Slip (ton/yr)	38.56
NOx Removal (%)	78.20
TSP Removal (%)	0.0
Initial Catalyst Layers	3.000
Reserve Catalyst Layers	0.0
Dummy Catalyst Layers	1.000
Active Catalyst Layers	3.000
Layers Replaced Yearly	0.5873

Dry Solids (ton/yr) 0.0

Process Type: Hot-Side SCR

1. Diagram | 2. Capital Cost | 3. O&M Cost | 4. Total Cost | 5. Cost Inputs | 6. Gas Summary

Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel (Coal) | Boiler | Air Preheater | NOx Control | Mercury Control | Particulate Control | SO2 Control | Solids Mgmt | Stack

	Major Flue Gas Components	Flue Gas In (moles/hr)	Flue Gas Out (moles/hr)	Flue Gas In (lbs/kWh)	Flue Gas Out (lbs/kWh)
1	Nitrogen (N2)	1.123e+05	1.123e+05	6734	6738
2	Oxygen (O2)	4947	4936	339.0	338.3
3	Water Vapor (H2O)	1.558e+04	1.772e+04	601.4	684.1
4	Carbon Dioxide (CO2)	2.093e+04	2.093e+04	1973	1973
5	Carbon Monoxide (CO)	0.0	0.0	0.0	0.0
6	Hydrochloric Acid (HCl)	19.70	19.70	1.538	1.538
7	Sulfur Dioxide (SO2)	402.7	397.1	55.26	54.49
8	Sulfuric Acid (equivalent SO3)	3.247	8.797	0.5569	1.509
9	Nitric Oxide (NO)	63.60	13.86	4.088	0.8910
10	Nitrogen Dioxide (NO2)	3.347	0.7297	0.3299	7.192e-02
11	Total	1.542e+05	1.564e+05	1.942e+07	1.958e+07
12					
13					
14					
15					

Process Type: Hot-Side SCR

1. Diagram | 2. Capital Cost | 3. O&M Cost | 4. Total Cost | 5. Cost Inputs | 6. Gas Summary

Multi-Pollutant Impacts of Emission Control Options (4)

Primary Emission Controlled			Multi-Pollutant Interactions	
Species	**Method**	**% Reduction**	**Pollutant**	**Effect**
NO_x	SCR	78%	PM	27% decrease
			SO_3	170% increase
			NH_3	trace increase

% change based on lbs/kWh (net)

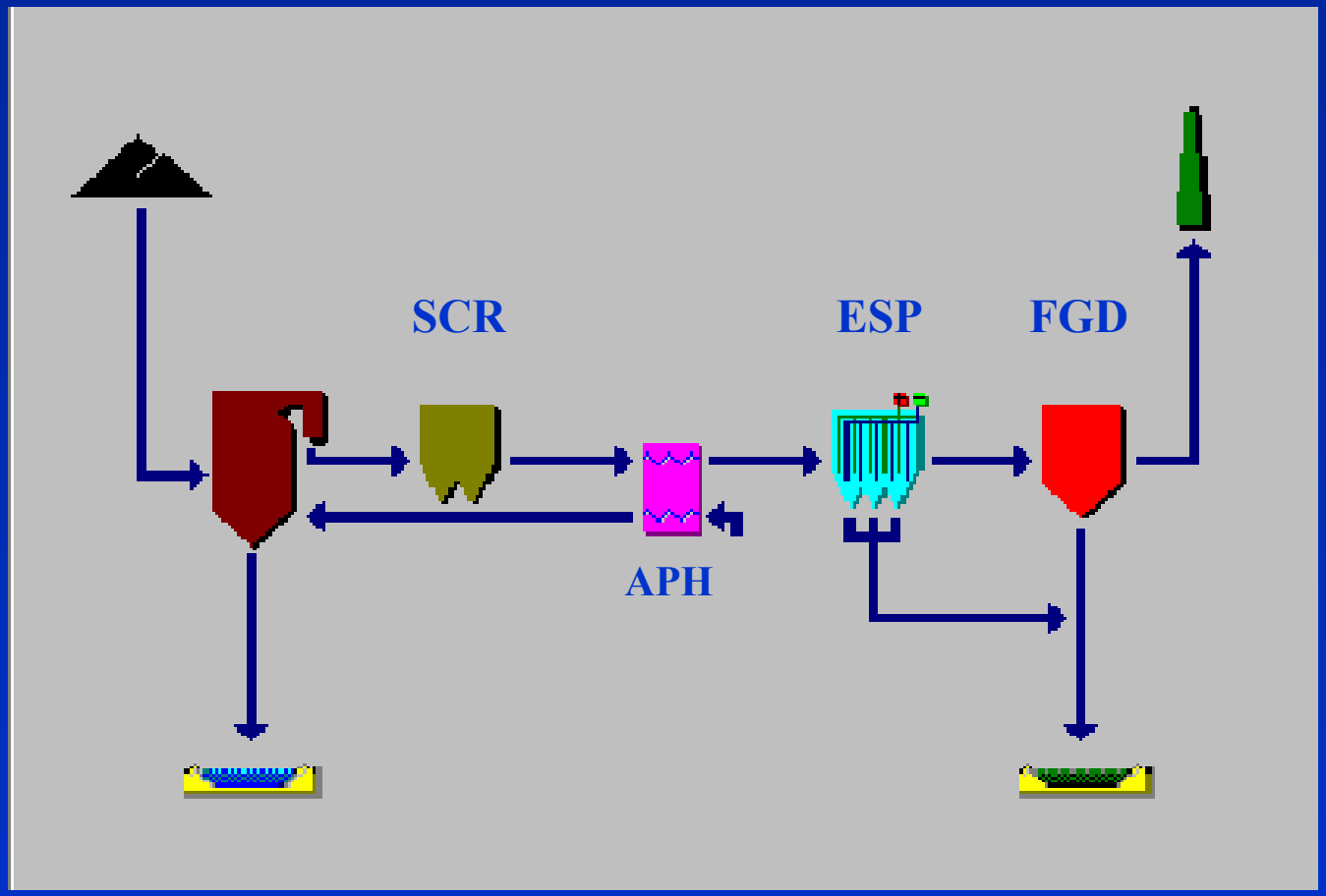
Case 5

Reduce both SO_2

and NO_x using

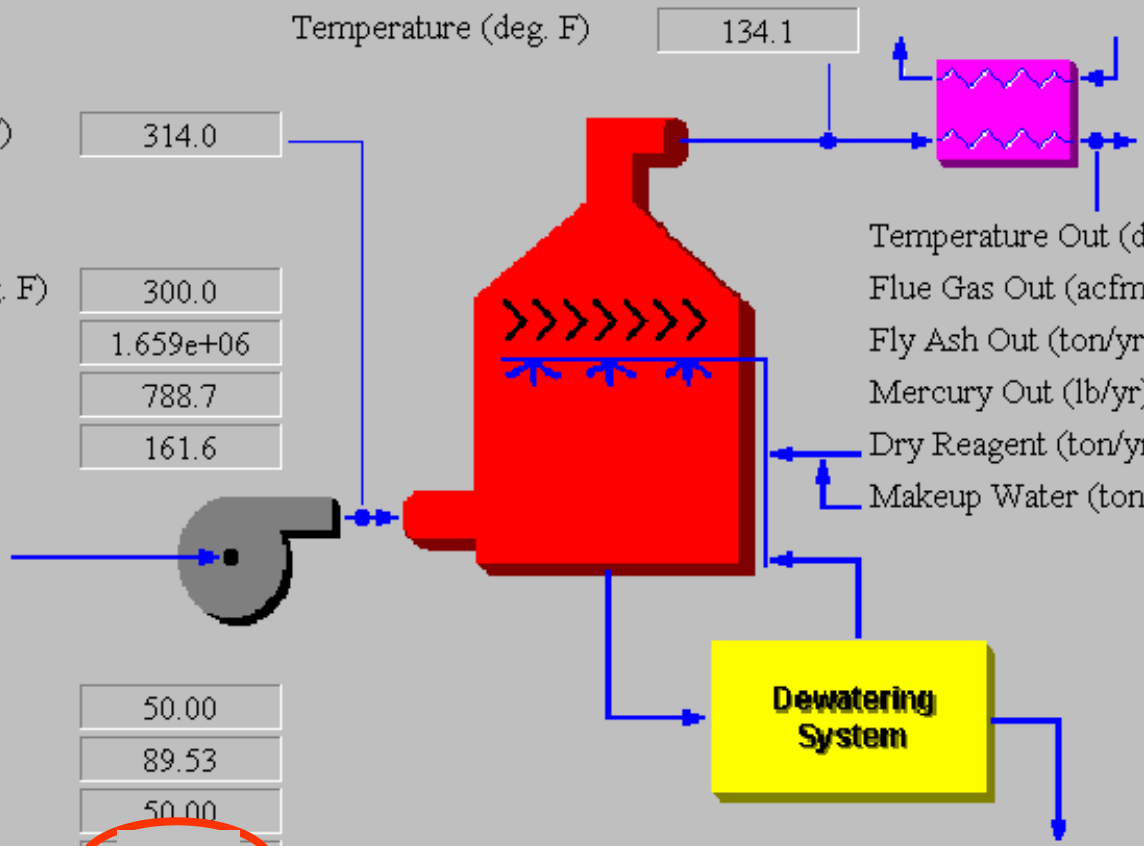
SCR plus wet FGD

Plant Configuration (5)



Configure Plant | Set Parameters | Get Results

Overall Plant | Fuel (Coal) | Boiler | Air Preheater | NOx Control | Mercury Control | Particulate Control | SO2 Control | Solids Mgmt | Stack



Temperature (deg. F)	134.1
Temperature (deg. F)	314.0
Temperature In (deg. F)	300.0
Flue Gas In (acfm)	1.659e+06
Fly Ash In (ton/yr)	788.7
Mercury In (lb/yr)	161.6
Temperature Out (deg. F)	152.0
Flue Gas Out (acfm)	1.455e+06
Fly Ash Out (ton/yr)	394.4
Mercury Out (lb/yr)	28.57
Dry Reagent (ton/yr)	1.170e+05
Makeup Water (ton/yr)	8.463e+05
Ash Removal (%)	50.00
SO2 Removal (%)	89.53
SO3 Removal (%)	50.00
Mercury Removal (%)	82.32
Wet FGD Solids (ton/yr)	2.130e+05

Process Type: Wet FGD

1. Diagram | 2. Capital Cost | 3. O&M Cost | 4. Total Cost | 5. Cost Inputs | 6. Gas Summary

Multi-Pollutant Impacts of Emission Control Options (5)

Primary Emission Controlled			Multi-Pollutant Interactions	
Species	**Method**	**% Reduction**	**Pollutant**	**Effect**
NO_x + SO_2	SCR + FGD	78% NO_x + 89% SO_2	Hg	88% decrease*
			PM	54% decrease
			CO_2	2% increase
			SO_3	40% increase
			Solids	150% increase

% change based on lbs/kWh (net) **Preliminary estimate; effect of SCR units is still under study.*

Conclusions

- Multi-pollutant interactions are complex (and often subtle); need a systems analysis
- Multi-pollutant strategies can reduce the cost of emission controls, *but* . . .
- The cost, performance and feasibility of such approaches depends a lot on the details of plant design and operation (especially for existing facilities)

Future Work

- Conduct detailed case studies of multi-pollutant options for existing plants
- Explore implications for policy analysis
- Assess benefits of advanced technologies
- Expand and update the IECM framework
  - Current technologies
  - Advanced technologies
  - Fuel options
  - Analysis capabilities