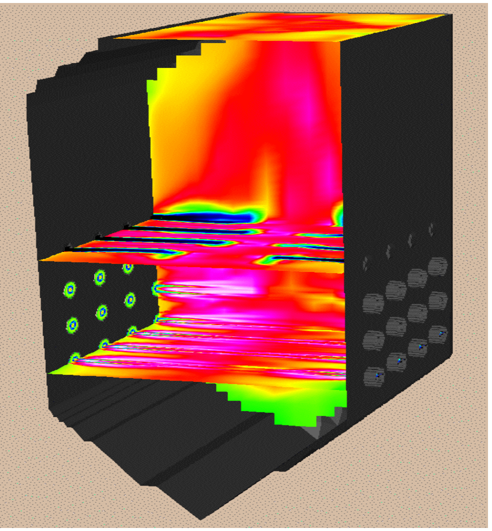

US Industry Experience Overview of NOx and SO2 Control

Stuart Dalton (sdalton@epri.com)

Director, Fossil / Emission Control

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Emissions from Electric Generating Units in the U. S. are Likely to be Reduced

Bush Administration's Clear Skies Initiative

Emission	2000 Tonnage	Proposed Annual Cap Tonnage	Year Cap Takes Effect
SO2	11.2 Mt	4.5 Mt	2010
		3.0 Mt	2018
NOx - east	4.35 Mt	1.58 Mt	2008
		1.16 Mt	2018
NOx - west	0.75 Mt	0.54 Mt	2008
Mercury	43 - 48 t	26 t	2010
		15 t	2018
CO2	2.3 Bt	Reduction of 18% in carbon intensity by 2012	

Note: Trading with banking allowed for all capped emissions.
All caps subject to review and revision up or down in 2010.

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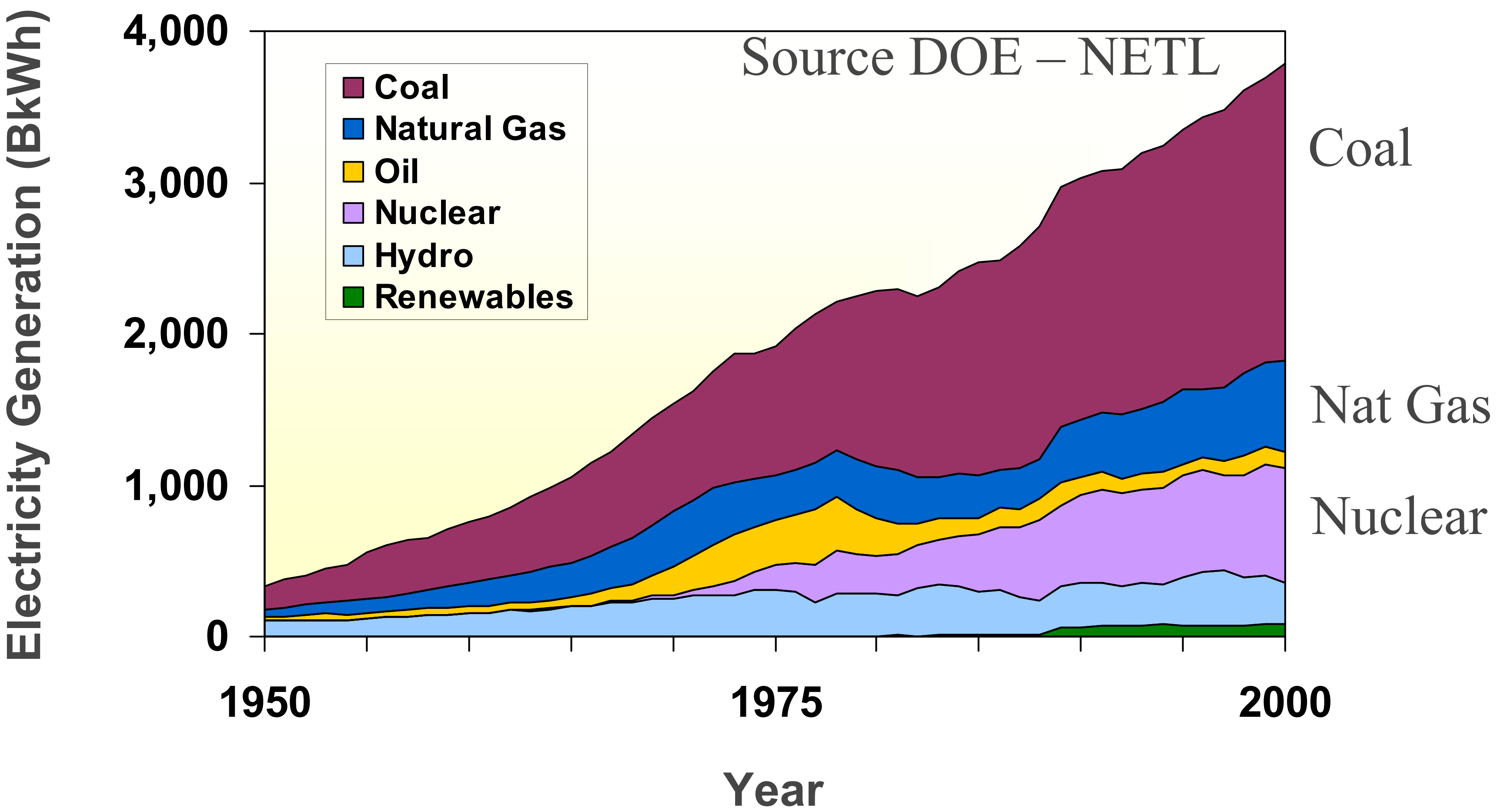
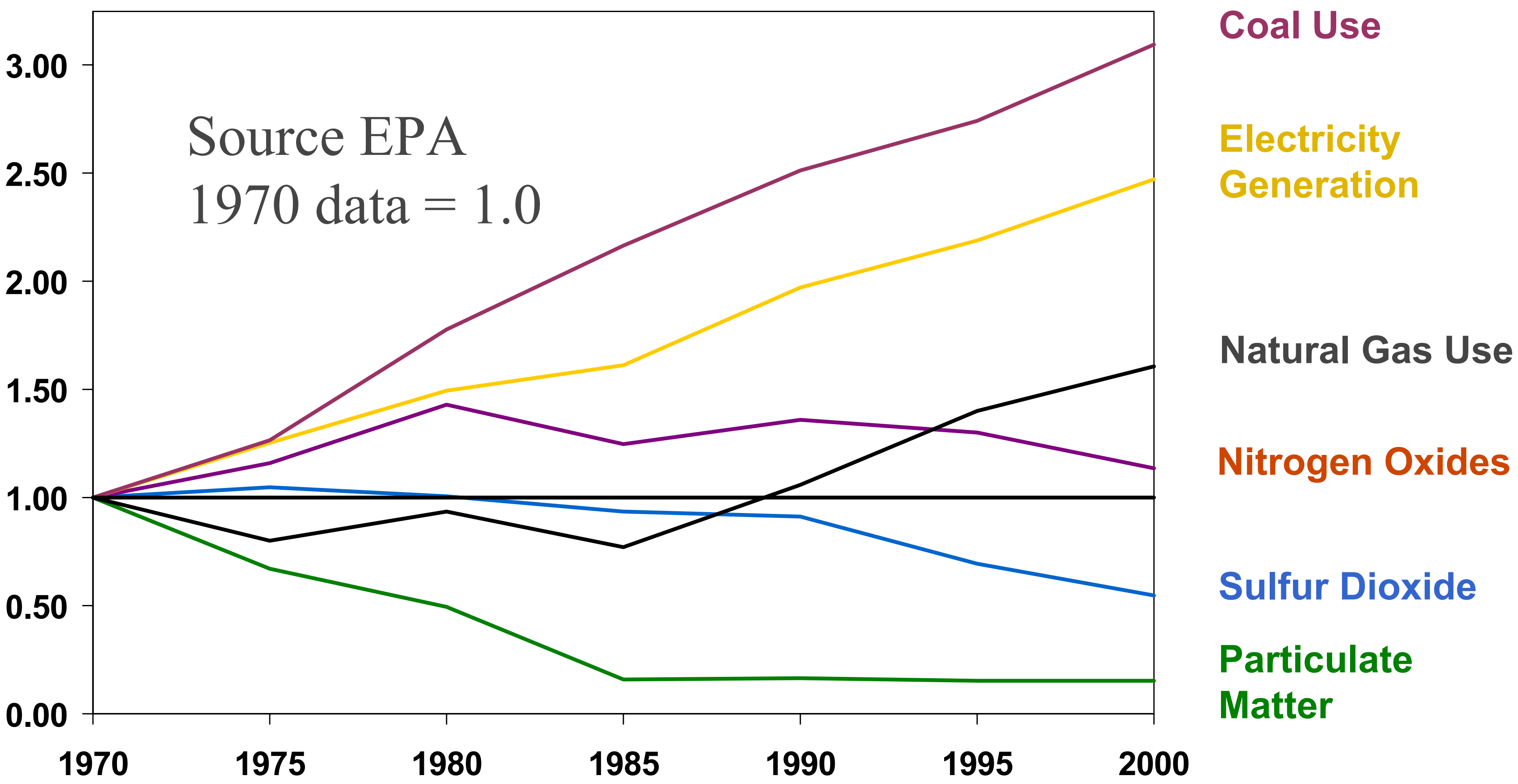
US– Generation Mix



Source: DOE/EIA

US Electric Generation, Fuel and Emissions Trends

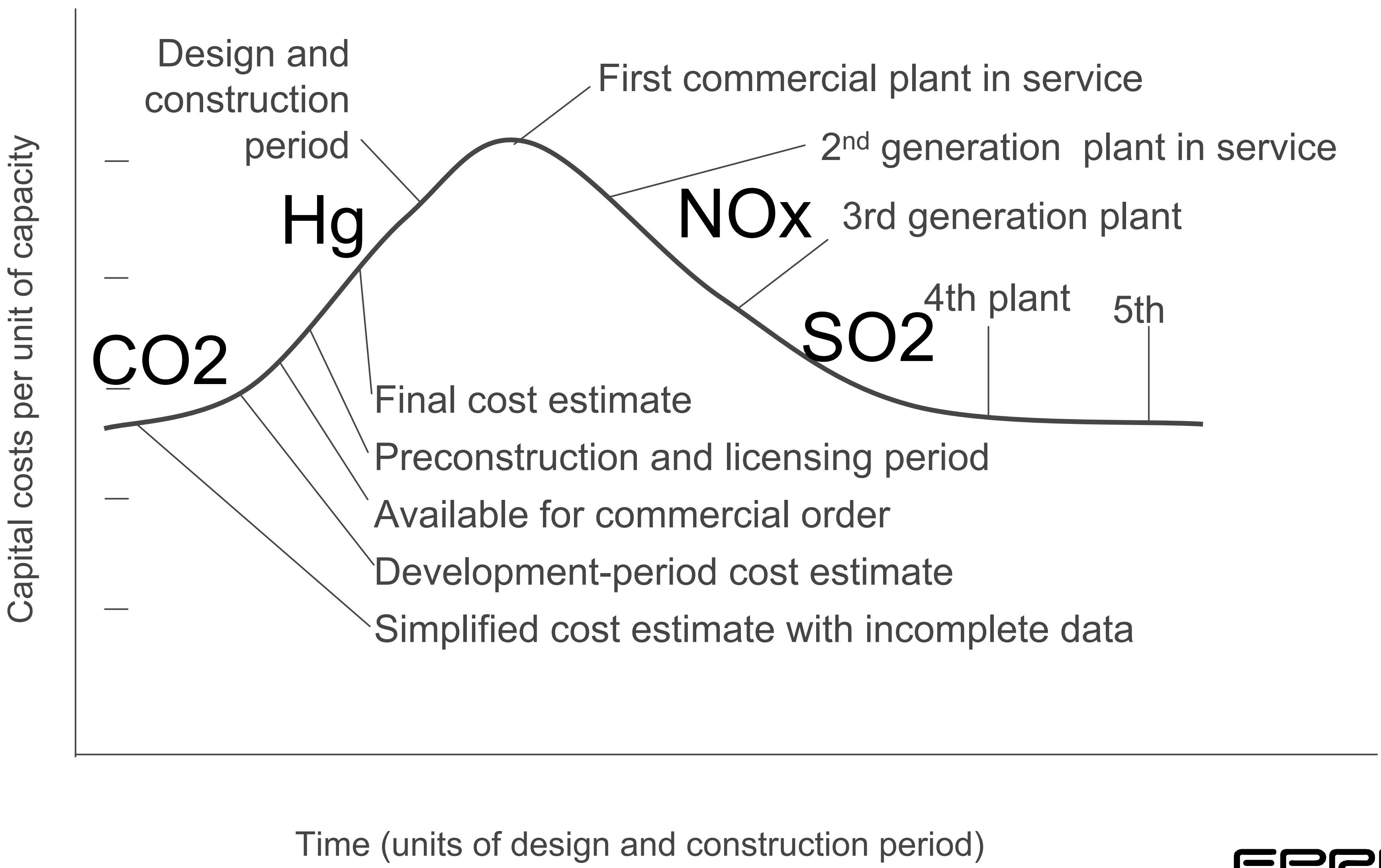


EPA, National Air Quality and Emissions Trends Report, 1999 (March 2001)
DOE, EIA Annual Energy Review

Current Concerns in the USA

- Existing coal plants may need to add additional emission controls
- Additional SOx, NOx, Particulate controls may be required over the next 15 years with emission trading
- Mercury control is likely either under “maximum” control (without regard to cost) or a more moderate control requirement
- Local state requirements and local air pollution will make the controls non-uniform
- CO2 control is very controversial but new research programs are likely

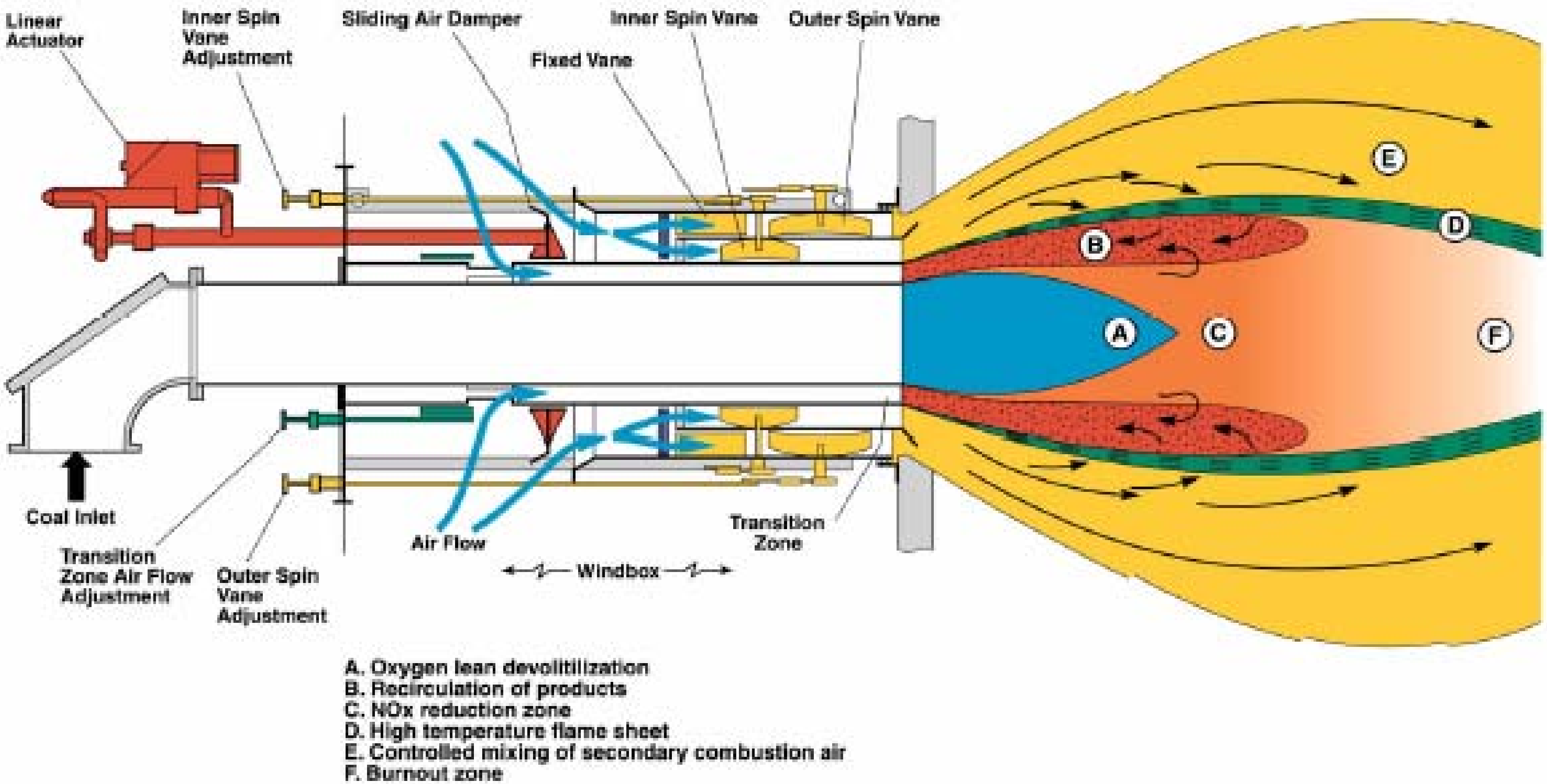
The Time and Cost for New Technology Introduction



NOx Mitigation Strategies

- Minimize formation
  - Restriction of fuel oxidation in early stages of combustion (combustion based technologies)
  - Advantages: Cost, installation schedule
  - Disadvantages: Potential for operability impacts, limited reduction levels
- Destruction following formation
  - Via “reburning” or utilization of a reagent such as NH_3, urea (SCR, SNCR)
  - Advantages: Can achieve < .15 #/Mbtu
  - Disadvantages: cost, on-site reagent

Low NOx Burners (LNB) – Combustion NOx Control



Graphic Source: http://www.netl.doe.gov/coalpower/environment/nox/

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Specific Combustion Based NOx Prevention Technologies

Technology	NOx Reduction (%)	Cost ($/kW)
Combustion Optimization	5-30	$40K-$250K one time
Burner Components	10-40 (wall) 15-35 (T)	3-7
Furnace Modifications	10-40	1-5
LNB Low NOx Burners	35-50 (wall) 30-40 (T)	10-25 (wall) 10-15 (T)
LNB+OFA	45-65 (wall) 35-55 (T)	10-40

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Tuning and Optimization

- Manual optimization always first step
- Computerized systems rely on digital control systems and artificial intelligence
  - Effectiveness highly variable
    - Boiler condition
    - Extent of electrically-driven controllers
    - Complexity of combustion systems, etc.

Burner Component Modifications

- Change equipment at tip of burner only
- Very cost-effective retrofit for pre-LNB(low-NOx Burner) systems
- Experience still limited -- general effectiveness???
- Ideal for
  - Boilers that can't tolerate LNB without major upgrades
  - Small, low-utilization units that will be averaged
  - Units with uncontrolled emissions and duct geometry ==> cost-effective with small SCR

Furnace Modifications

- Involves strategic redistribution of burner specific fuel / air ratios (e.g., OFA [overfire air], fuel/air biasing) to minimize NOx
- Typically utilizes computational fluid dynamics (CFD) modeling to assess impacts on boiler performance (LOI [loss on ignition], corrosion, HR [heat rate], etc.)
- Best results with lower rank fuels, but viable for most applications due to minimum hardware change-out

Low-NOx Burners

- LNB (Low NOx Burners) or LNCFS (Low NOx Concentric Firing System)
- Manages air/fuel mixing in flame
- Wall-fired boilers -- replace burner
- Tangentially fired units -- modify windbox arrangement and replace fuel injectors and air ports
- Mature technology, but not issue-free (today)
  - Unburned carbon -- ash reuse impacts
  - Waterwall wastage
  - Not always plug-and-play

LNB + Overfire Air (OFA)

- Manages air/fuel mixing at burner and in boiler
  - Reduce air to burners, add higher up through OFA ports
  - Limited to units with sufficient height
- Called LNCFS-2 or -3 or TFS2000 for T-fired
- Considerations same as LNB, but exacerbated
  - Can also reduce boiler efficiency and/or change deposition pattern

What Causes Waterwall Wastage?

Main Culprits or "Bad Actors"

Pyrite

Sulfur

Chlorine

Culprits materialize with staged combustion for low NOx

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Fireside Corrosion Predictor

- **Application specific:**
  - Fuel properties
  - Particle size distribution
  - Boiler design
- **Enables proactive boiler management:**
- New low NOx systems
  - Changed fuels or blends
  - Viability of combustion based mitigation strategies (mill upgrades, strategic biasing)

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NOx Destruction (e.g., Post-Combustion) Technologies

Technology	NOx Reduction (%)	Cost ($/kW)
Reburning	25-40 (lean) 45-65 (conv.)	3-6 (lean) 15-30 (conv.)
SNCR	15-40	10-20
SCR	50-85	60-140
Hybrids	55-95	SNCR<hybrid<SCR

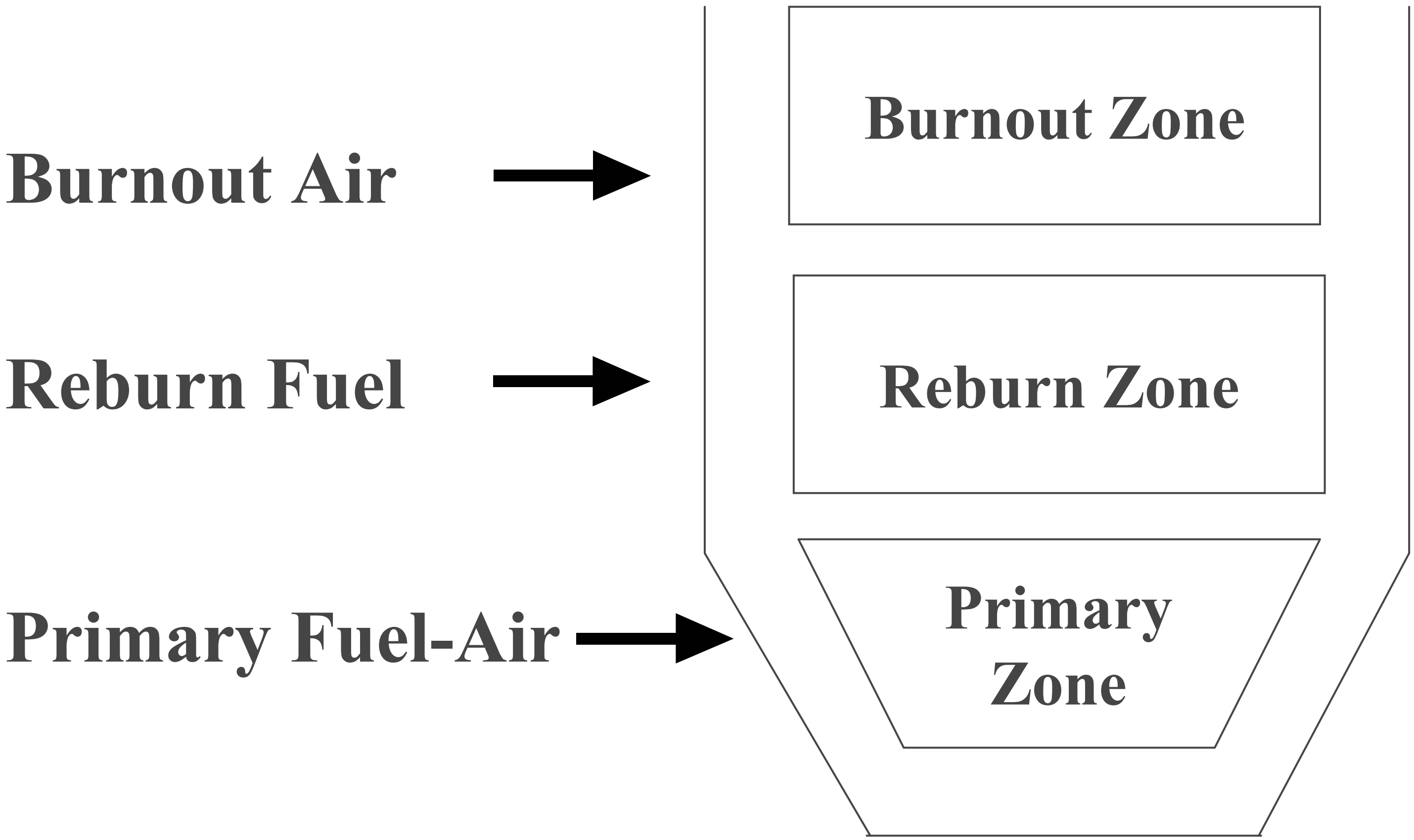
Reburning

- Burns gas “rich” above main combustion zone to reduce some of NOx formed below

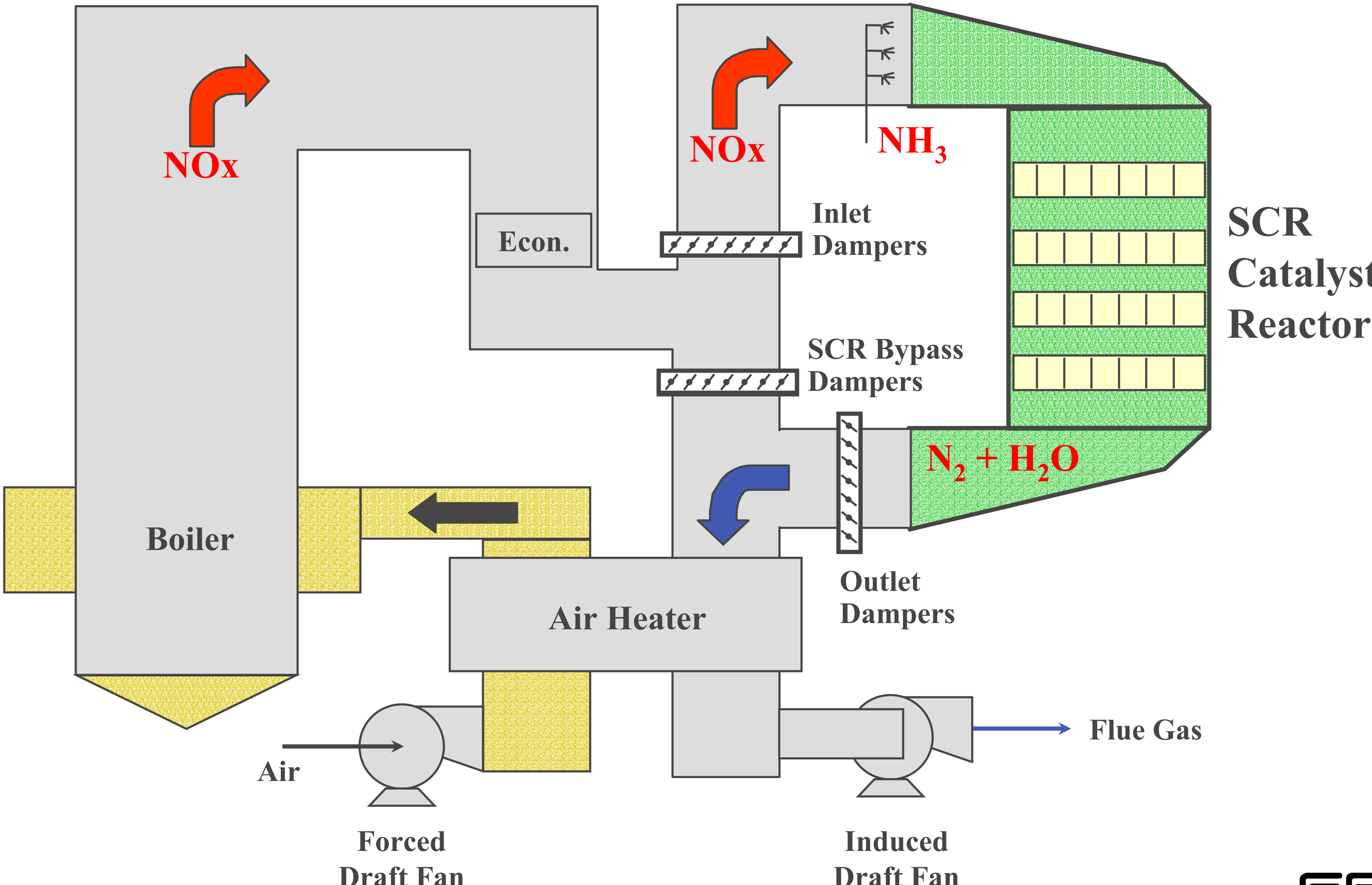
  $NO + CH_i \Longrightarrow HCN \Longrightarrow NH; \; NH + NO \Longrightarrow N_2$

- General types include:
  - Conventional
  - Fuel Lean (FLGR)
  - Amine-enhanced (AEGR)
- Requires adequate furnace volume and height
- Costs determined by gas price, availability
- Experience on large units and with FLGR, AEGR limited

Reburning Schematic



Selective Catalytic Reduction (SCR) – NOx



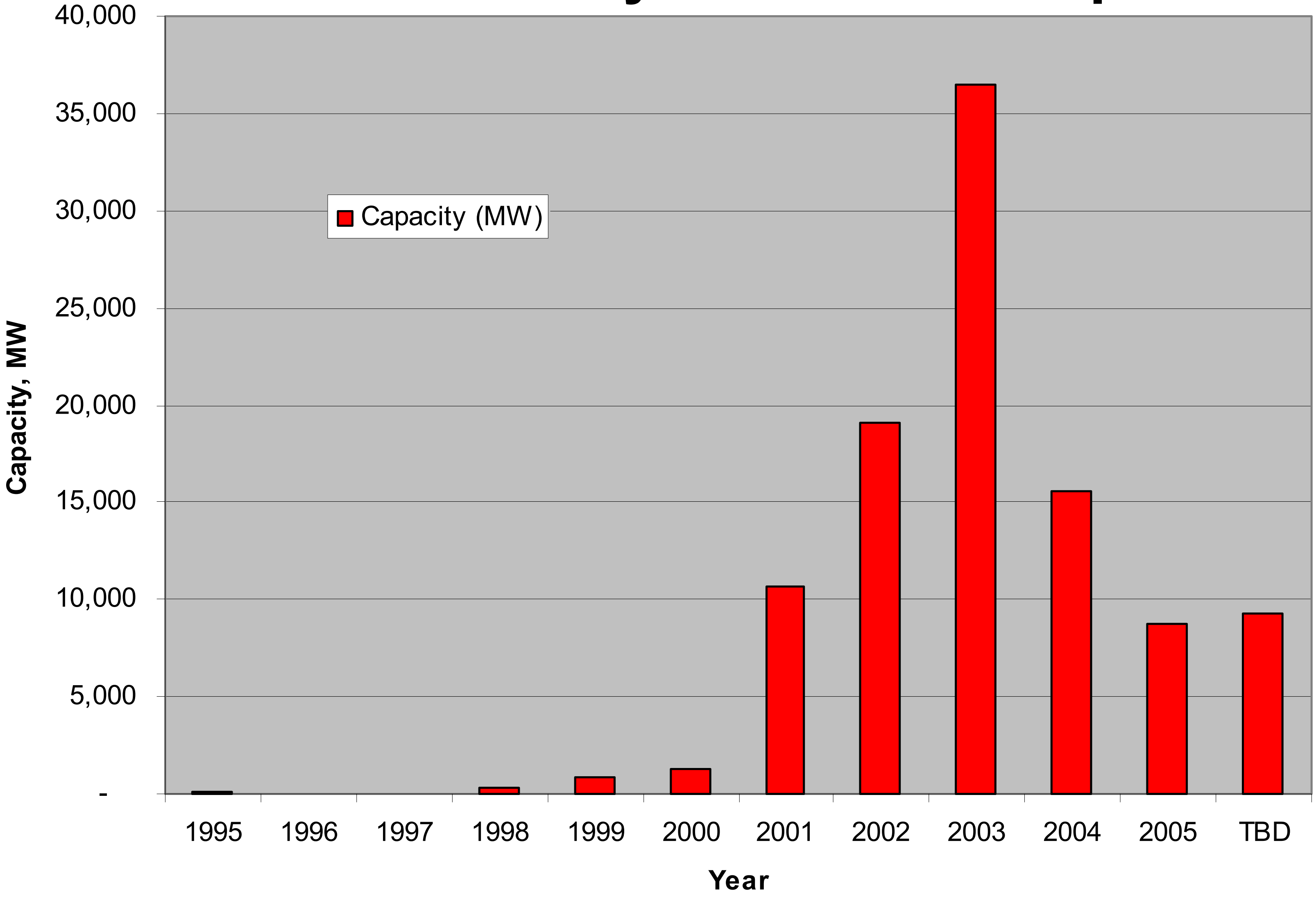
Selective Catalytic Reduction (SCR)

- Catalyst promotes same reaction at lower temperature (e.g., downstream of economizer)
  - Better process control ==> higher NOx removal
  - Requires substantial equipment ($$, space, lead time)
- Limited experience in US
  - High alkali fuels may be problematic
- Advanced catalysts are being investigated
  - Minimize reagent
  - Improve activity
  - Cold end (downstream of air heater)

Hybrids of Combustion and SCR

- Several options
  - In-duct SCR + air heater SCR
  - SNCR + either/both of above
  - SNCR + smaller SCR
- Opportunities to reduce costs when need more than "prevention" and less than SCR
- Very site specific
  - Emissions
  - Duct configuration
- A few exploratory installations

Capacity of SCR-Equipped Coal-Fired Units - Totals by First Year of Operation



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Selective Noncatalytic NOx Reduction (SNCR)

- Inject urea or ammonia near top of boiler

$$NO + NH_i \Longrightarrow N_2 + H_2O$$

- Effectiveness very dependent on boiler configuration - proper gas temperature
- Process is a NOx vs. NH_3 trade-off
  - Air heater pluggage (SO_3 from coal)
  - Ash contamination

Power Producer's Perspective

The goal is not "lowest NOx" but emissions compliance at <u>lowest cost</u>

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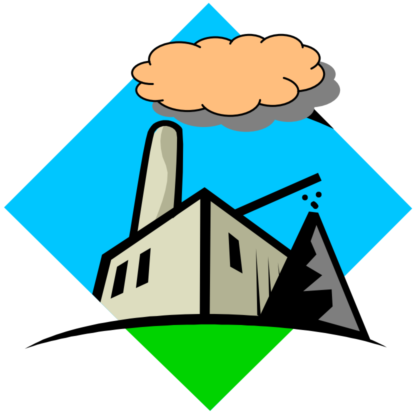
Considerations Impacting the Cost of NOx Compliance

- NOx compliance level is a moving target
- Anticipated plant life, dispatch philosophy
- Specific plant design and fuel considerations
- Operability impacts (e.g., HR, slagging / fouling, corrosion, LOI)
- Benefits of technology combinations
- Future O&M costs of GRB, SNCR, SCR uncertain
- Future fuel characteristics (S, Cl, FR, N, etc) will impact both NOx levels and operability.

SCR Aggravates Acid Plume



- Primarily issue with med-hi S coal
  - SO_3 already high
  - Likely to have FGD, hence wet plume
  - SCR oxidizes $SO_2 \rightarrow SO_3$
    - Can double SO_3 concentrations
- 1st line of defense = design to minimize oxidation
  - Determine realistic SO_3 levels
  - Include stringent oxidation specs in bid package
  - Work with bidders to minimize cost
    - Catalyst chemistry, morphology, etc.
    - Catalyst volume
    - SCR inlet temperature

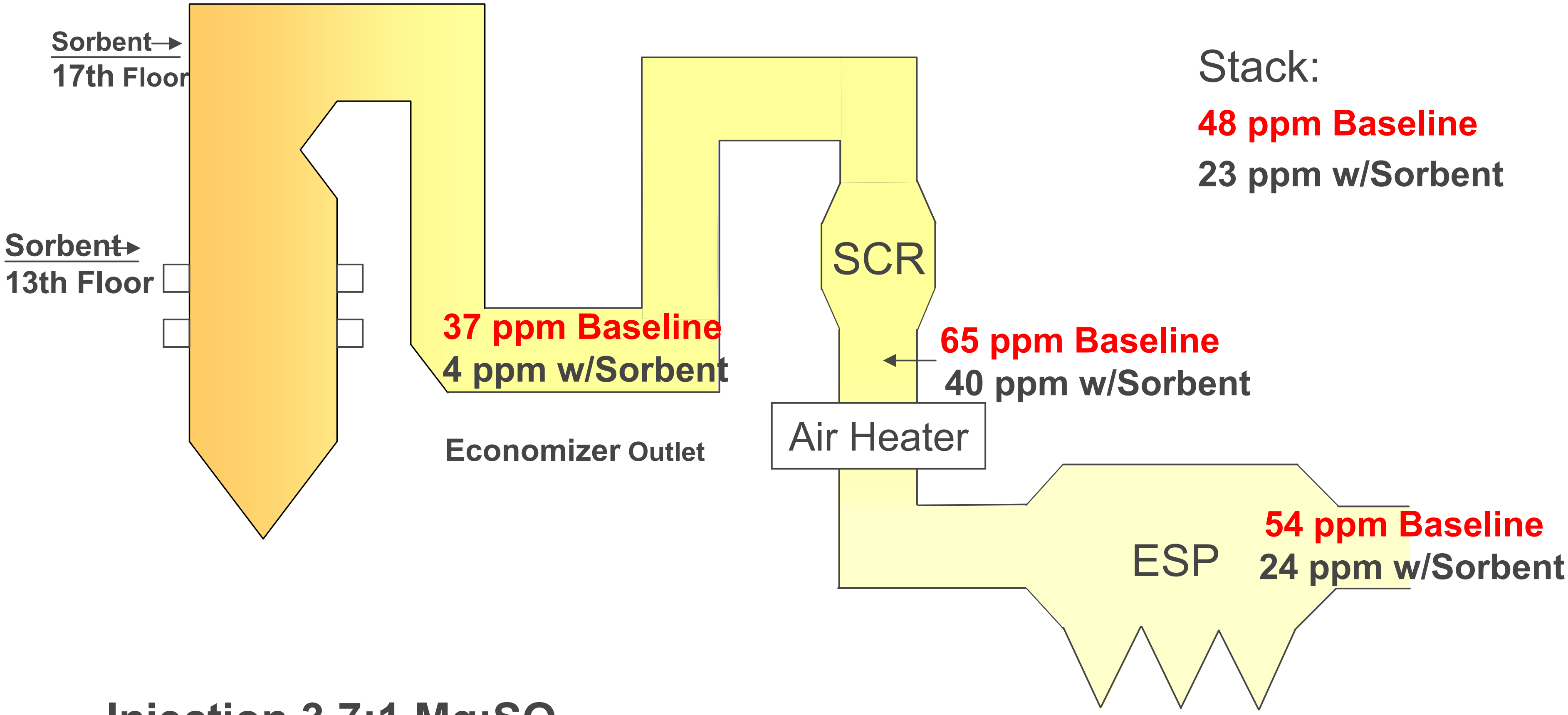
After-the-Fact Countermeasures to Plume

- Furnace $Mg(OH)_2$ injection

- Back-end sodium bisulfite (SBS) injection
  - Commercially offered process

- Water injection to lower SCR inlet T and back-end $Ca(OH)_2$ injection also demonstrated

Gavin (American Electric Power Plant) Typical Results



Injection 3.7:1 Mg:SO_3

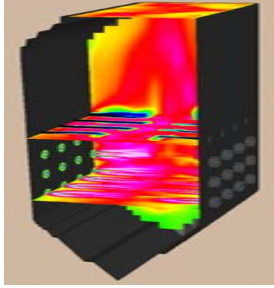
Results of Sodium Bi-Sulfite Injection Post-Air Preheater

- Left stack = not treated
- Right stack = treated

SCR/SNCR – Odor Issues

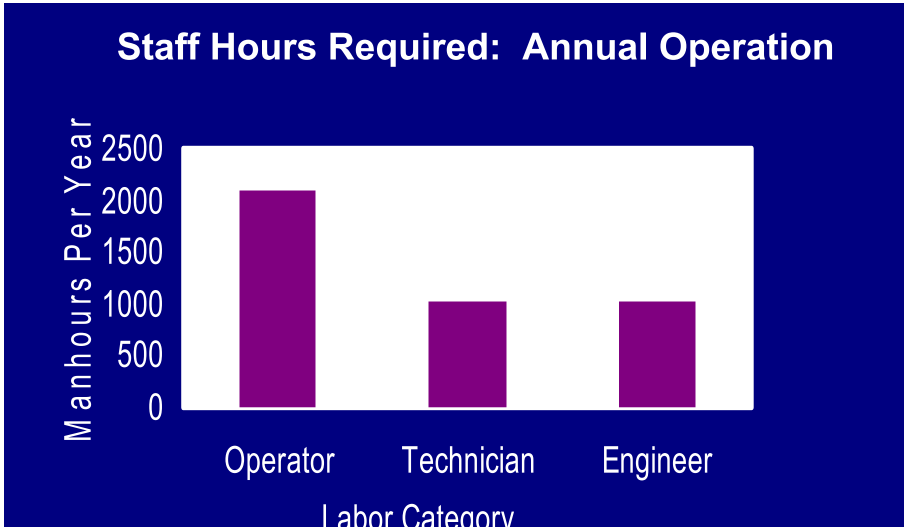
- Ammonia "slip" can adsorb on ash
  - Slip higher with SNCR than SCR
  - Amount adsorbed depends on ash chemistry
- By-product sales issue is smell
  - Concrete using ash biggest market
    - NH_3 released during mixing
    - Engineering properties not affected
- Disposal also a potential issue
  - Pond – NH_3 can promote algae growth, metals release
  - Landfill – rain will cause odor with basic ash
  - Mine backfill – Whew!!!

Lower Cost NOx via Combustion Modification



- Vendors of equipment want to sell hardware but it may be expensive
- Many low- capital cost emission controls can be done via optimizing existing equipment and combustion modification – good for initial NOx reduction of 10-50%
  - Biased firing- setting burners to provide different amounts of air & fuel – bottom fuel rich, top fuel lean
  - Burners out of service use top burners as overfire air ports and overfeed coal to the bottom row
  - Minor burner modifications instead of new burners
- This is a major role for EPRI with generation companies

Post-Combustion NOx Control Program



O&M Guidelines:

- Factors Affecting SCR Performance
- Specific O&M Practices
- Diagnostic methods
- Ammonia safety issues
- Seasonal considerations
- Catalyst management
- Reactor inspection
- Required O&M labor and contracted services

SO_2 Control

SO2 – Tripling Coal Use With 30% <u>Less</u> SO2

- The US has added over 100 GW of Flue Gas Desulfurization (FGD) over the past three decades to reduce sulfur emissions and is adding more
- Many firms have switched from high-sulfur coal (>2%) to low-sulfur coal (typically < 0.5%)
  - Generators learned about the issues in burning lower heating value coal with lower sulfur (particulate collection issues, lower output, waste changes etc)
- A market for “Emission Allowances” has been a huge success in reducing the cost of SO2 control in the US
  - Each firm is allocated “allowances” by US EPA which decrease over time and then they buy or sell allowances to match their emissions
  - This allows sulfur to be a part of the economic decision – if you want to emit more , you buy more credits one Tonne currently equals about $250

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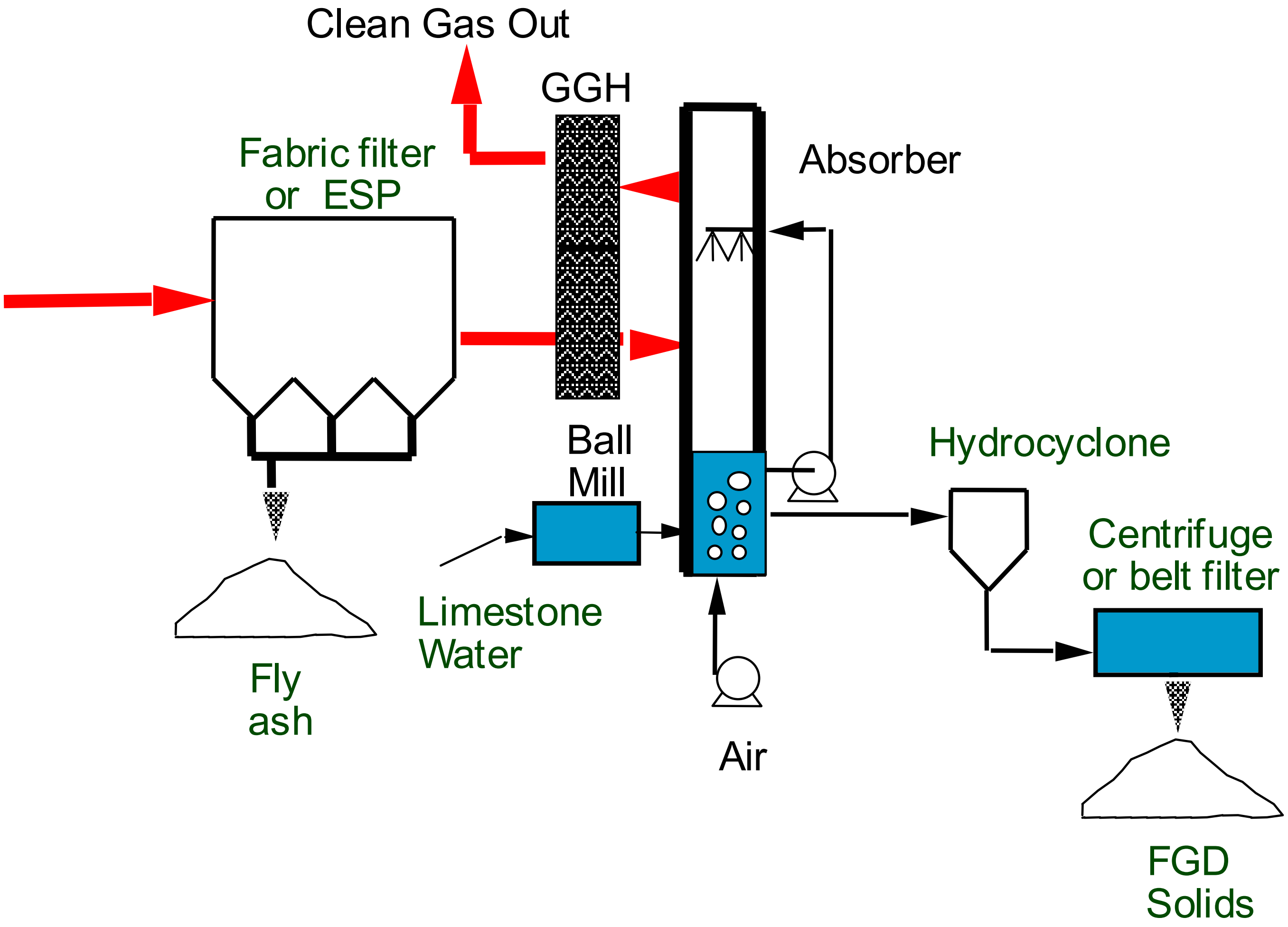
US SO_2 Emission Reduction Policy and Implications

- Other policies limiting SO_2
  - Fine particulate (PM2.5)
    - Sulfates (from SO_2) are major component of ambient PM2.5 in Eastern US
      - Health effects debated
  - Visibility (haze downwind of plant)
  - Further acid rain reductions
- Plans are to add additional SO2 control and this will mean >$10B of new SO2 controls in the US – primarily wet limestone and lime spray drying (capable of >90% removal)

Status of SO_2 Controls

- Flue Gas Desulfurization (FGD) and spray drying mature technologies dry powder is a niche technology
  - 99.5% ΔSO_2 possible with wet FGD (highest capital but lowest operating on high sulfur coal)
  - 90% with spray dryer (used especially on low sulfur)
  - 50-70% with dry powder (e.g., sodium bicarbonate/ sodium carbonate) only used in a few US sites
- Cost is major issue
  - Capital – suppliers bidding10-30% lower
    - Technology, construction management, business reasons
  - Operation and maintenance – EPRI research

Flue Gas Desulfurization Example Forced Oxidation - Gypsum



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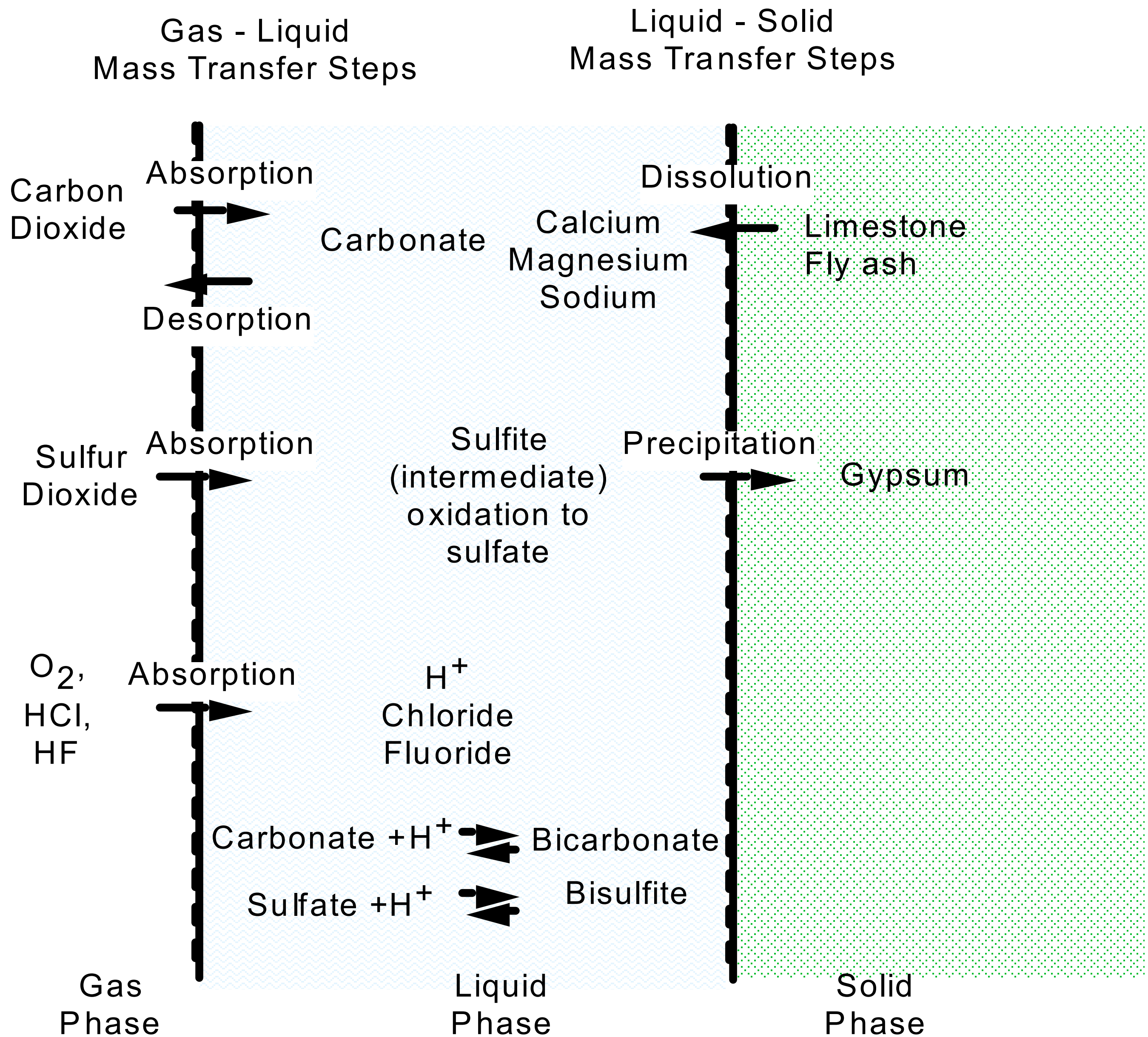
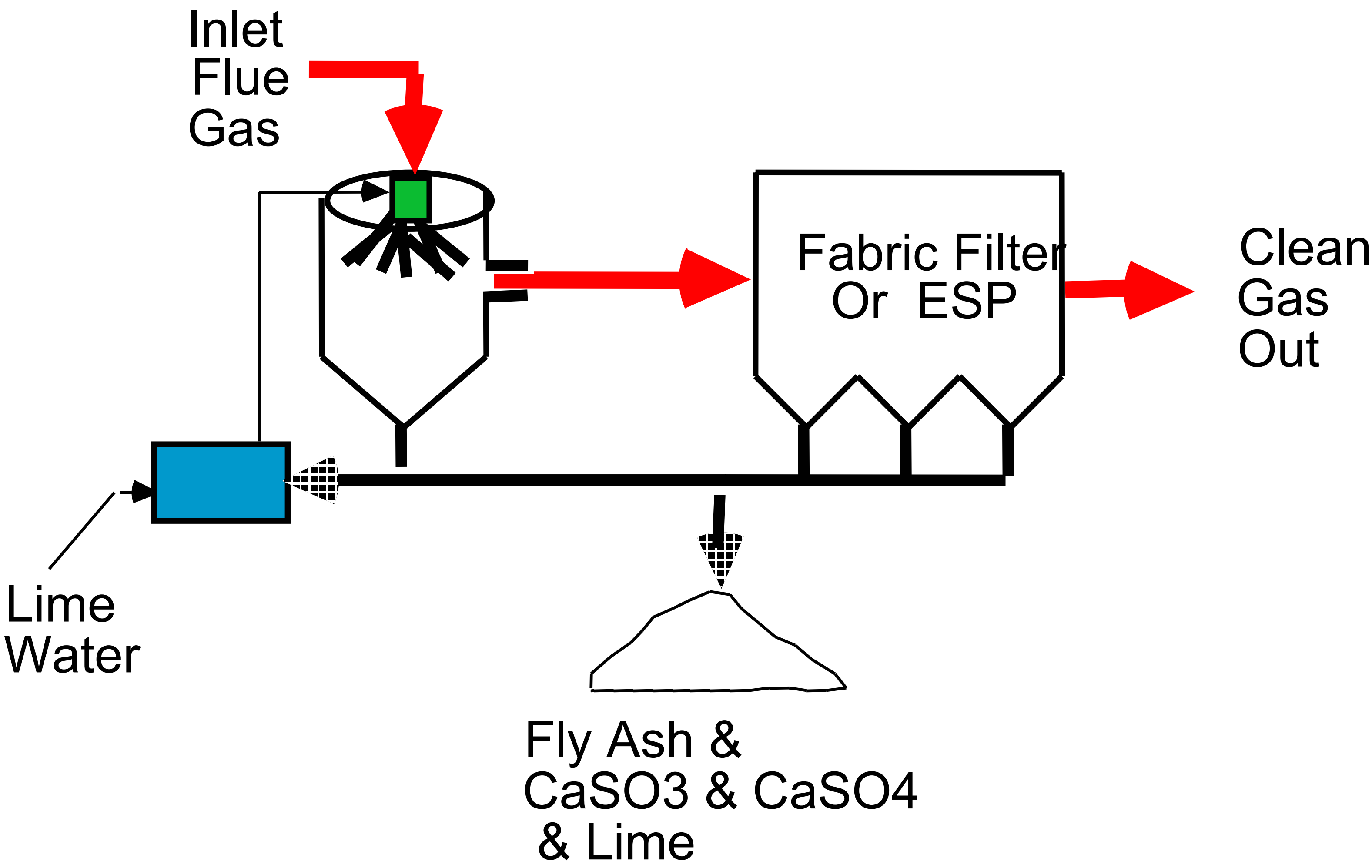
Chemistry Limestone Gypsum



Spray Drying



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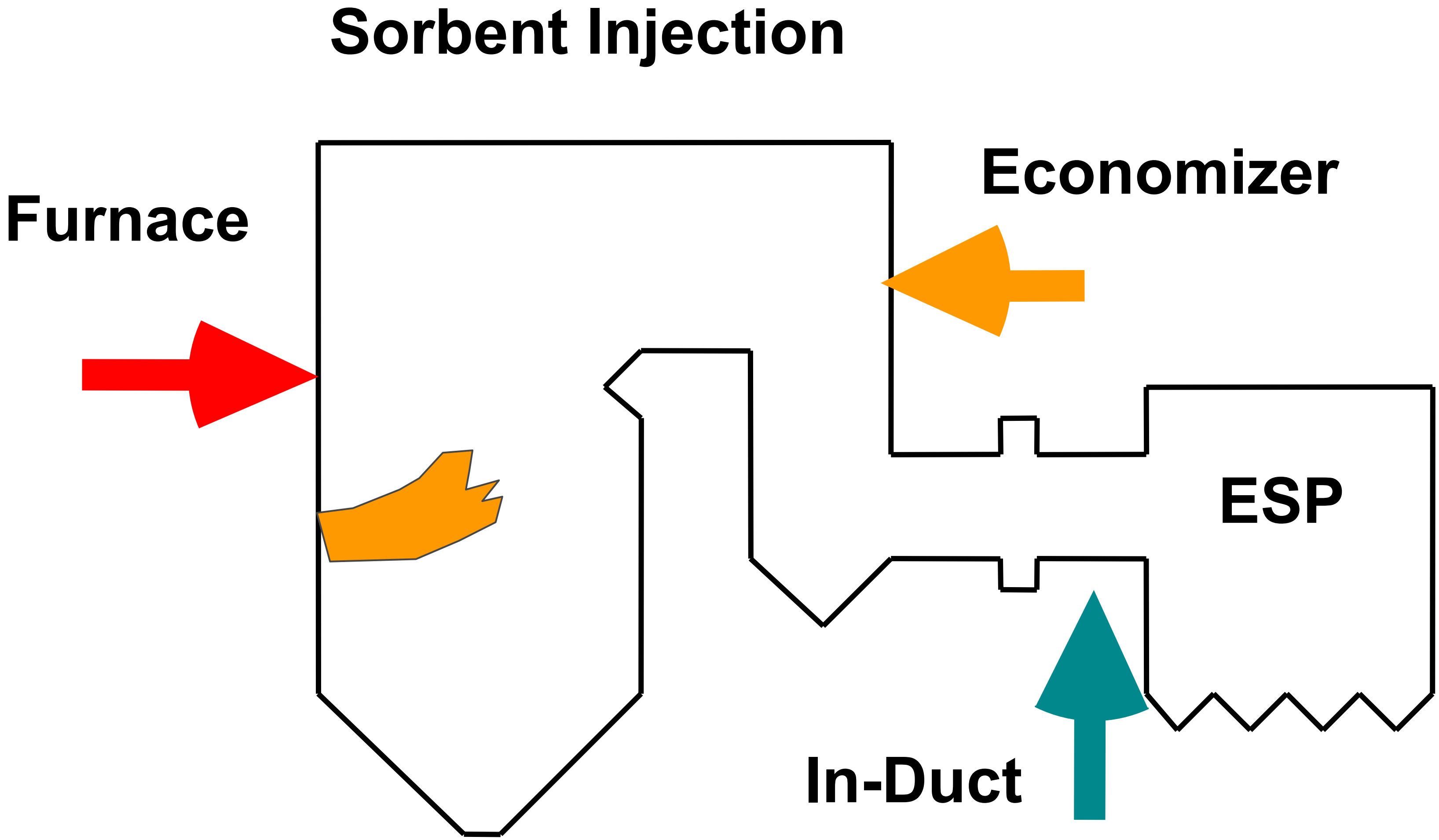
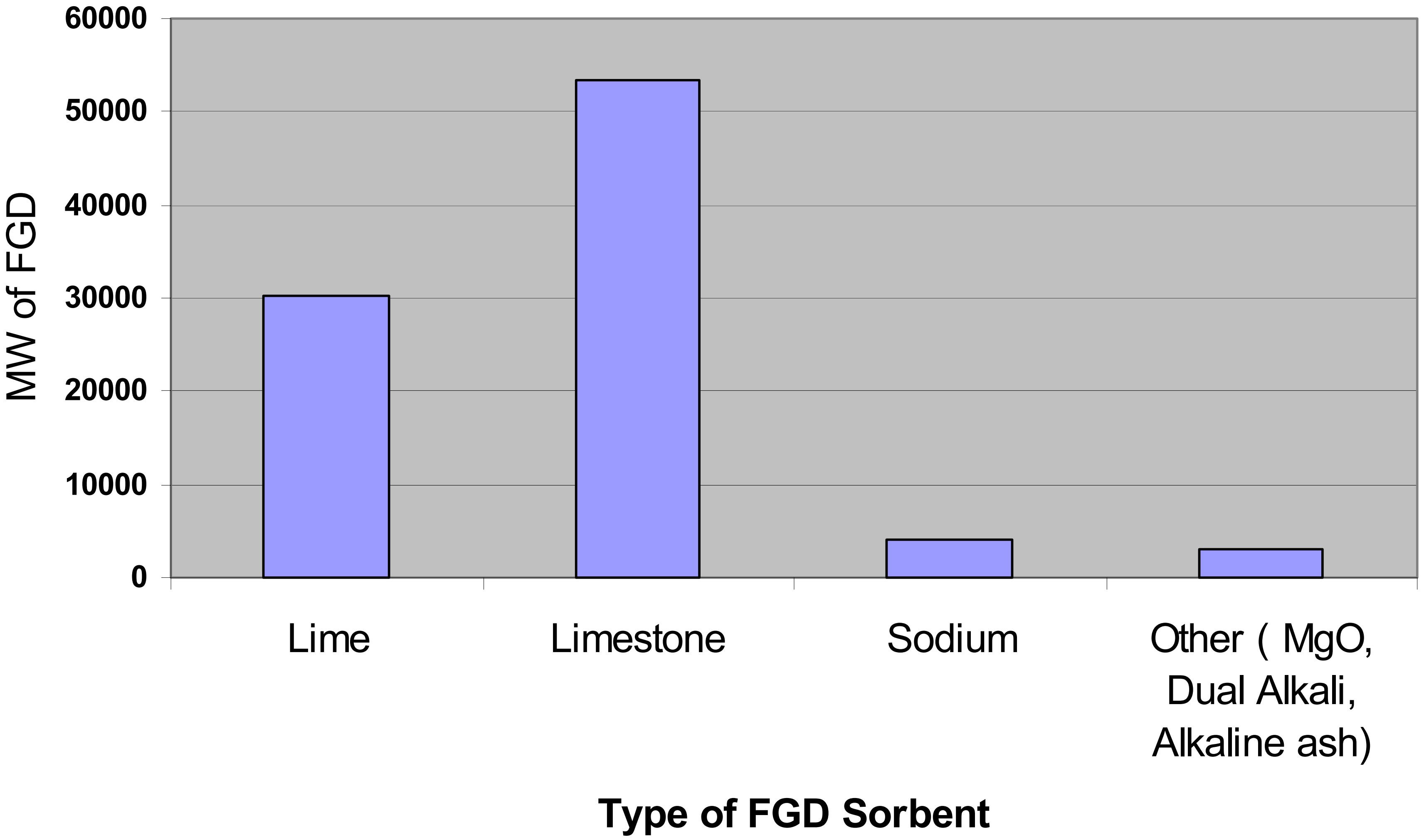
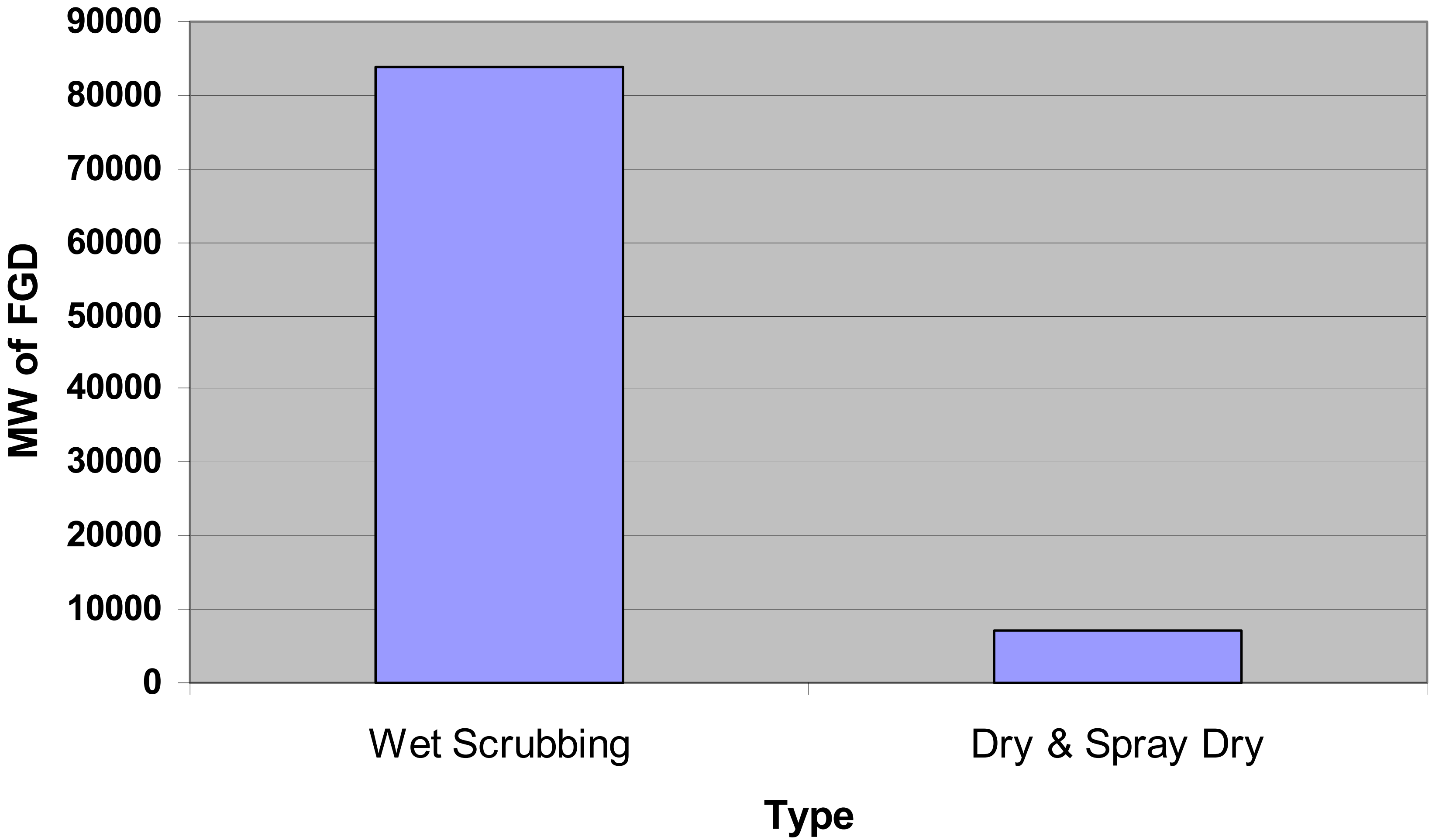
SO2 Sorbent Injection



FGD Installations in the USA by Sorbent



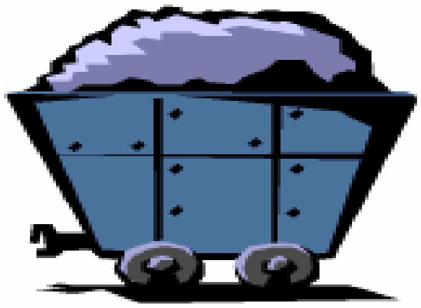
Type of FGD – Dry or Wet



SO2 and NOx Control via FGD and SCR – shown together

Source US EPA projections under Clear Skies Initiative using IPM model

Other SO_2 Control Methods



- Fuel switching
  - Low-sulfur (eastern) bituminous
    - Particulate control changes need to be dealt with (resistively of ash changes making capture via electrostatic precipitator difficult)
  - Very low sulfur Powder River Basin (PRB) subbituminous
    - Reduces sulfur, but can de-rate plant performance
    - Has NOx benefits, but mercury disadvantages
- Circulating dry scrubber just entering market
- Multi- pollutant control (SOx, NOx, Particulate, Hg) ideas are being developed (over 28 new processes being reviewed by EPRI)

The Real Opportunity for Cost Savings

- Possible improvements for FGD and spray dryers are small
- Integrated environmental controls (IEC) offer hope for 50+% reductions over separate controls
  - Benefits may not be great compared to advanced FGD and SCR
  - Benefits could be substantial if need control mercury and/or upgrade particulate control $\geq$ 99.7%

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EPRI R&D Focus on SO_2 Control

- Process vendors focus is selling new equipment – capital cost is an issue
- EPRI focus is on lower cost alternatives
- Understanding fuel switch impacts
- Operating cost minimization
  - Cost saving operating procedures
  - Updates on advanced materials and coatings
- Design and operation for improved availability
  - Automated remote monitoring
  - Design guidelines for trade-off between redundancy and availability

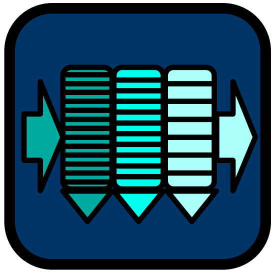
EPRI SO_2 Expertise

- Training – videos & classes
- Economics – FGDCOST spreadsheet to estimate FGD cost for a specific site
- Operation Guidelines:
  - Optimization of high efficiency FGD
  - Limestone selection
  - Cycling operation
  - Benchmark O&M practices for least-cost operation
  - Waste disposal
  - FGDPRISM (FGD process chemistry)

EPRI SO_2 Expertise (concluded)

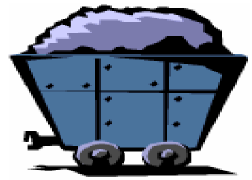
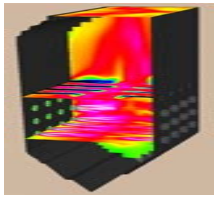
- Design guidelines/reports
  - Mist eliminators
  - Chloride removal (corrosion issue)
  - Bid specification
  - High efficiency designs
  - Materials selection
  - Retrofit design improvement study

SO2 & Particulate Control



- China has many Electrostatic Precipitators for particulate control but fuel switching for SO_2 control will mean new challenges
- EPRI has developed Operational procedures for dealing with issues -- impacts of NO_x controls, fuel switching on ESPs, etc.
- Solutions that benefit users with less capital investment – one example is humidification (water addition)
- EPRI has developed unique concepts -- advanced power supply good for coal switching
- Important information on other technologies impacts on particulates -- fine particle collection by FGD, evaluation of emerging technologies

Environmental Support

- EPRI has been working with developers and industry for 30 years in emission control
- EPRI has been working on coal quality impacts and changes worldwide in Europe, South Africa and North America and as China changes coal we can help understand impacts
- Lower cost controls and operation have been an important EPRI focus
- We do work on behalf of the power generators to reduce costs