Reinhold Environmental Ltd.

2009 APC Round Table & Expo Presentation

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SO_3 and Fine Particulate Mitigation

2009 APC/PCUG Conference

By Sam Kumar & Al Moretti

Air Pollution

- **Air Pollution is not a recent phenomenon**
- **In 1272, King Edward I of England tried to clear the smoke laden sky's over London by banning the use of "sea coal"**

SO_3 and Fine Particulate Mitigation

- Issues
- Sources
- Measurement
- SO_3 Control
  - Dry Sorbent
  - Wet ESP

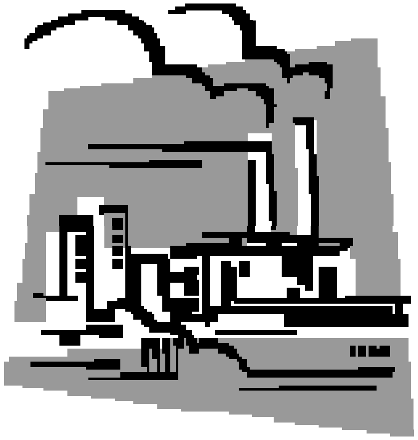
SO_3 and Fine Particulate Mitigation

- **Issues**
- **Sources**
- **Measurement**
- **SO_3 Control**
  - **Dry Sorbent**
  - **Wet ESP**

Particulates

- **Particulate is a term employed to describe dispersed airborne solid and liquid particles.**

- **Effects of particulates include:**
  - **Impaired visibility**
  - **Soiling of surrounding areas**
  - **Aggravates effects of SO_2**
  - **Human respiratory problems**



What is Fine Particulate?

According to the US EPA :

- **Fine particles are 2.5 micrometers in aerodynamic diameter and smaller.**
- **Typically in aerosol form**
- **Believed to pose the greatest health risks. Because of their small size fine particles can lodge deeply into the lungs.**
- **Referred to as $PM_{2.5}$**

These particles can be directly emitted from thebsources or they can form when gases emitted from the source react in the air.

How Small is Fine Particulate?

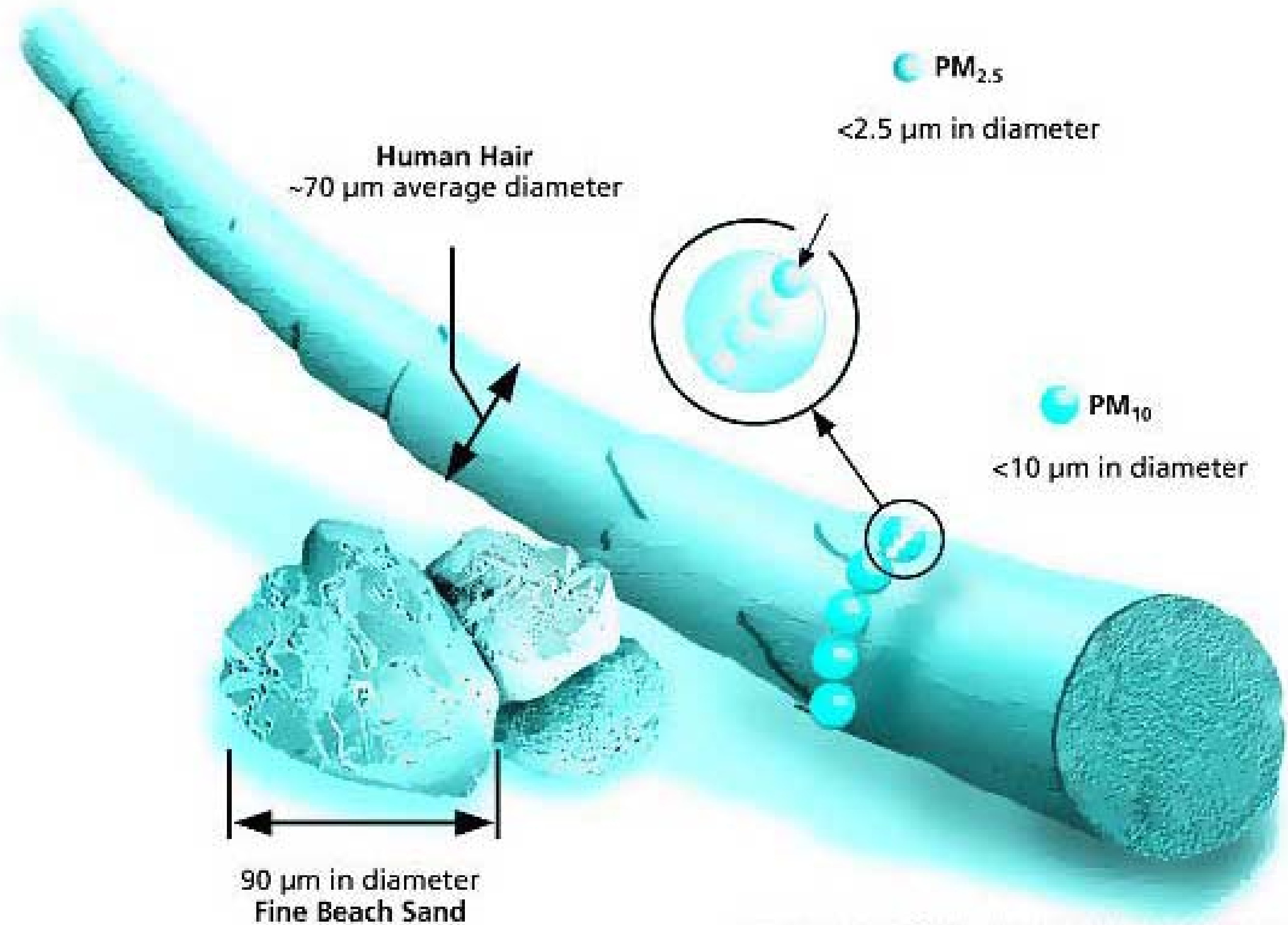
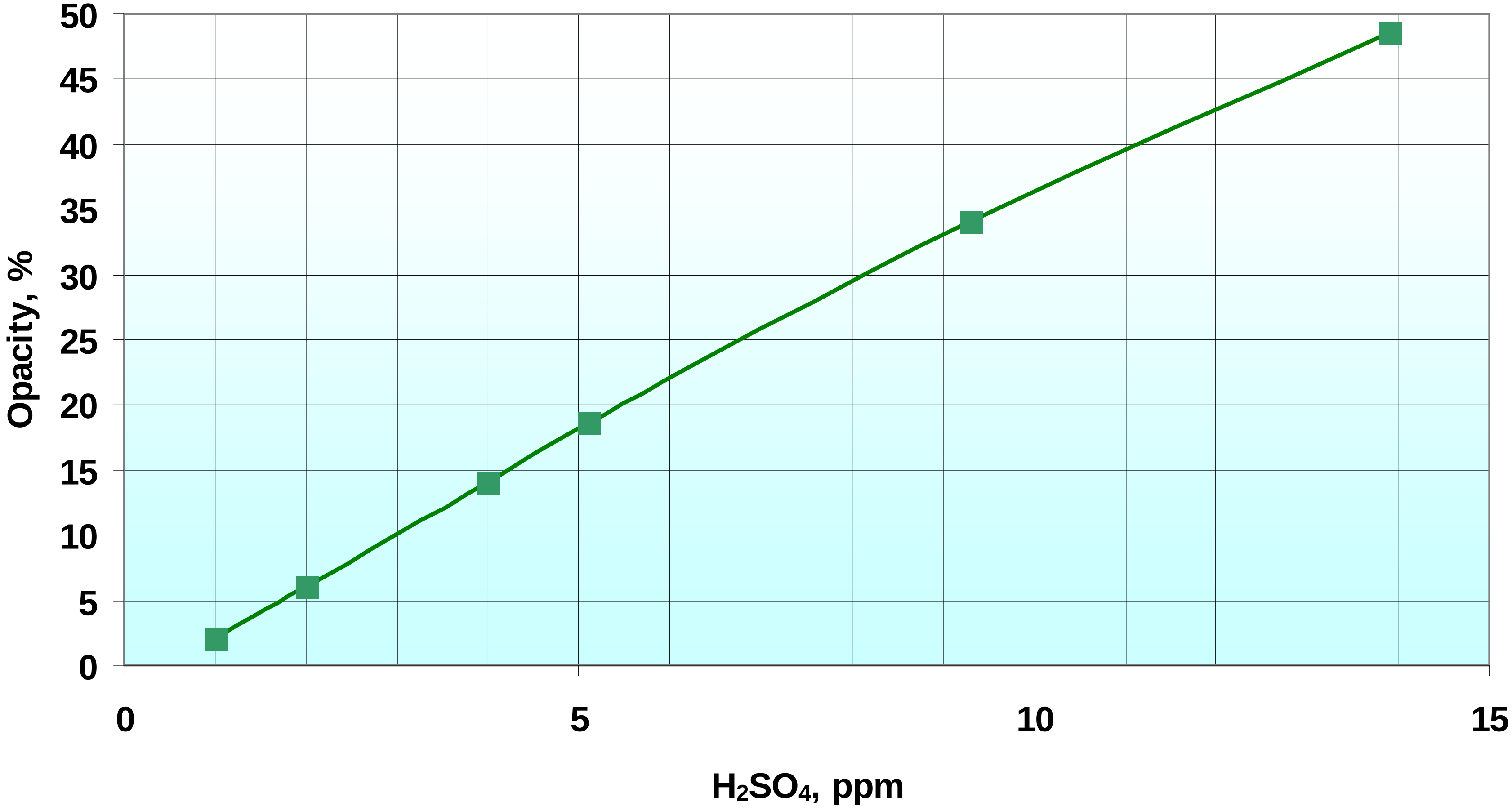


Image courtesy of EPA, Office of Research and Development

The Issues with SO_3

- **Control of sulfuric acid mist may be required for permits as $PM_{2.5}$**
- **Corrosion of air heaters and flues**
- **Adsorbs on flyash and PAC readily which reduces Hg removal**
- **Stack Opacity**
- **Difficult to Measure**

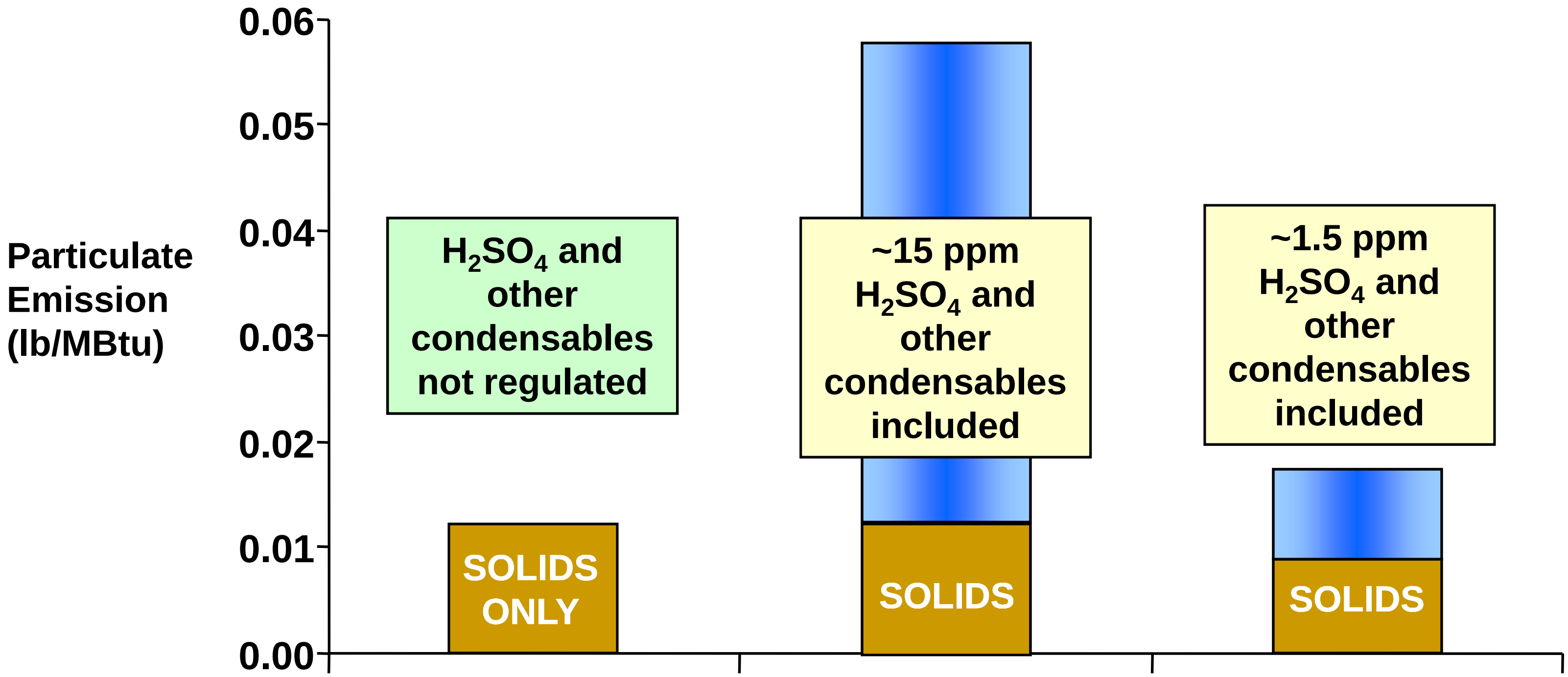
Predicted Plume Opacity for Large Unit with Dry ESP & Scrubber
(after evaporation of water fog)



Graph presented by Southern Research Institute,
APC Expo, SO_3 Mitigation Panel, Tampa, 7/05

Example of a Blue Plume

Particulate Permit Requirements Redefined for Power Plants (New Plants)



Pre - 2002

2002+
Total particulate permit requirement redefined

2004+
Permit levels for total particulate, including condensables, are significantly reduced

Wet FGD Stack Particulate Emission Includes:

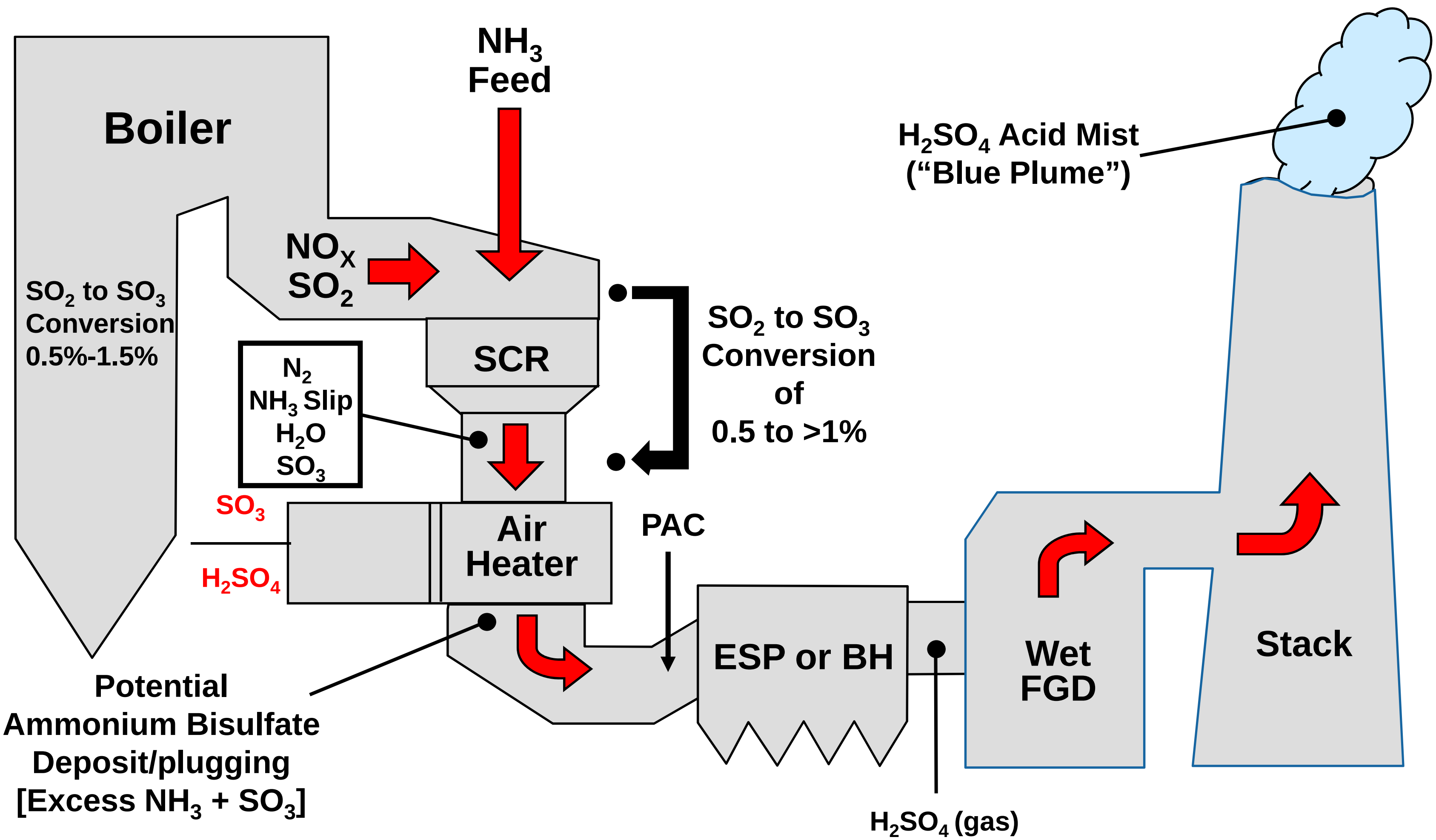
- Flyash
- Gypsum carryover
- H_2SO_4
- Other Condensable

SO_3 and Fine Particulate Mitigation

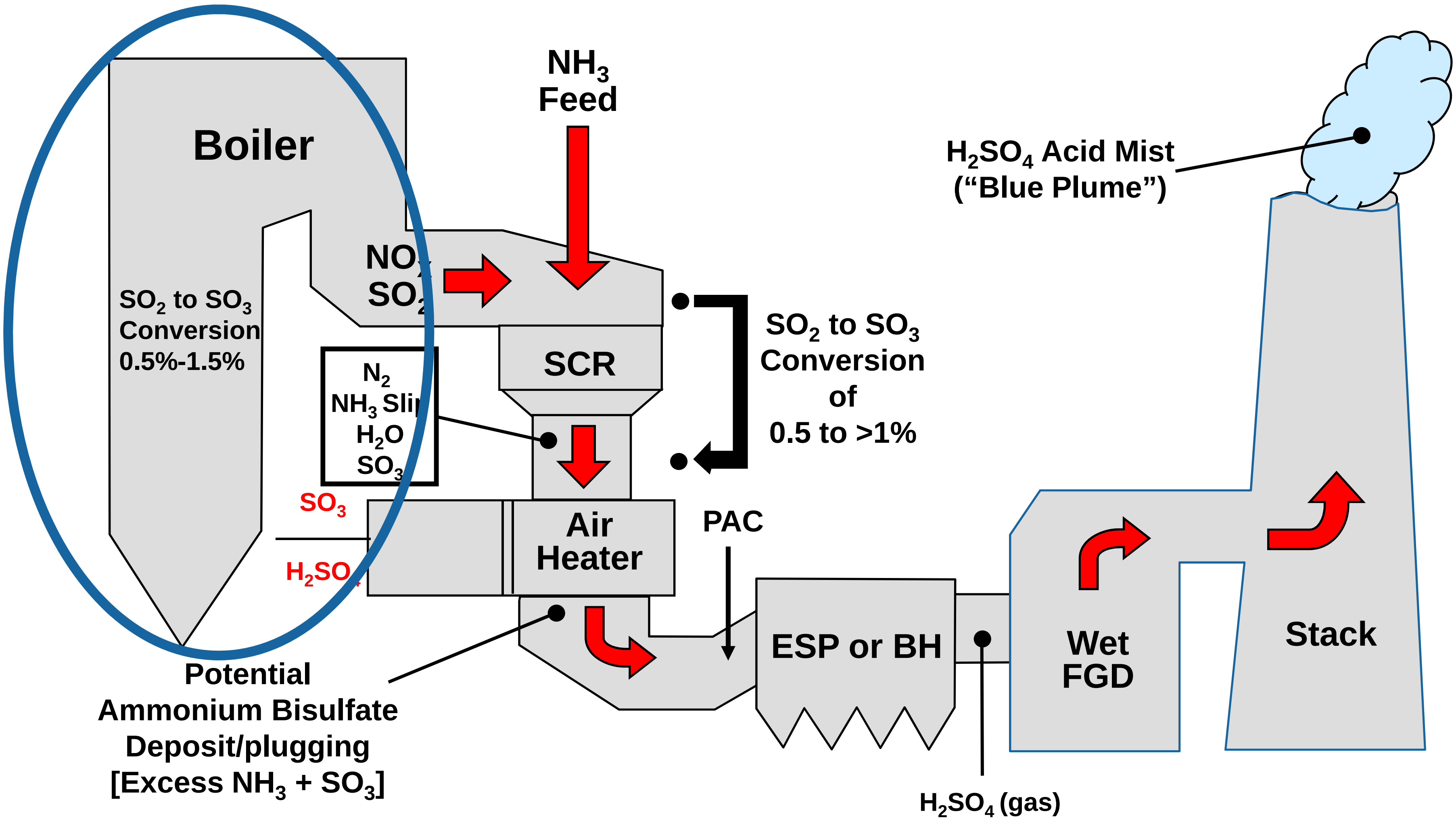
- **Issues**
- **Sources**
- **Measurement**
- **SO_3 Control**
  - **Dry Sorbent**
  - **Wet ESP**

Industry-Wide Issue: Bituminous Coal

SO_2 to SO_3 Conversion



Boiler Conversion



SO_3 Formation in a Combustor

- **When a fuel containing sulfur is fired in a combustor, the sulfur in the fuel combines with oxygen and forms gaseous sulfur dioxide (SO_2)**

- **Some SO_2 is further oxidized into sulfur trioxide (SO_3) through gas phase combustion reactions with catalytic compounds such as iron oxides or vanadium**

$$SO_2 + FeO_x => SO_3 + FeO_{x-1}$$

SO_3 Formation in a Combustor

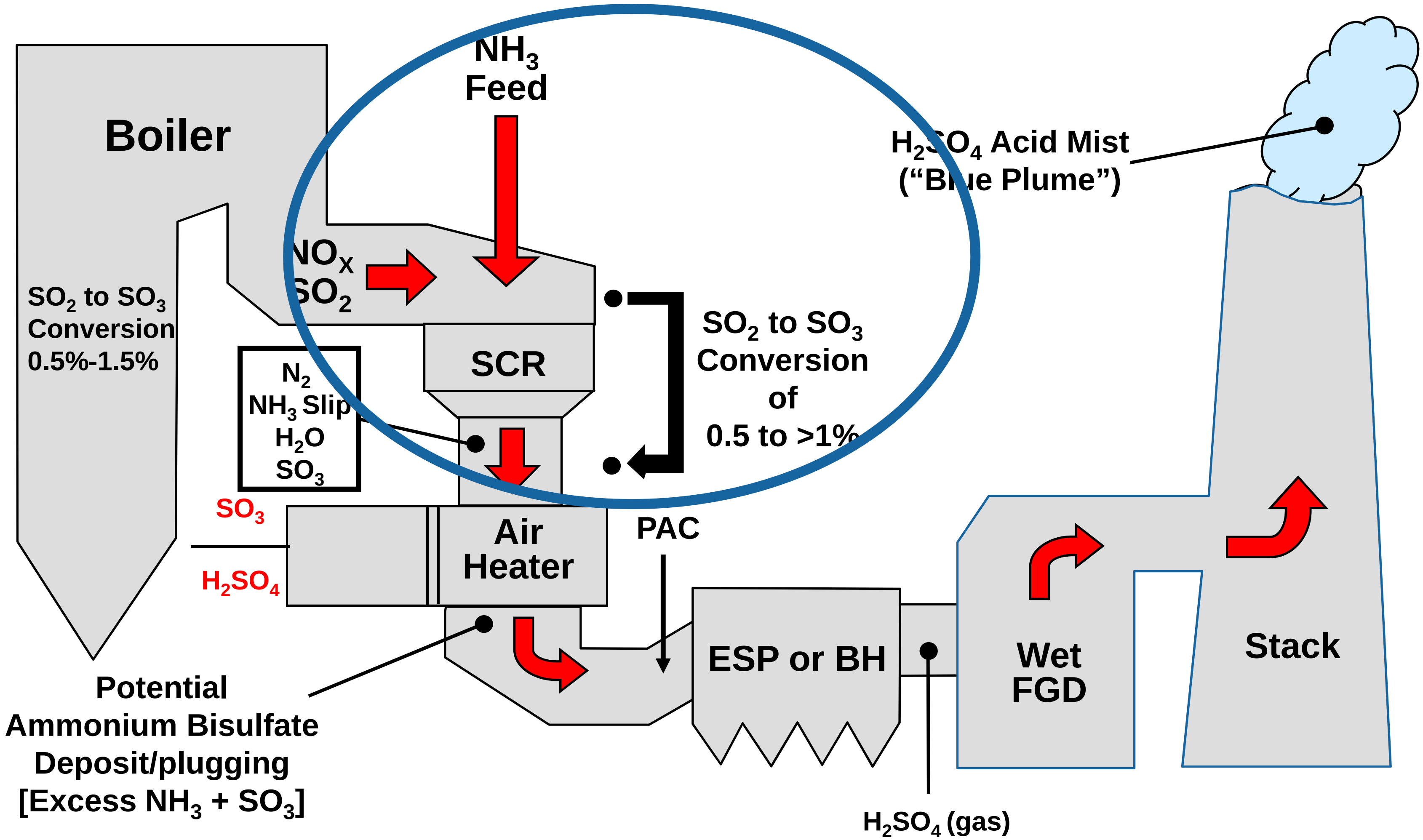
Oxidation reaction based on temperature, excess O_2, coal sulfur content, boiler load, area of tubes in boiler and amount of fouling on the tubes

- **Can be oxidized on boiler surfaces**
- **Ash build up on tubes reduces oxidation**
- **Fe in coal can increase conversion**
- **Vanadium in the fuel causes oxidation**
- **Ash composition – amount of alkali**

SO_3 Formation in a Combustor

- **Power River Basin (PRB) coal**
  - **<0.5% conversion due to high alkalinity in ash**
- **Eastern Bituminous Coal**
  - **Typically in the range of 0.5% to 1.5%**
- **Petroleum Coke or Fuel Oil**
  - **Typically over 2% conversion due to high vanadium content**

SCR Conversion

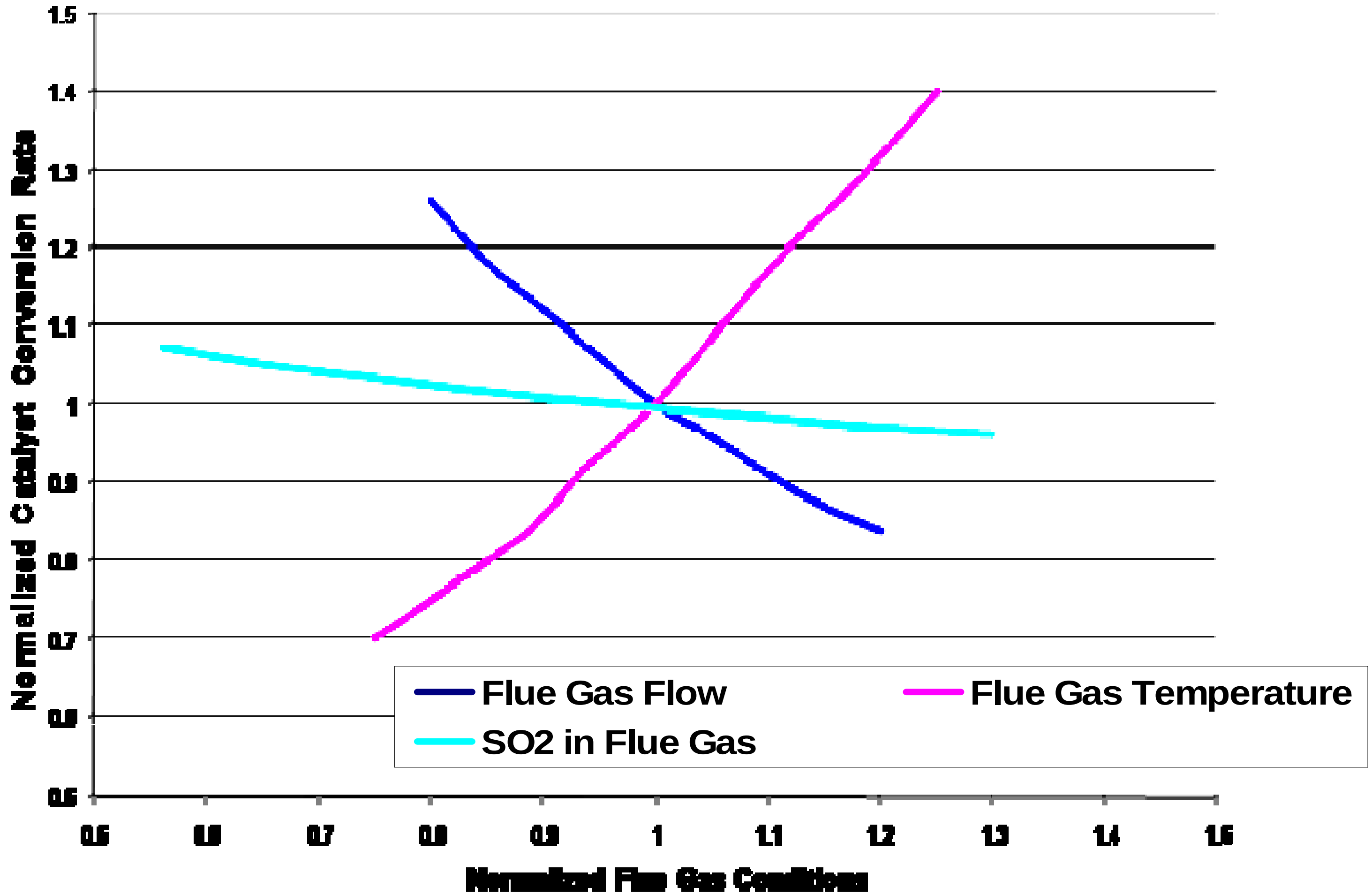


SO_3 Formation in the SCR

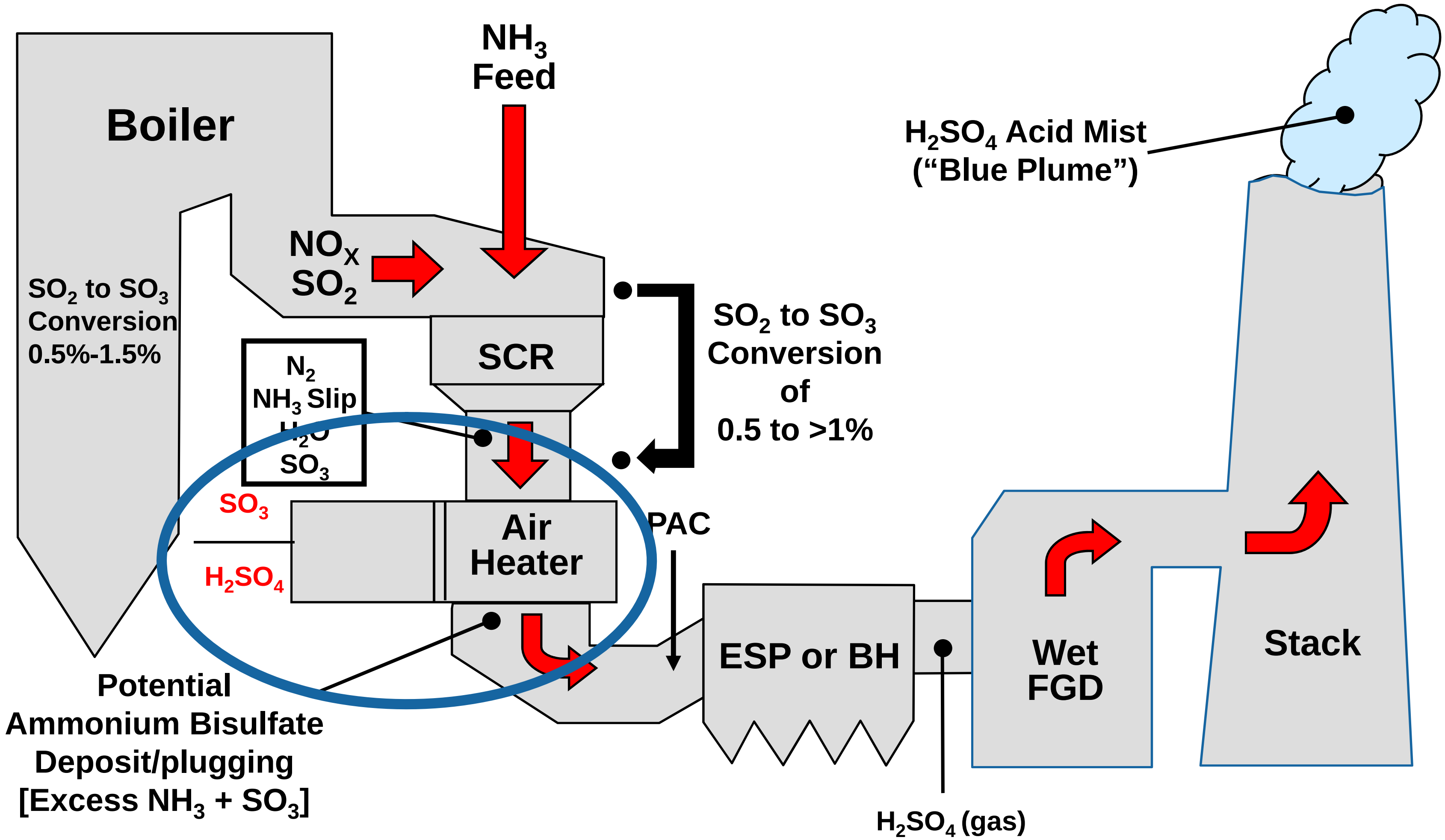
Some of the SO_2 is converted to SO_3 in the SCR

- SCR catalyst type affects conversion ratio – typical 0.5% to >1% percent conversion of SO_2 to SO_3 in the SCR
- Conversion rate affected by gas temperature, flow rate and SO_2.
- Conversion rate increases without NH_3 injection

Flue Gas Effects on SO_2 Conversion



Air Heater Removal

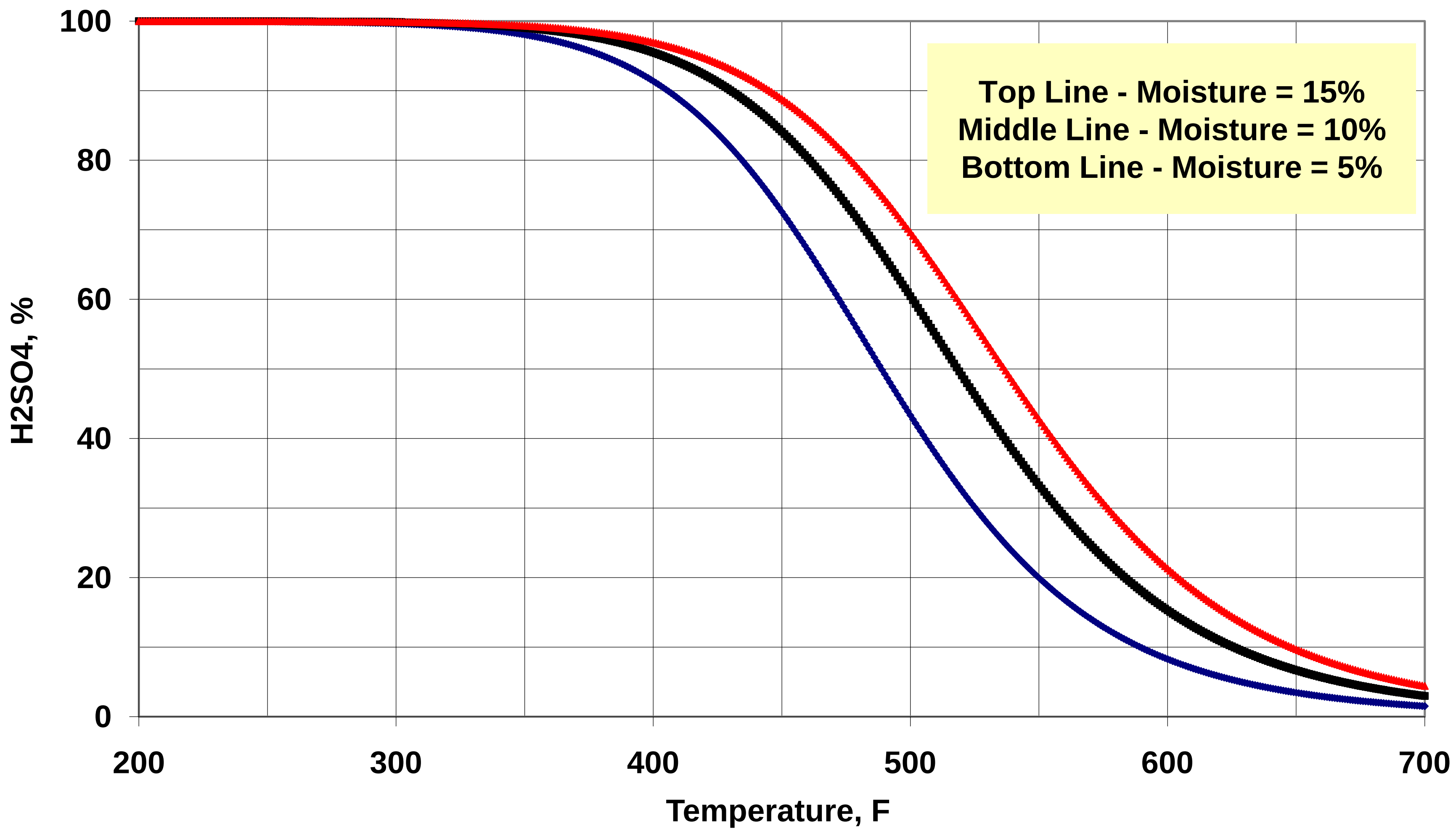


Formation of H_2SO_4

- SO_3 combines with H_2O to form H_2SO_4 vapor below approximately 1000°F
  - SO_3 is hydroscopic
- Typically forms as flue gas passes through the air heater

$$SO_3 + H_2O \rightarrow H_2SO_4$$

SO_3 to H_2SO_4 Conversion

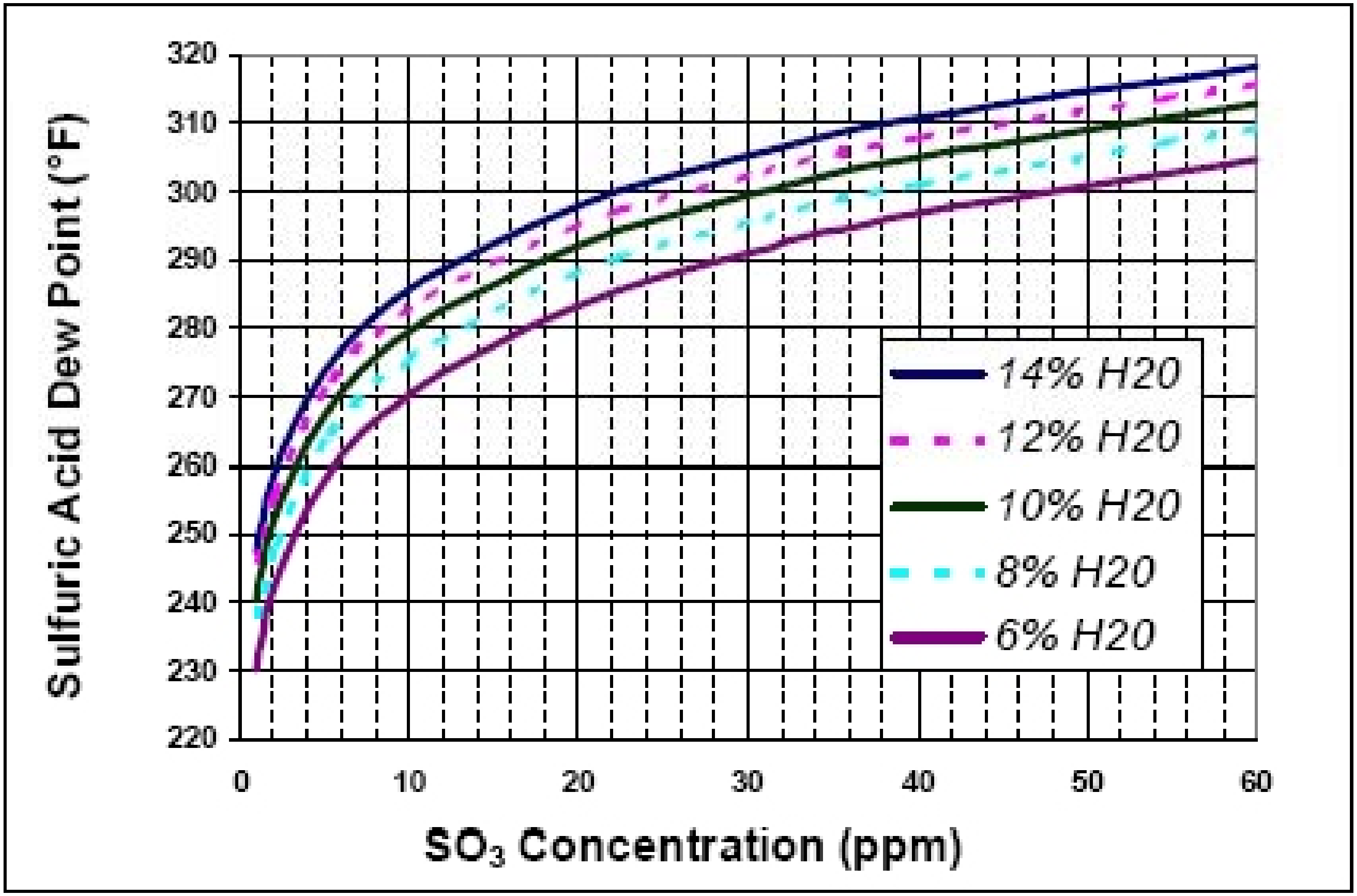


Formation of H_2SO_4

Condensation to H_2SO_4 liquid occurs below the acid dew point temperature

- **Acid dew point temperature varies with H_2SO_4 (as SO_3) concentration, pressure and moisture content**
- **As concentration increases, acid dew point temperature increases and vice versa**

SO_3 Acid Dew Point Curve

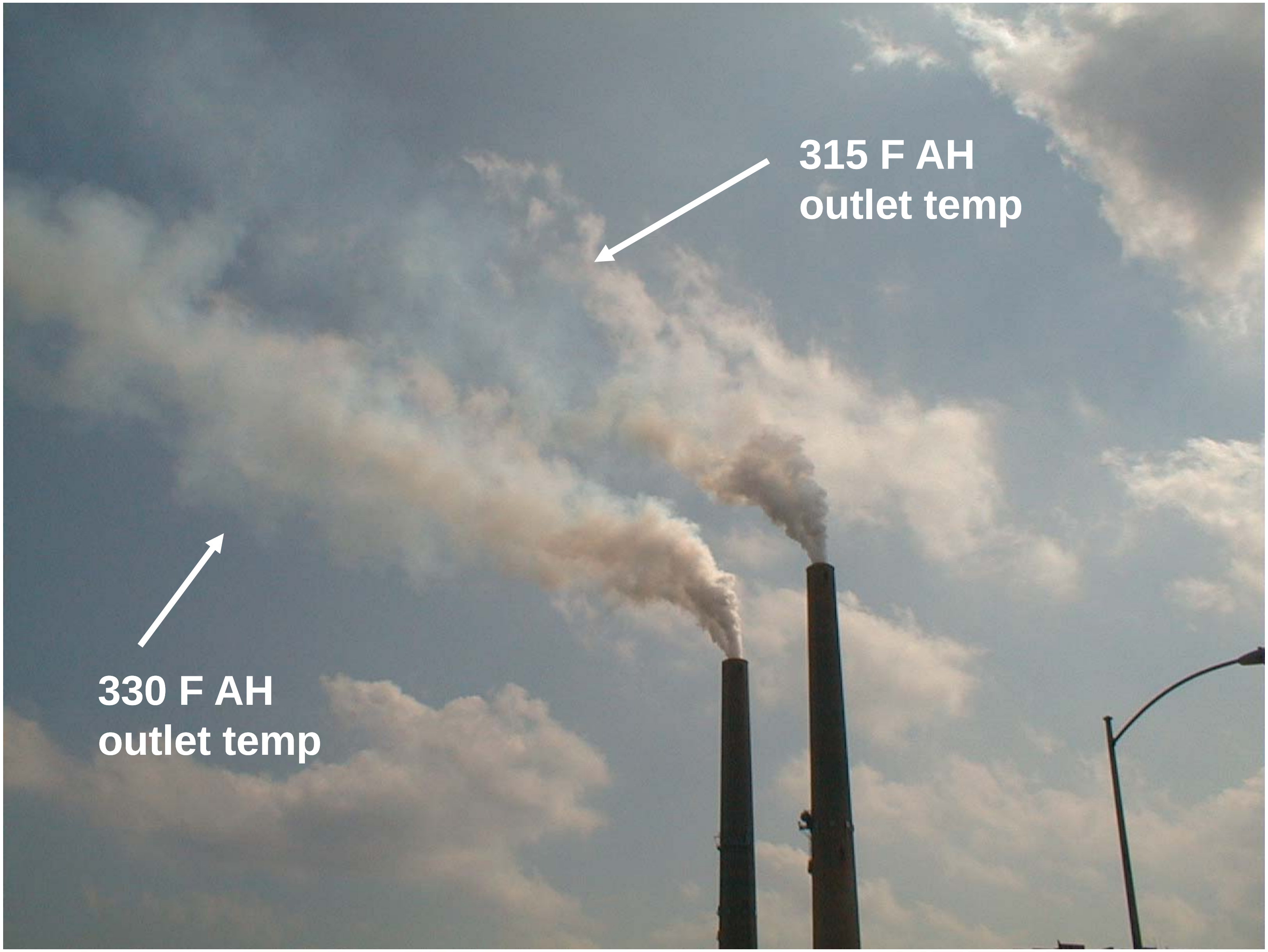


SO_3 Removal in Air Heater

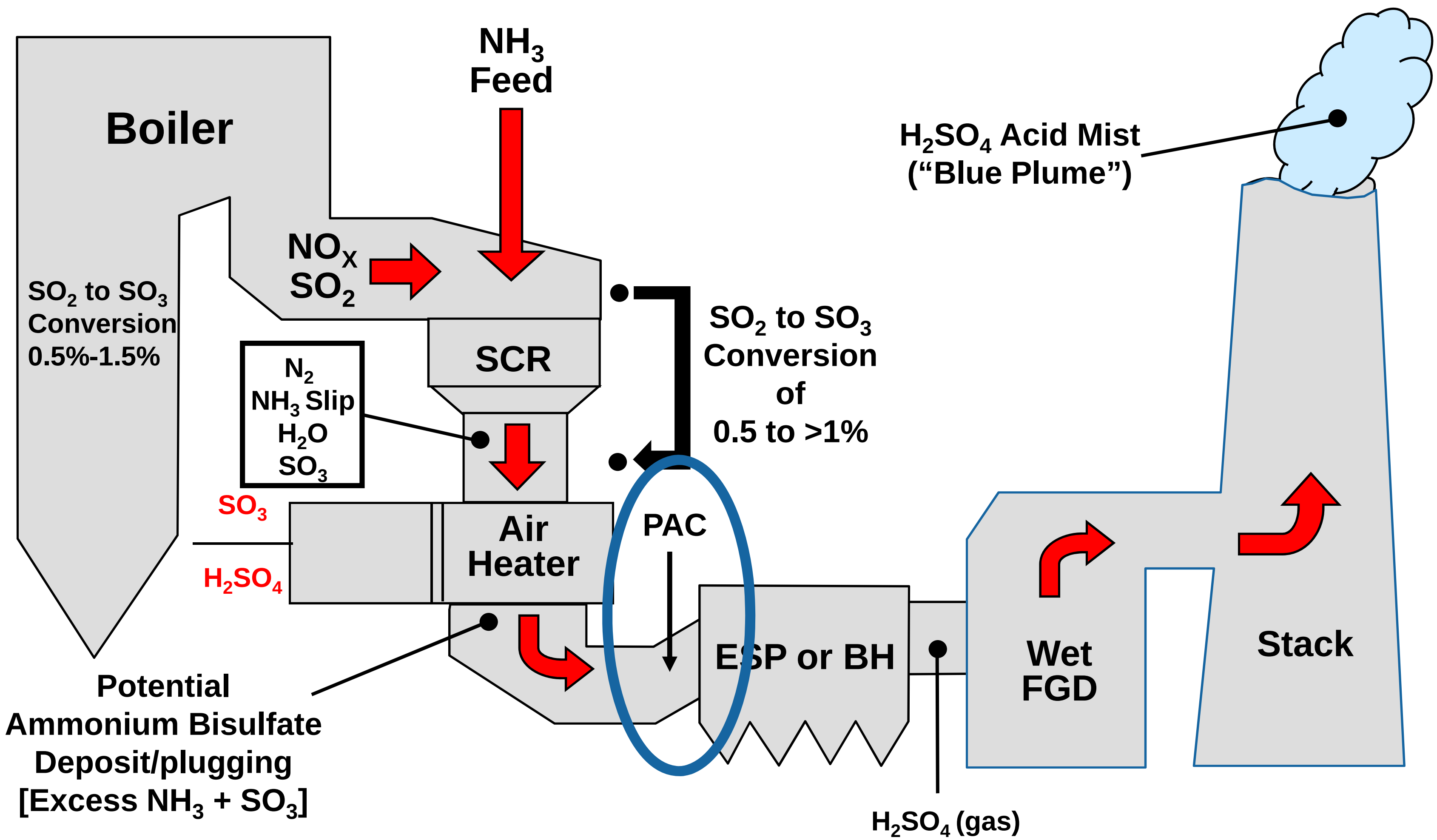
- Some of the acid (H_2SO_4) condenses and impinges on the colder surfaces of the air heater causing a portion to be caught in the air heater baskets and the ash

- The amount of SO_3 captured in A/H Depends on:
  - Air heater design
  - Cold end metal temperature
  - Operating gas temperature
  - Fuel and ash constituents

- Typically 20-30% of SO_3 entering the air heater is removed for Eastern Bituminous Coal


315 F AH
outlet temp
330 F AH
outlet temp

The Effect of SO_3 on Hg Control



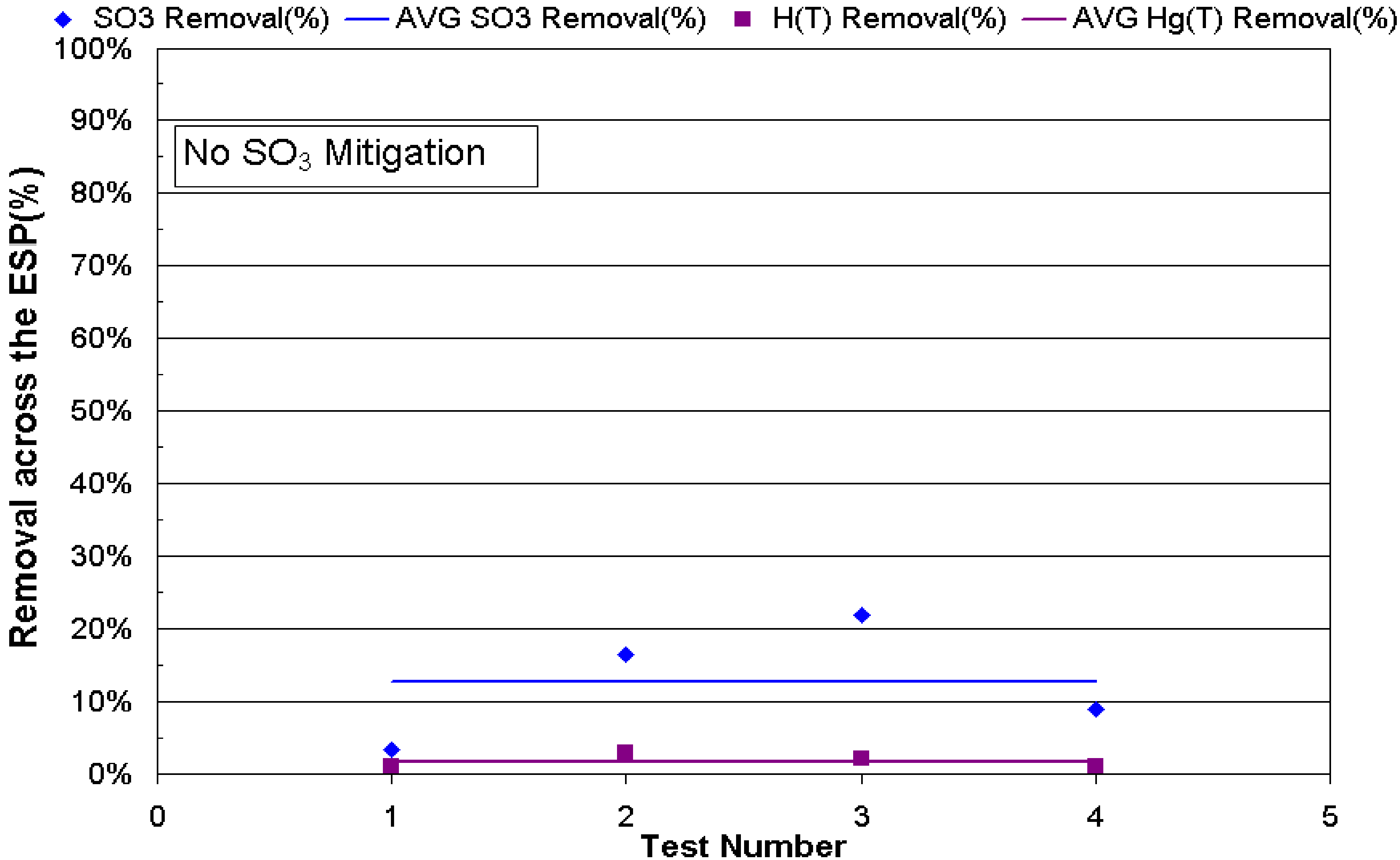
The Effect of SO_3 on Hg Control

- **SO_3 effects unburned carbon (poor man's PAC)**
  - ✓ **Poisons UBC by adsorbing on the surface (and)**
  - ✓ **Competes with mercury for the active sites**

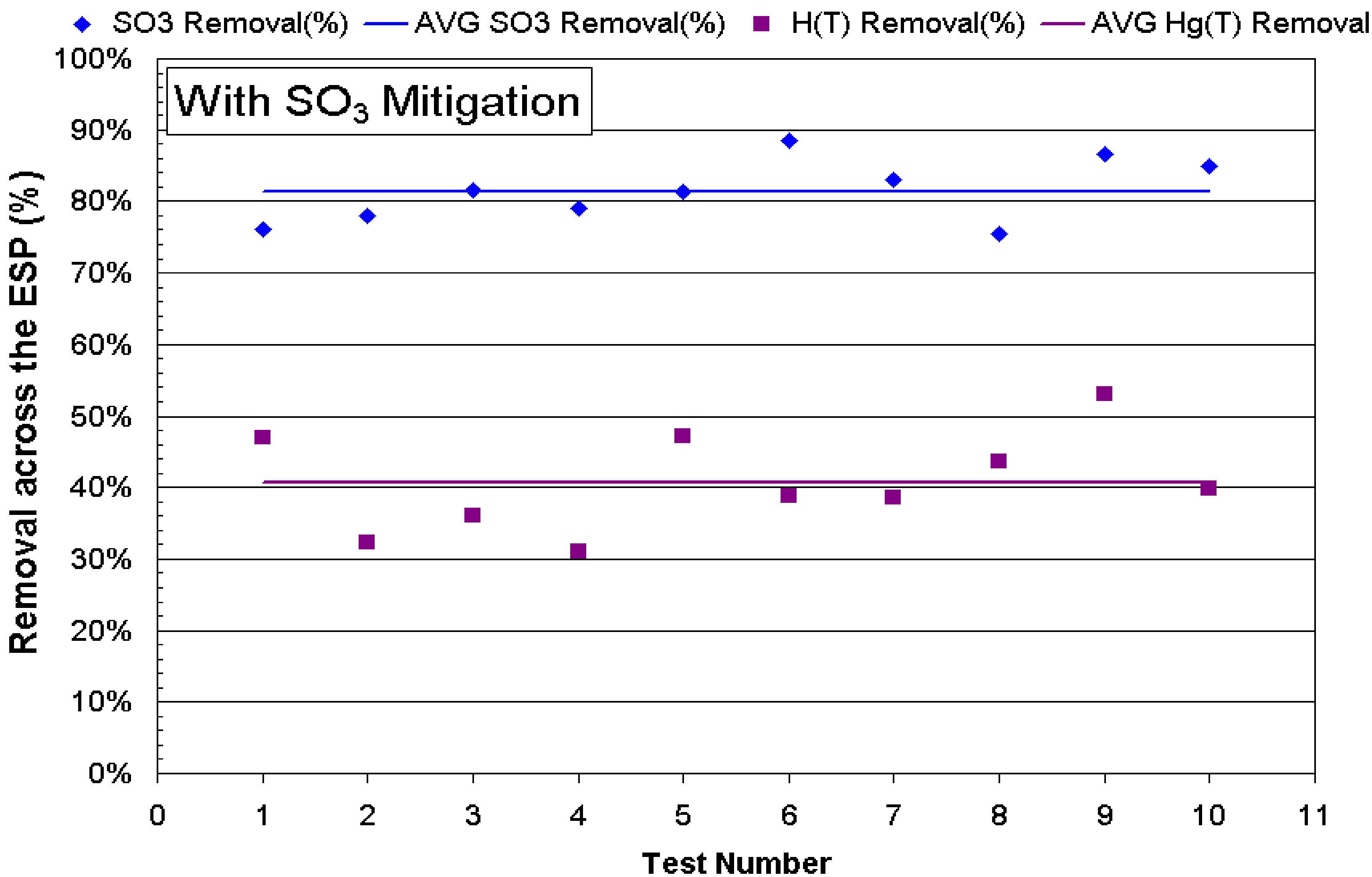
- **SO_3 also impacts powdered activated carbon for mercury control**
  - ✓ **SO_3 concentrations in the range of 5-10 ppmd reduce mercury removal capabilities of PAC**

As the concentration of SO_3 increases, PAC consumption increase

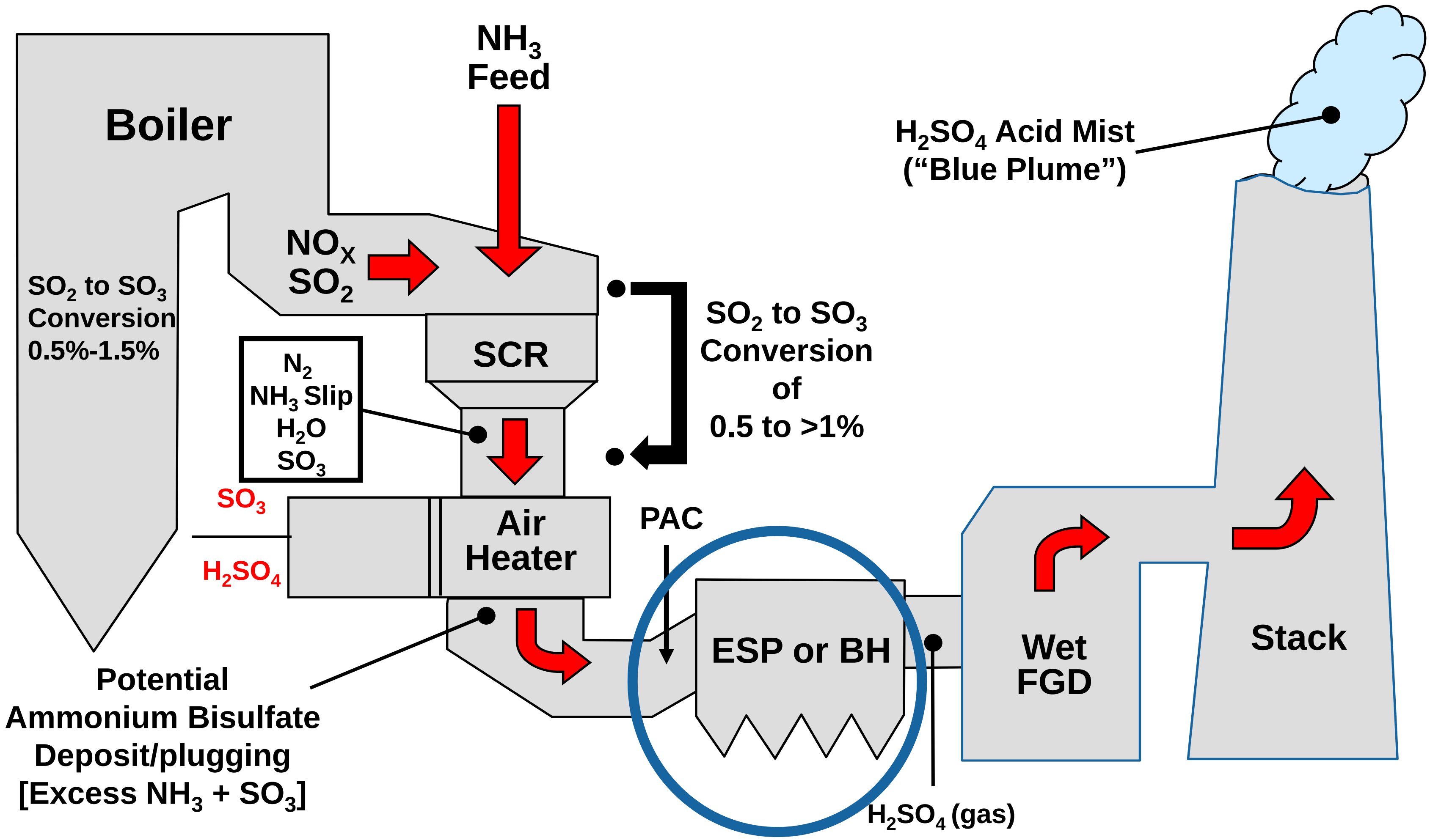
Hg Removal Across the ESP with No SO_3 Mitigation



Hg Removal Across the ESP with SO_3 Mitigation

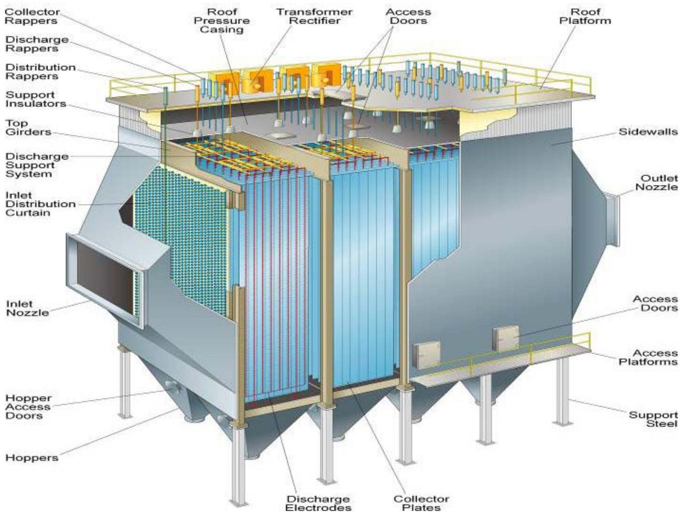


Particulate Device Capture



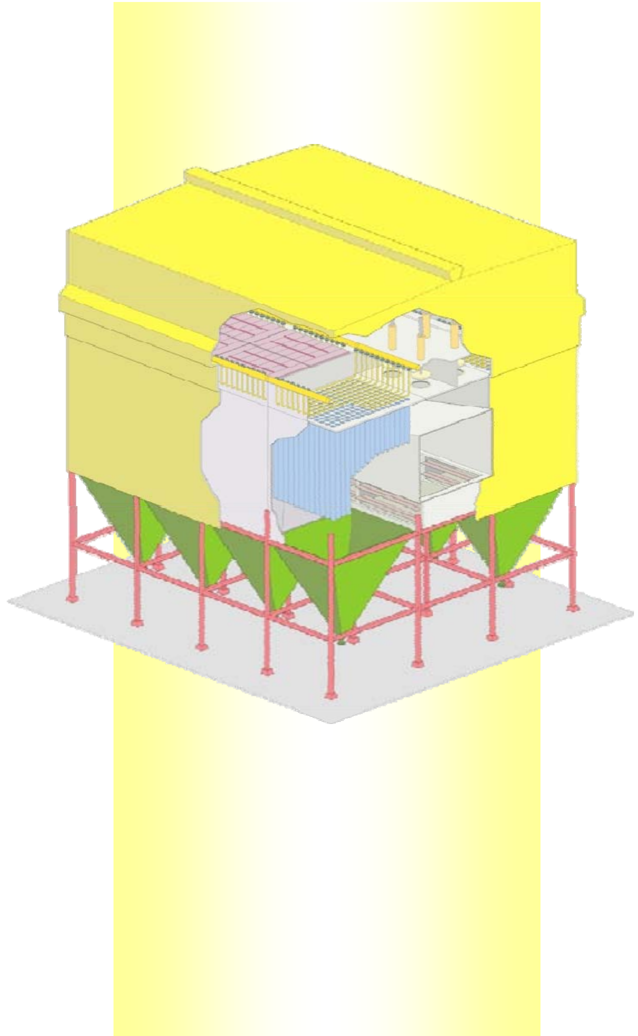
Capture of SO_3 in Dry ESP

- **Dry ESP is the industry standard for particulate capture on units burning medium to high sulfur fuels**
- **Condensed H_2SO_4 removal efficiency is dependent on:**
  - **Type of ESP (hot or cold side)**
  - **Alkalinity in the ash**
  - **Size of the H_2SO_4 aerosol particle size**
  - **Flue gas temperature**
  - **Overall particulate removal efficiency**



Depends on some SO_3 for greatest performance

Removal in Fabric Filter



As ash is removed in the fabric filter, a cake builds up on the bag

- **Depending on the alkalinity of the ash, this cake can enhance removal as the H_2SO_4 passes thru the bags**

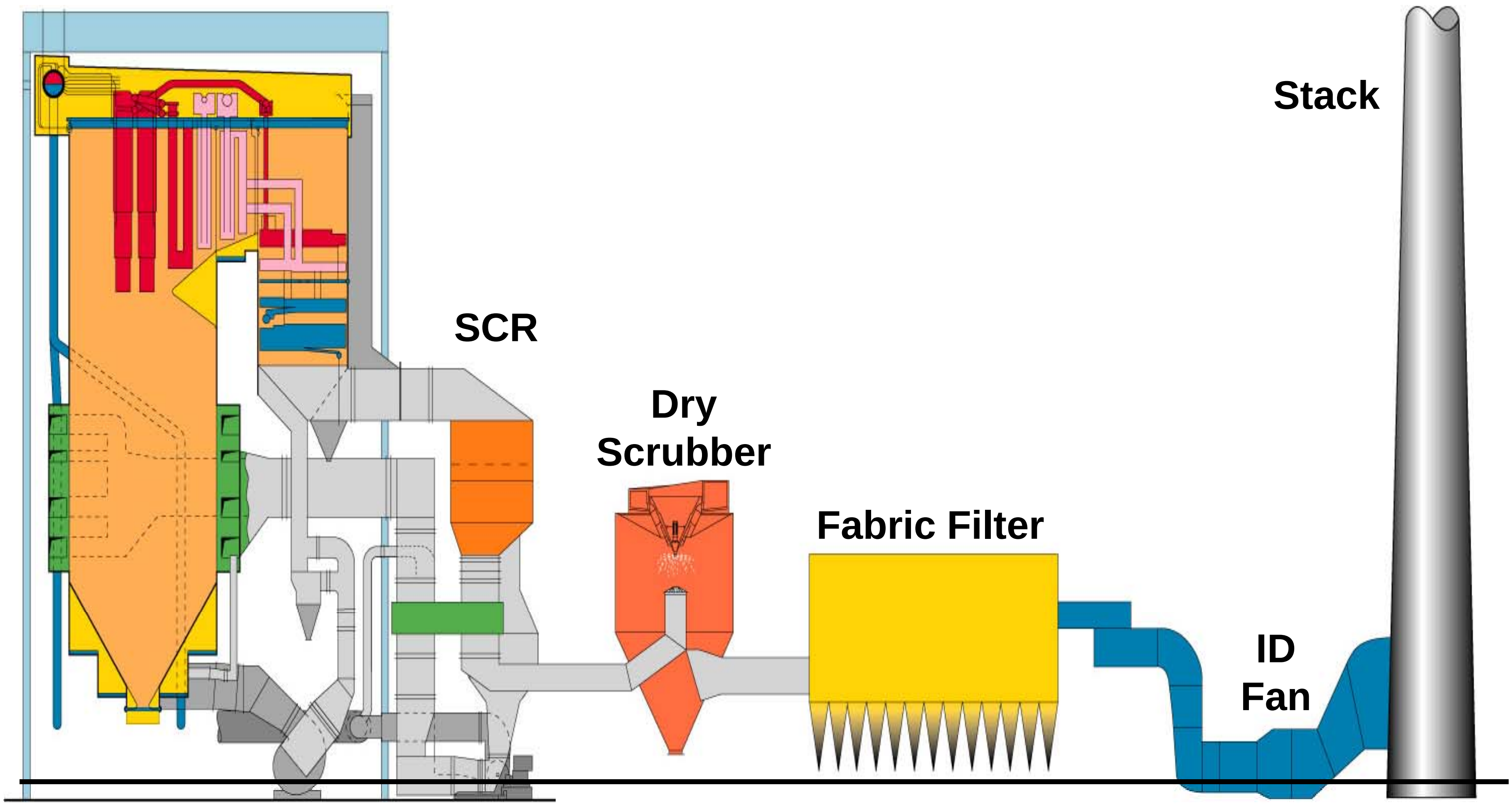
Fabric filter is utilized:

- **After A/H for primary particulate control device**
- **Or as the particulate collector in Dry FGD system**

Fabric Filter and Dry ESP Comparison

- **Data on low sulfur fuels indicates that a fabric filter is more effective at capturing H_2SO_4**
- **ESP allows for lower inlet operating temperatures compared to fabric filter which equates to greater boiler efficiencies**
- **Fabric filter operation is limited by:**
  - **Fabric material of the bags**
  - **Flue gas temperature**
  - **Acid dew point**

Typical Dry Scrubber & Fabric Filter



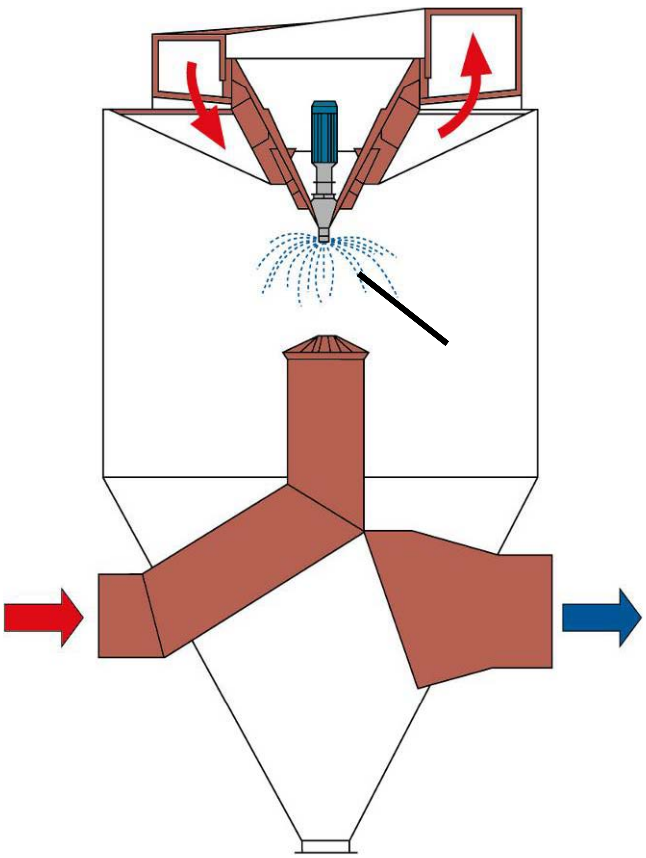
Dry FGD / Fabric Filter and SO_3

Lime slurry is injected as the regent

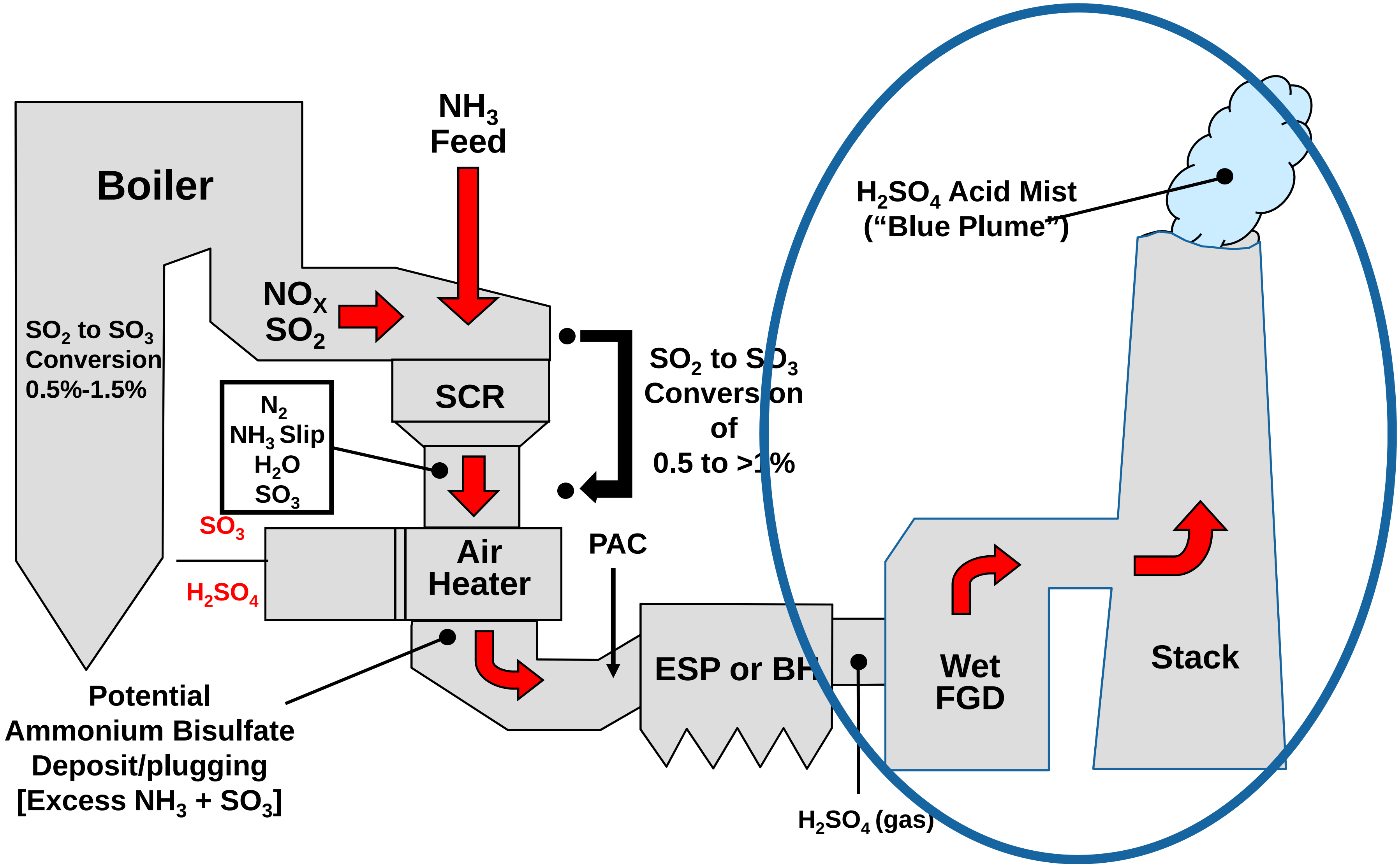
Reacts with SO_2 and SO_3 in SDA and on filter cake in baghouse

Effective system control of SO_2 and SO_3 for lower sulfur fuels including PRB coals

Measured H_2SO_4 emissions of <1 ppm (based on PRB coal)



Wet FGD – Vapor to Mist Conversion

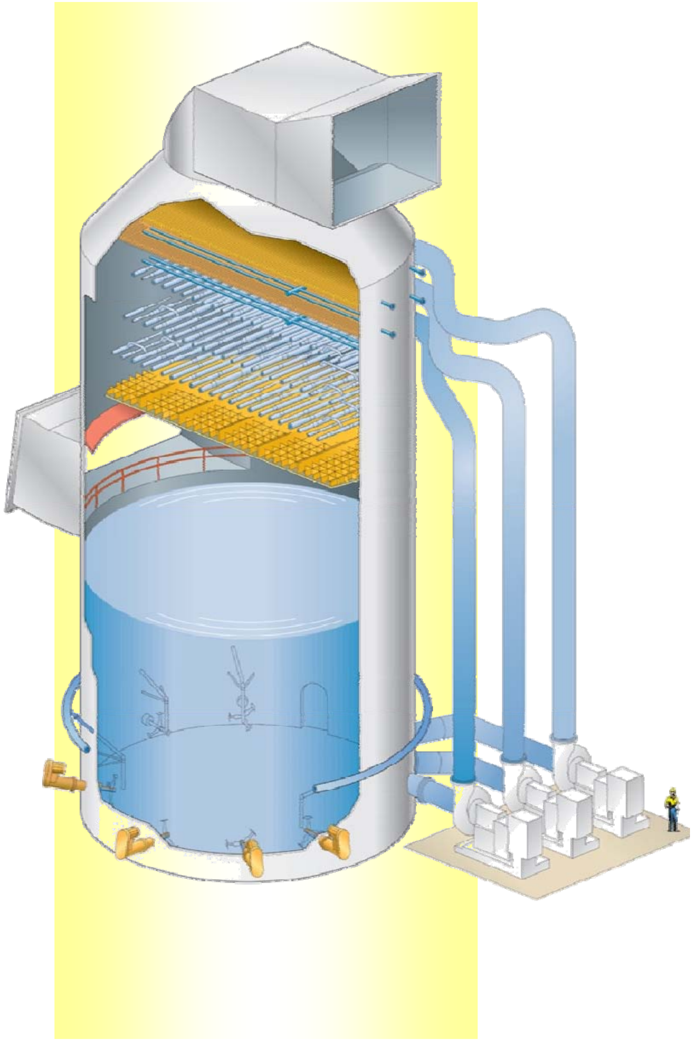


Mechanism for H_2SO_4 Removal in Wet FGDs

- **A Wet FGD system provides the ideal conditions for aerosol formation**

- **As the flue gas enters the scrubber quench zone, the H_2SO_4 vapor is quickly cooled below its dew point**
  - **The rapid condensation that takes place in the scrubber results in ultra-fine (sub-micron) aerosols, 0.4 – 0.7 microns**
  - **The size of the H_2SO_4 aerosol particle may be dependent on how fast it is condensed**

- **Removal of the aerosol in the scrubber is dependent on particle size**
  - **This explains the variability in acid mist removal in scrubbers in a given plant**



H_2SO_4 Acid Mist Formation in WFGD

H_2SO_4 Acid Mist Formation in Wet FGD (cont'd)

- Even though a portion of H_2SO_4 is removed across a WFGD, it may not be enough to reduce opacity
  - In the WFGD, forms an aerosol that contributes to a visible, trailing "Blue Plume"
- Small amounts of H_2SO_4 (> 5 ppmv) can cause opacity issues at the stack
- High stack opacities are typically associated with eastern bituminous fuels, due to:
  - Higher S coal
  - Low ash alkalinity
- Less buoyancy with wet (cooler) plumes which can result in touchdown at certain ambient conditions (i.e. high ambient temperatures)

SO_3 and Fine Particulate Mitigation

- Issues
- Sources
- **Measurement**
- SO_3 Control
  - Dry Sorbent
  - Wet ESP

SO_3/H_2SO_4 and $PM_{2.5}$ Measurement

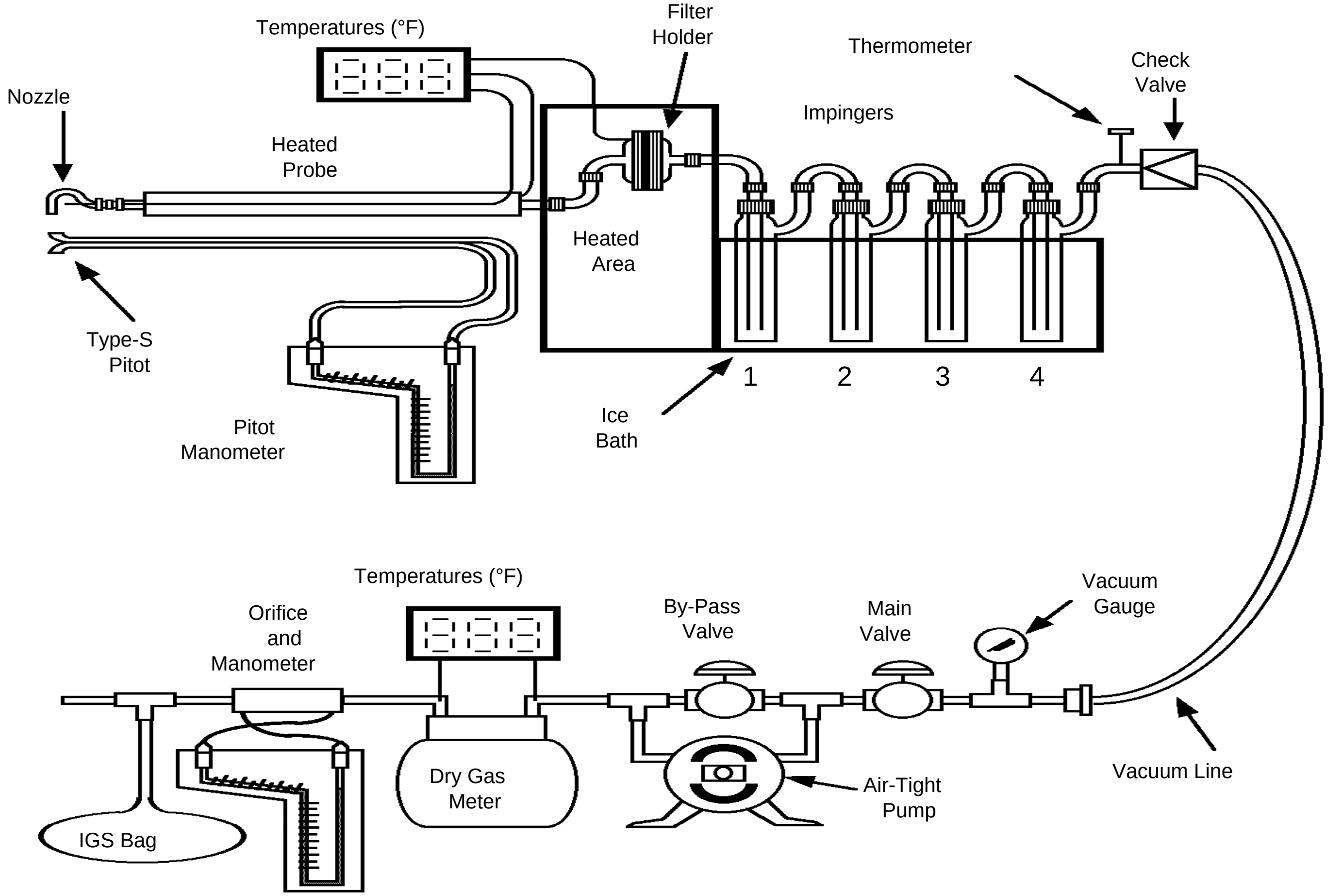
H_2SO_4

- **Method 8**
- **Controlled Condensation**

$PM_{2.5}$ (Total Particulate)

- **Filterable Fraction**
  - **Method 201A (in hot gas stream)**
  - **Method 5B (in saturated gas stream)**
- **Condensable Fraction**
  - **Method 202**
  - **Controlled Condensation (as QC check)**

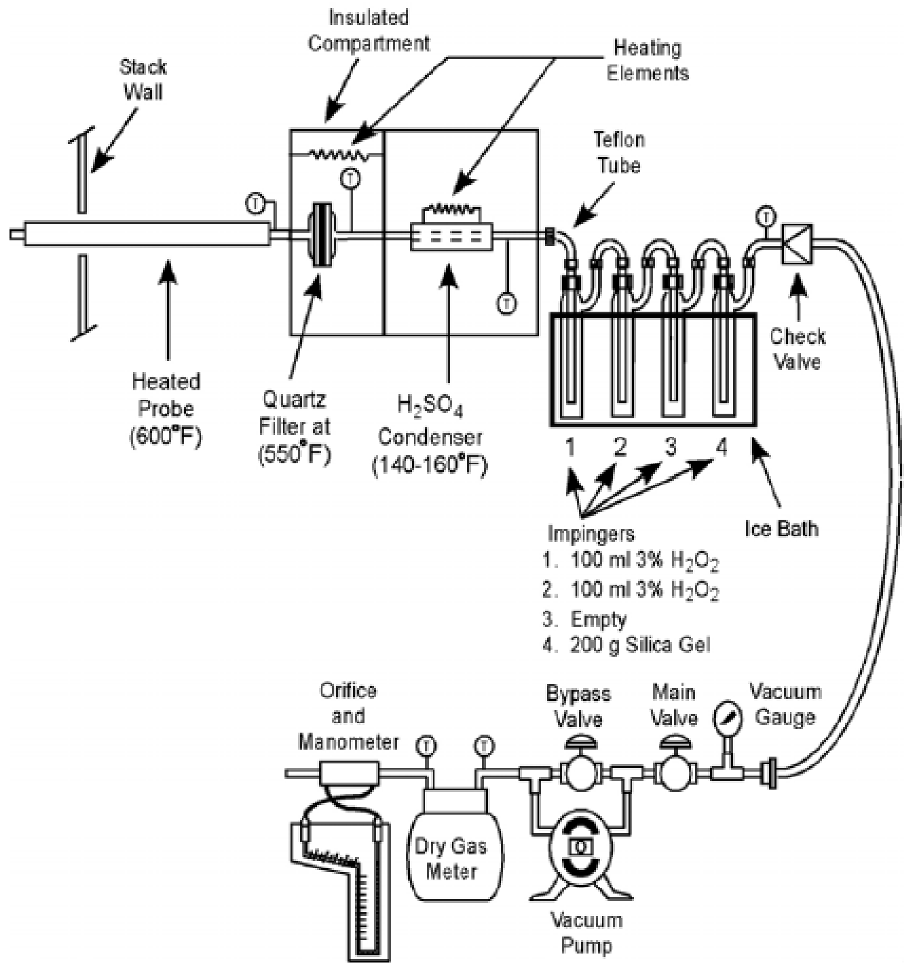
EPA Method 5B + 8 Sampling System



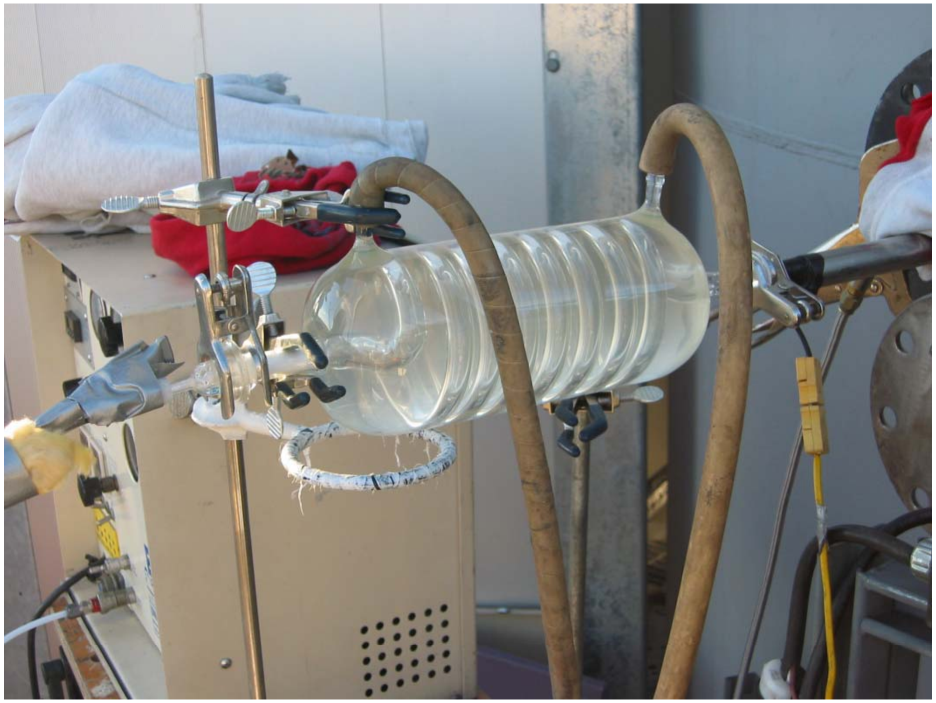
IMPINGER 1 = 80% ISOPROPANOL

IMPINGER 2 = 3% H_2O_2

SO_3 Measurement by Controlled Condensation System



"Controlled Condensation" for SO_3 vapor Method utilizes a glass condenser operated in a controlled temperature water bath (140F)



SO_3 and Fine Particulate Mitigation

- Issues
- Sources
- Measurement
- SO_3 Control
  - Dry Sorbent
  - Wet ESP

SO_3 Control

Injection Options:

- **Sorbent injection (ammonia, calcium, magnesium, or sodium compounds)**

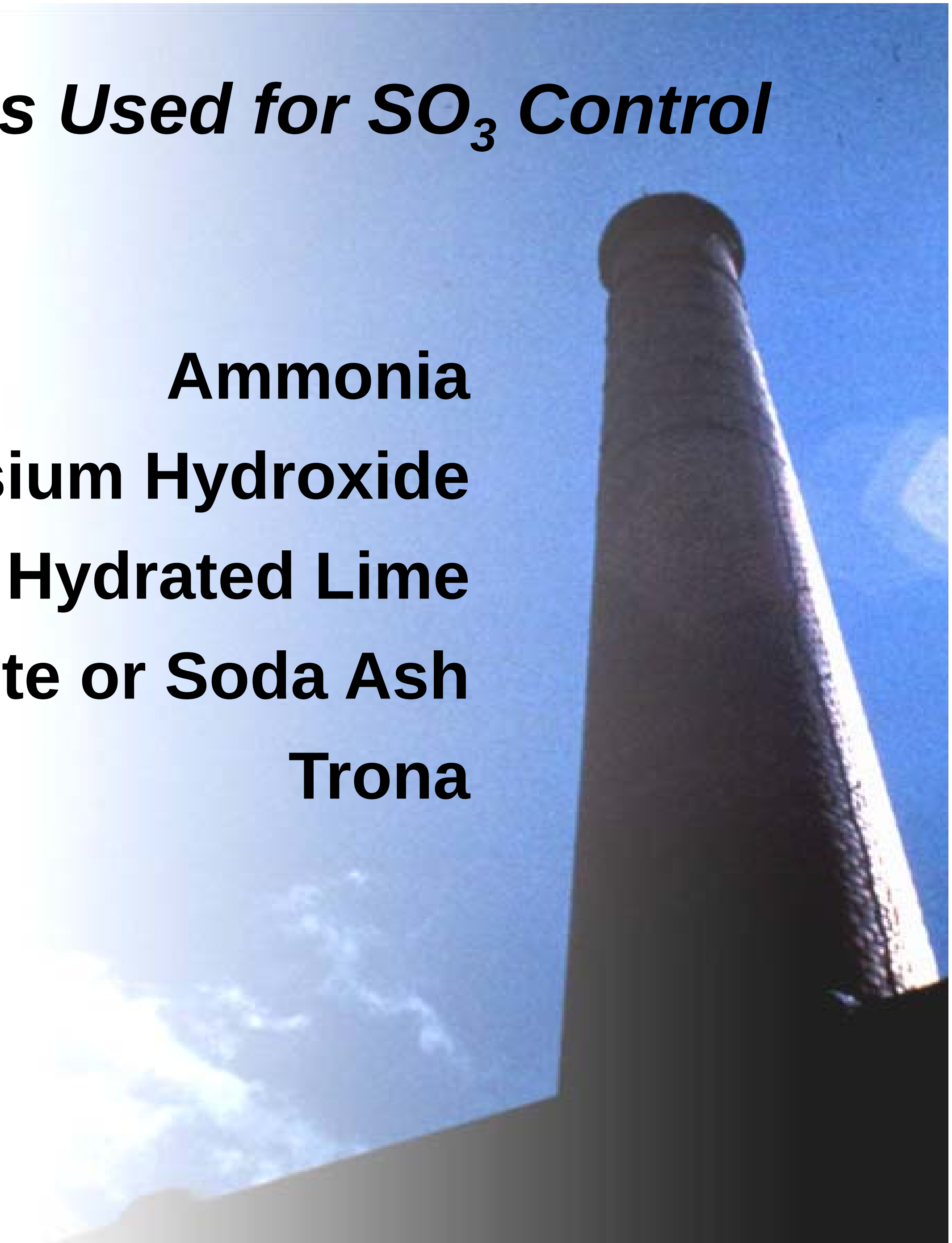
Hardware Solution:

Wet ESP

SO_3 and Fine Particulate Mitigation

- **Issues**
- **Sources**
- **Measurement**
- **SO_3 Control**
  - **Dry Sorbent**
  - **Wet ESP**

Popular Sorbents Used for SO_3 Control



Ammonia

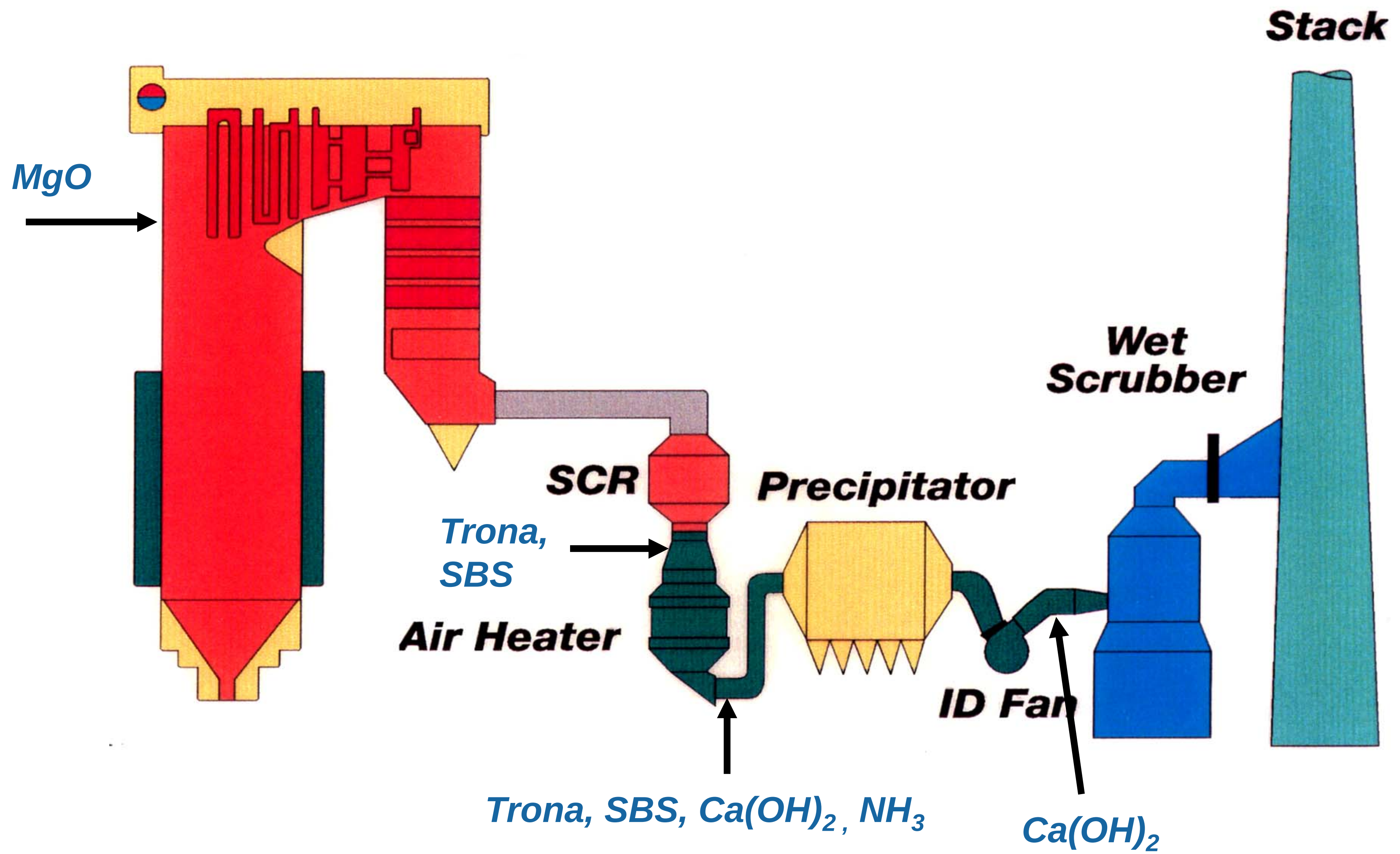
Magnesium Hydroxide

Hydrated Lime

Sodium Bisulfite or Soda Ash

Trona

Sorbent injection Locations (Typical)



Ammonia

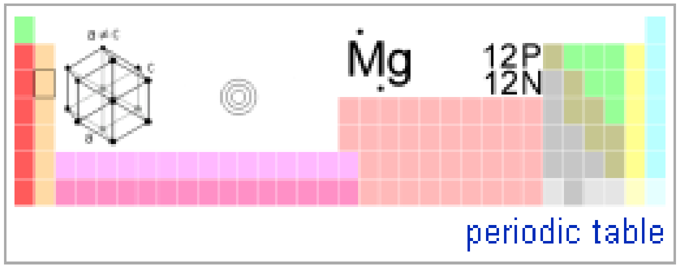
- Typically injected downstream of the air heater and upstream of the ESP to form ammonium bisulfate and/or ammonium sulfate
- Ammonia has minimal capital and O&M costs compared to other technologies
  - Plants with an SCR system already have ammonia on site, which could be utilized for SO_3 mitigation
- Good for 20 ppm SO_3, Removal in the 80% range

Ammonia

- The use of ammonia for SO_3 mitigation can impact flyash sales
  - Ammonia off-gassing from fly ash is a concern
  - Sites that stabilize scrubber sludge by mixing it with fly ash and lime could experience odor problems
  - Additional equipment may be required to burn off ammonia
- ABS formation may cause buildup in flues and cause ESP operational problems from ammonia salts
- There is also a risk of increased stack ammonia emissions

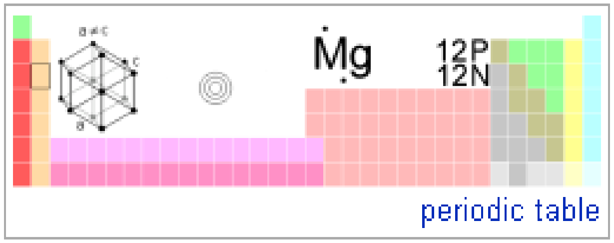
Magnesium Hydroxide

- Magnesium-based sorbents are primarily injected in the furnace
  - $Mg(OH)_2$ is effective at capturing SO_3 formed during the combustion process in the furnace
  - Not shown to be effective in controlling SO_3 formed from the catalyst
  - Typically used in conjunction with mitigation technology
- This sorbent can also have a beneficial impact in reducing slag formation on furnace surfaces
- $Mg(OH)_2$ build-up on tubes may help to reduce SO_2 to SO_3 Oxidation in boiler



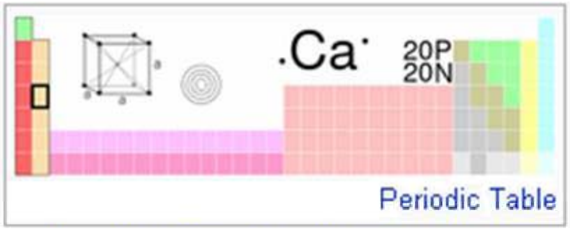
Magnesium Hydroxide

- O&M factors include nozzle maintenance and the wear associated with pumping an abrasive slurry
- Capital costs must include the slurry preparation equipment needed, and if winter operation is required, heat tracing and insulation of slurry pipes
- Reagent Cost is very costly



Hydrated Lime

- Hydrated lime, $Ca(OH)_2$, has been successfully utilized as a means to mitigate SO_3
- Injected on a dry basis after the air heater and ahead of the particulate collector or in front of FGD
- Injection system is simple keeping capital costs to a minimum
- Sorbent is readily available



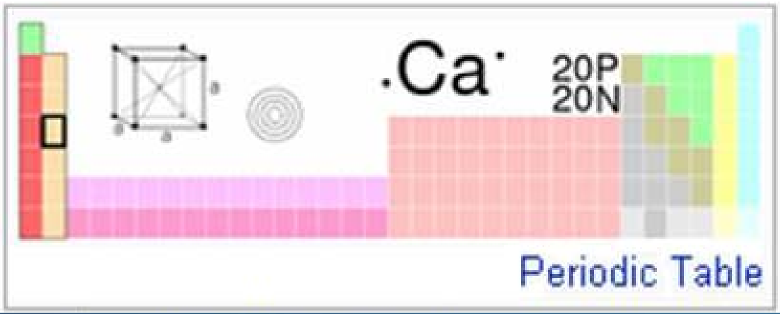
Hydrated Lime

- Not all hydrated lime is the same. Surface areas and available Ca(OH)2 should be considered in any evaluation.

- Works better with large ESP's

- Does not impact ash sales

- Lime tends to not be as reactive as sodium based sorbents. Thus may require a longer residence time than sodium sorbents to maintain similar SO_3 reduction



Sodium Bisulfite (SBS) or Soda Ash

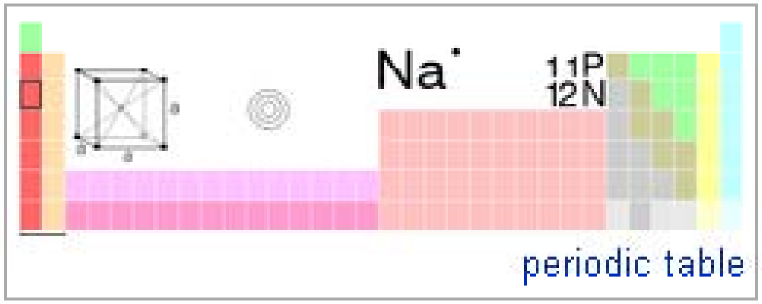
Sodium Bisulfite (SBS) or Soda Ash is very effective at removing SO_3

It is injected as a liquid

SBS can be purchased commercially or the by-product of a dual alkali FGD can be used

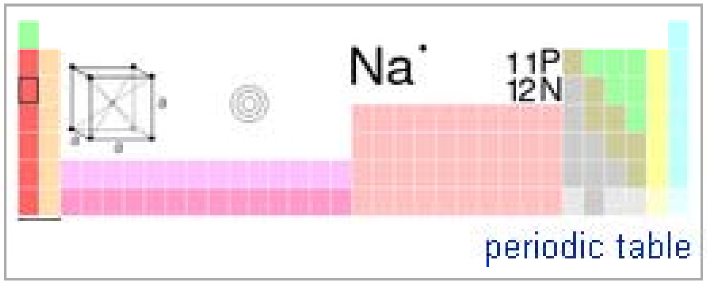
There are some reported maintenance issues:

- **Nozzles**
- **Duct deposition**
- **Air heater fouling has occurred when injected prior to air heater**



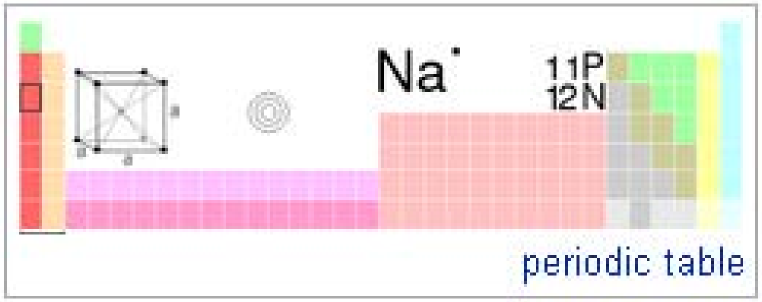
Sodium Bisulfite (SBS) or Soda Ash

- **Dual Fluid Atomizer is used for injection. Thus, compressed air is required for atomization**
- **Increased residence time is required to evaporate the moisture in slurry when compared to an all dry system**
- **Field tests have shown some improvement in ESP operation**



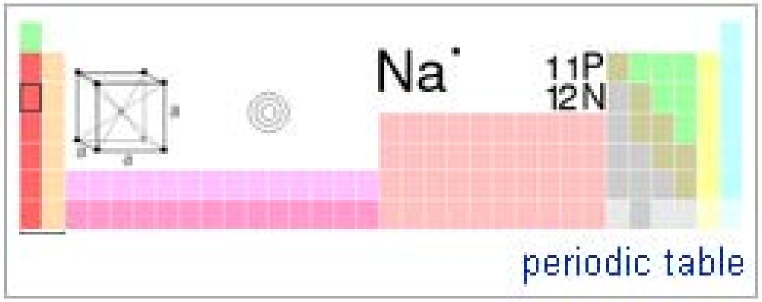
Trona

- **Like other sodium sorbents, Trona is very reactive and effective in removing SO_3**
- **Large mineral deposits found in Green River, Wyoming area**
- **Trona is used to manufacture Soda Ash**
- **Dry Trona is relatively benign and unreactive, minimizing plant safety concerns**



Trona

- Trona calcines in the flue causing a “popcorn” effect which increases the surface area and reactivity
- Trona is injected in dry form which reduces the capital investment required to get it to the flue gas. Typically injected downstream of the Air Heater
- An additional benefit of injecting Trona is improved DESP performance by reducing the resistivity of the ash
- Flyash consideration

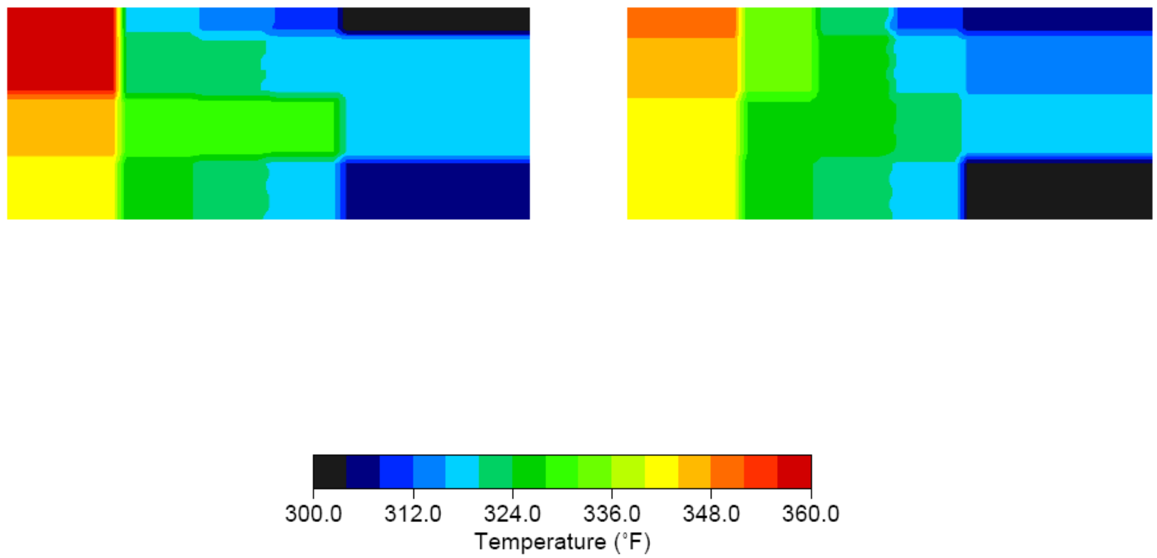


Dry Sorbent Injection - Key Design Parameters

- **Even flow distribution at injection location**
- **CFD Modeling**
- **Preferred Residence time must be considered for chosen sorbent**
- **Nozzle design, dispersion nozzle rather than open pipe**
- **With temperature stratification leaving the air heater, it is important to match the sorbent injection with the acid gas stratification**
  - **Optimizes removal and minimizes sorbent usage**
  - **Higher temps correlate to higher acid concentrations**

Formation of H_2SO_4

Air Heater Outlet Temperature Profile



SO_3 and Fine Particulate Mitigation

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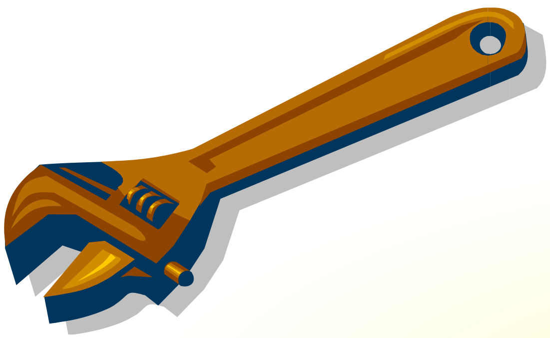
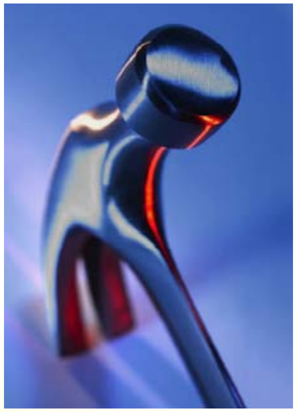
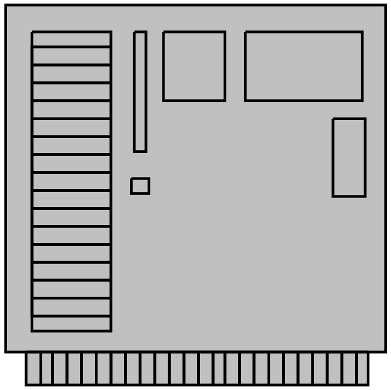




Wet ESP

"Hardware Option"

The Ultimate Solution for SO_3 and PM 2.5



Wet ESPs Are Not New!

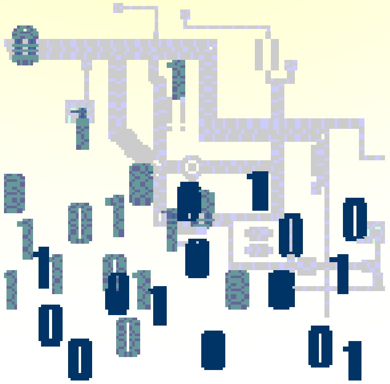
First commercial ESP was a wet unit put in service in 1907 in California for collection of acid mist

Wet ESPs have been used in the following industries/applications:

- **Non-ferrous smelters**
- **Steel industry**
- **Spent acid plants**
- **Paper industry**
- **Incineration**
- **Power plants burning unique fuels**

Thousands of industrial Wet ESPs have been installed since 1907

Wet ESP Theory



Wet ESP Theory

- **The basic theory of a Wet ESP is the same as a Dry ESP**
  - **a Wet ESP requires a water spray system rather than a system of plate & DE rappers**

- **Because acid mist is removed from a Wet ESP in the form of a solution, hoppers are typically replaced with a drainage system**

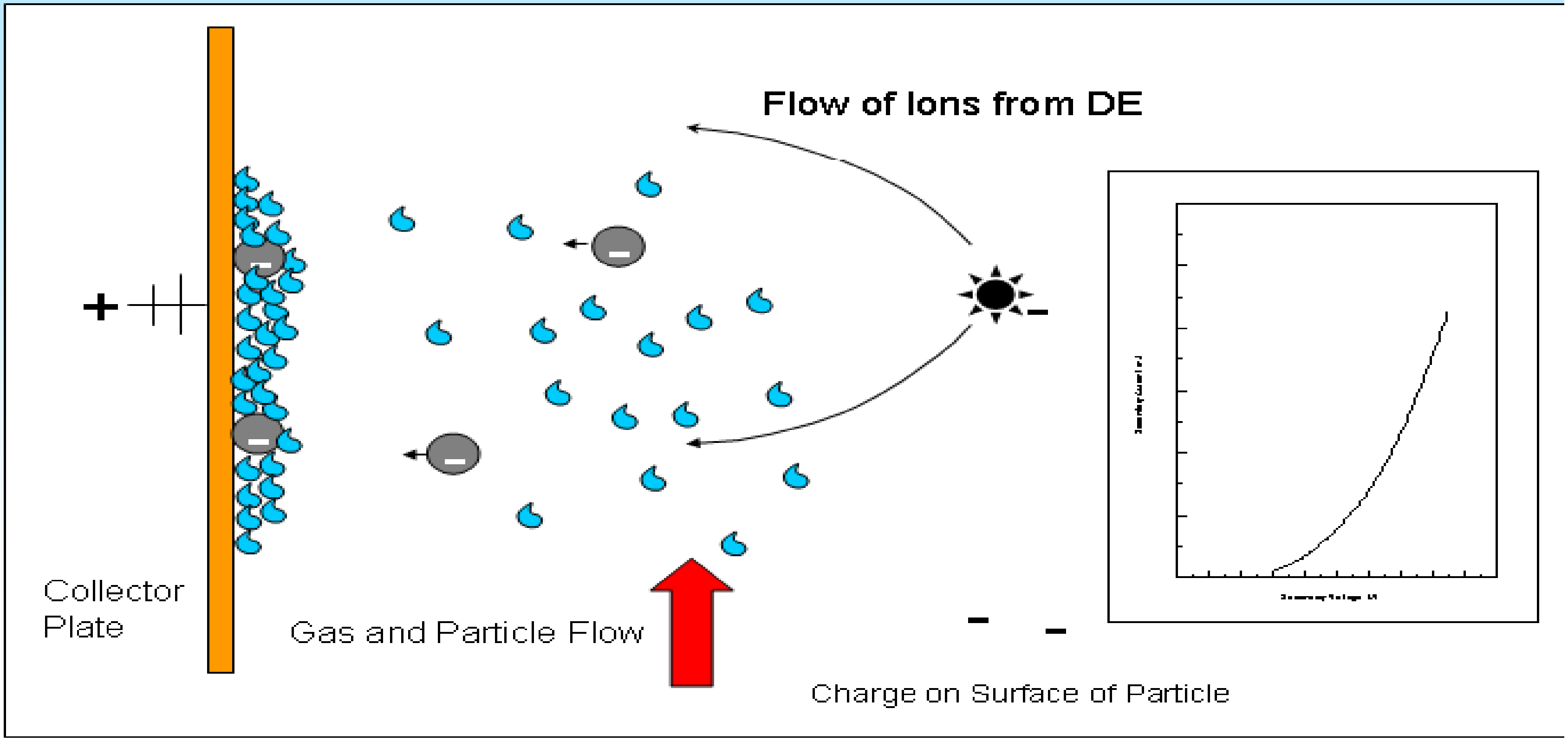
- **Wet ESP's have several advantages over a Dry ESP**
  - **Can handle condensed particulate from scrubber**
  - **Compatible with scrubbers**
  - **Eliminate entrainment of captured particles**

- **Wet ESP's are not limited by the particle resistivity, since the humidity in WESP lowers the resistivity of normally highly resistive particles**

Dry ESPs vs. Wet ESPs

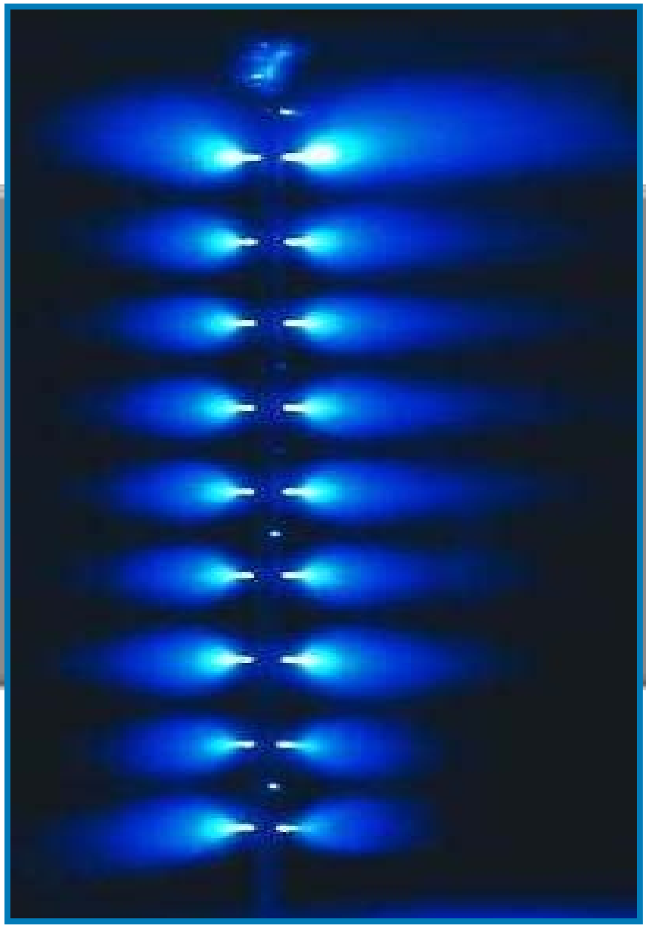
	Dry ESP	Wet ESP
Gas Temperature	250 - 850F range	Saturation temperature (typically 130F in Wet FGD)
Gas Humidity	< 10% typical	100%
Power Density	Variable with coal sulfur content and ash chemistry	Significantly higher than Dry ESP
Resistivity	Critical design factor	Not a design factor
Gas Velocity	5 fps ±	10 fps ±
Treatment Time	10 seconds ± typical	1- 5 seconds ± typical
Re-entrainment	Important factor	Not a factor
Corrosion	Mild steel (typical)	Specialty metals and/or plastics

Wet ESP Theory



Corona

The Corona is the electrically active region of the gas stream formed by the electric field



Deutsch-Andersen Equation

$$E=1-e^{-(Aw/V)}$$

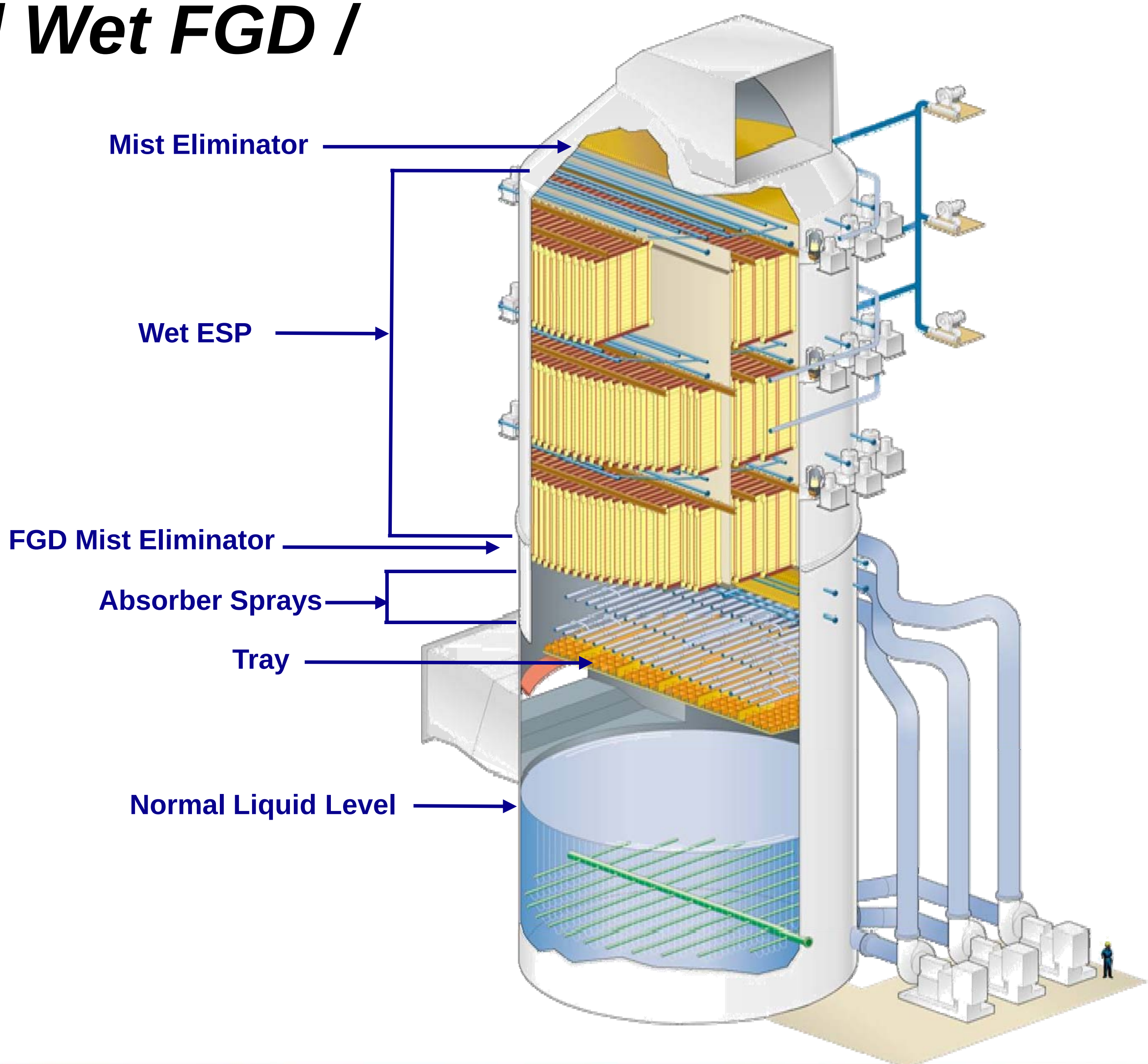
E = Collection Efficiency
V = Flue Gas Volume – ACFS
A = Total Collection Area - ft²
w = <u>Average</u> Migration Velocity - ft/sec

Types of Utility Wet ESPs
for Future New & Retrofit Installations

Close-Coupled (Integrated) Wet ESP

Wet FGD with Stand-Alone Wet ESP

Integrated Wet FGD / Wet ESP



New Brunswick Power – Coleson Cove Units 1 & 2

• System Size:	2 x 550 MW
• Flue Gas Flow Rate	1,451,528 ACFM
• Fuel:	Orimulsion/Fuel Oil
• Acid Mist Removal Efficiency:	90+%
• No. of WESP Gas Paths:	4
• No. of Fields	3
• Flow Orientation	Vertical Upflow
• Start Up Date:	2004

Types of Utility Wet ESPs for Future New & Retrofit Installations

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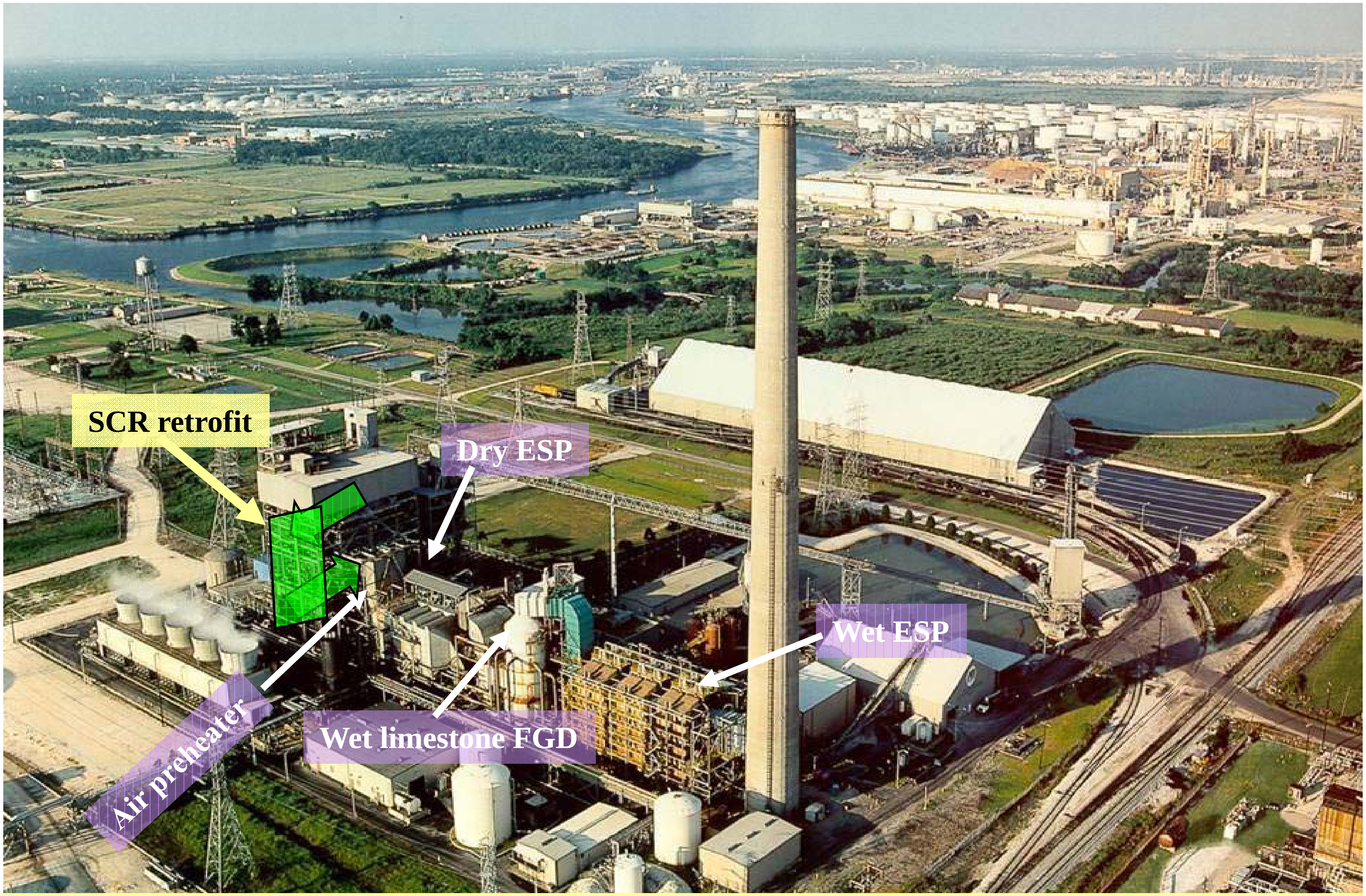
AES Deepwater Cogeneration Plant – Plate Vertical



AES Deepwater – 160 MW gross, 100% petroleum coke pulverized boiler

AES Deepwater Unit 1 – Wet ESP

• Flue Gas Flow Rate	634,000 ACFM
• Fuel:	Petroleum Coke (8% Sulfur)
• Particulate Removal Efficiency:	99%
• Acid Mist Removal Efficiency:	91%
• Stack Opacity:	<10%
• No. of WESP Modules:	12
• No. of Fields	3
• Flow Orientation	Vertical Upflow
• Start Up Date:	1986

Longest Operating Utility Size WESP in North America

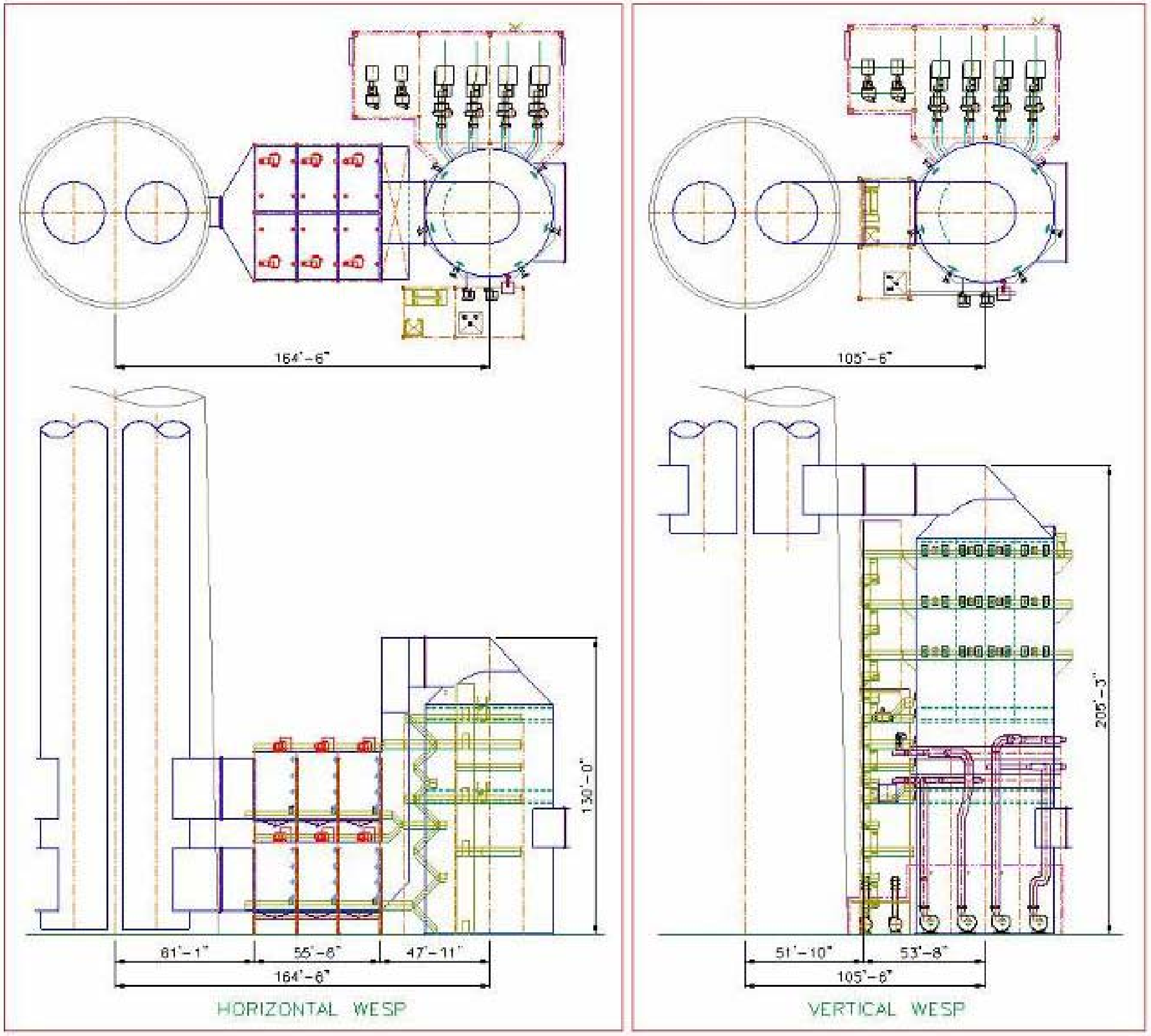
Wet ESP Module "F" – Total Particulate & SO_3 (corrected)

	Total Particulate		Filterable		Condensable		SO_3	
	WESP inlet, lb/MBtu	WESP outlet, lb/MBtu	WESP inlet, lb/MBtu	WESP outlet, lb/MBtu	WESP inlet, lb/MBtu	WESP outlet, lb/MBtu	WESP inlet, lb/MBtu	WESP outlet, lb/MBtu
Ave	0.0642	0.0090	0.0231	0.0019	0.0410	0.0071	0.0301	0.0035

Total Particulate – Ave of 3 x 2 hr test runs

SO_3 – Ave of 3 x 1 hr test runs

Horizontal (Standalone) vs. Integral Wet ESP



Wet ESP Washing Methodology

1. ***Intermittent***
   - **Thorough washing with fresh water and section by section**
   - **Spent water serves as necessary FGD makeup (i.e. no net system increase)**

2. ***Continuous Irrigation***
   - **Typically used with non-conductive collecting electrode material**
   - **Requires extra water or recycle system**
   - **Requires maintenance**

3. ***Continuous Spray/Fogging***
   - **Requires extra water or recycle system**
   - **Dependent on proper design/maintenance**
   - **Offers use of more cost effective lower grade alloys**

4. **Combination of above**

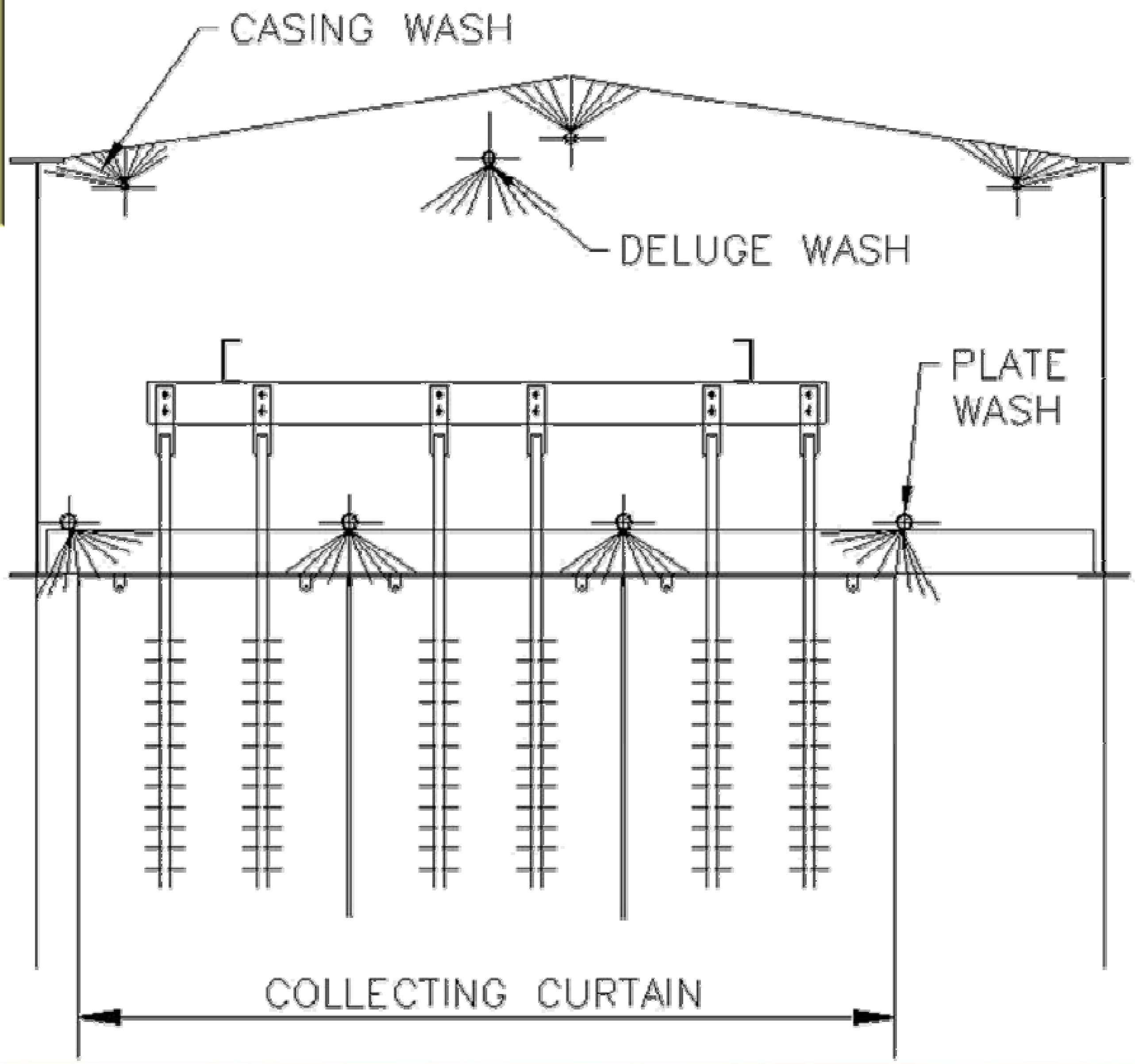
Wet ESP Wash Systems

Continuous Wash System (internal wash system)

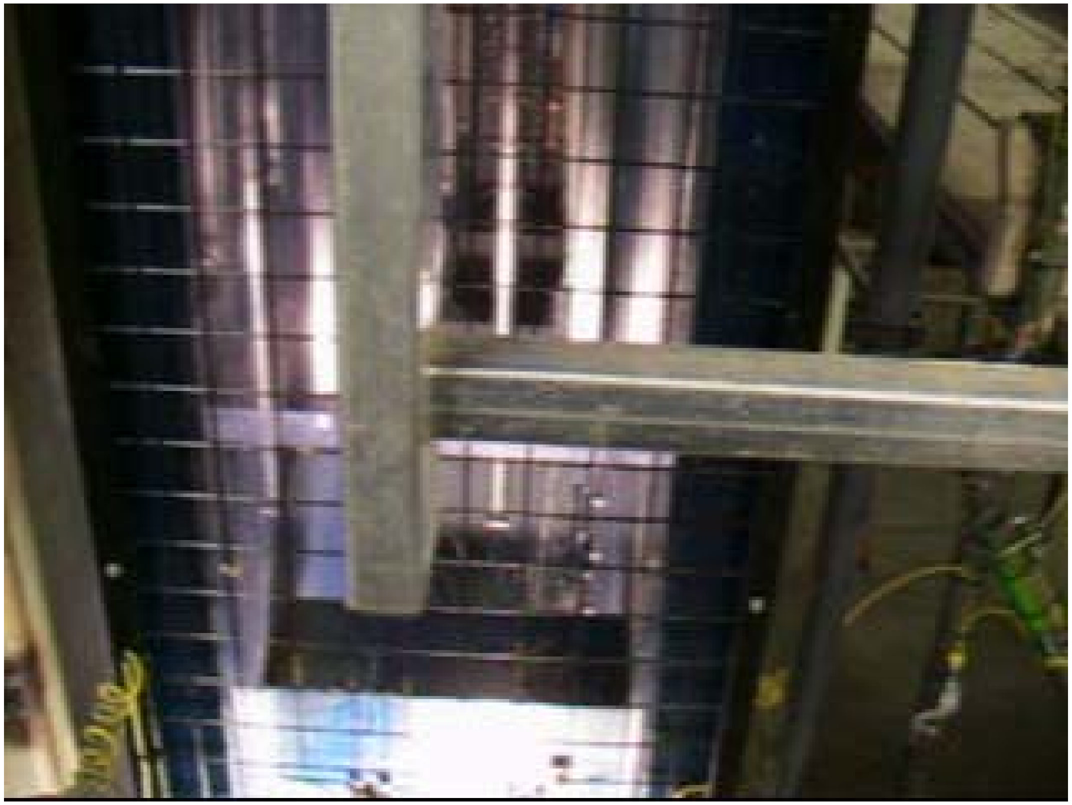
- Plate wash sprays
- Inlet casing wetting sprays
- Roof wetting sprays

Deluge system

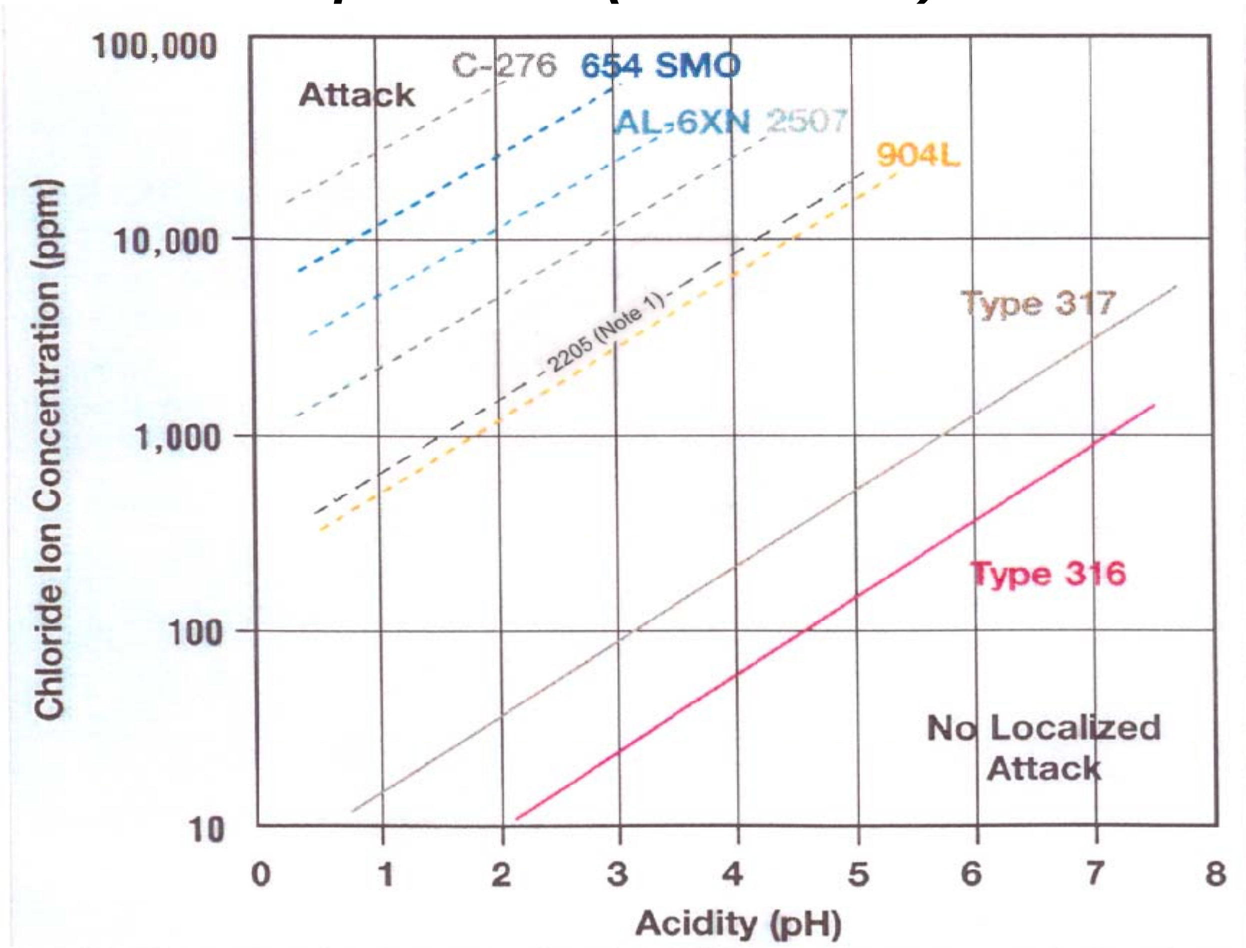
Wet ESP Washing



WESP Test Rig



Approximate Service Limits for Stainless Steels and Nickel-Base Alloys in Flue Gas Condensates and Acid Brines at Moderate Temperatures (140 – 176 F)



Note 1: This service limits plot for Alloy 2205 was super-imposed on this Figure by Babcock & Wilcox

Wet ESP for SO_3 Mitigation

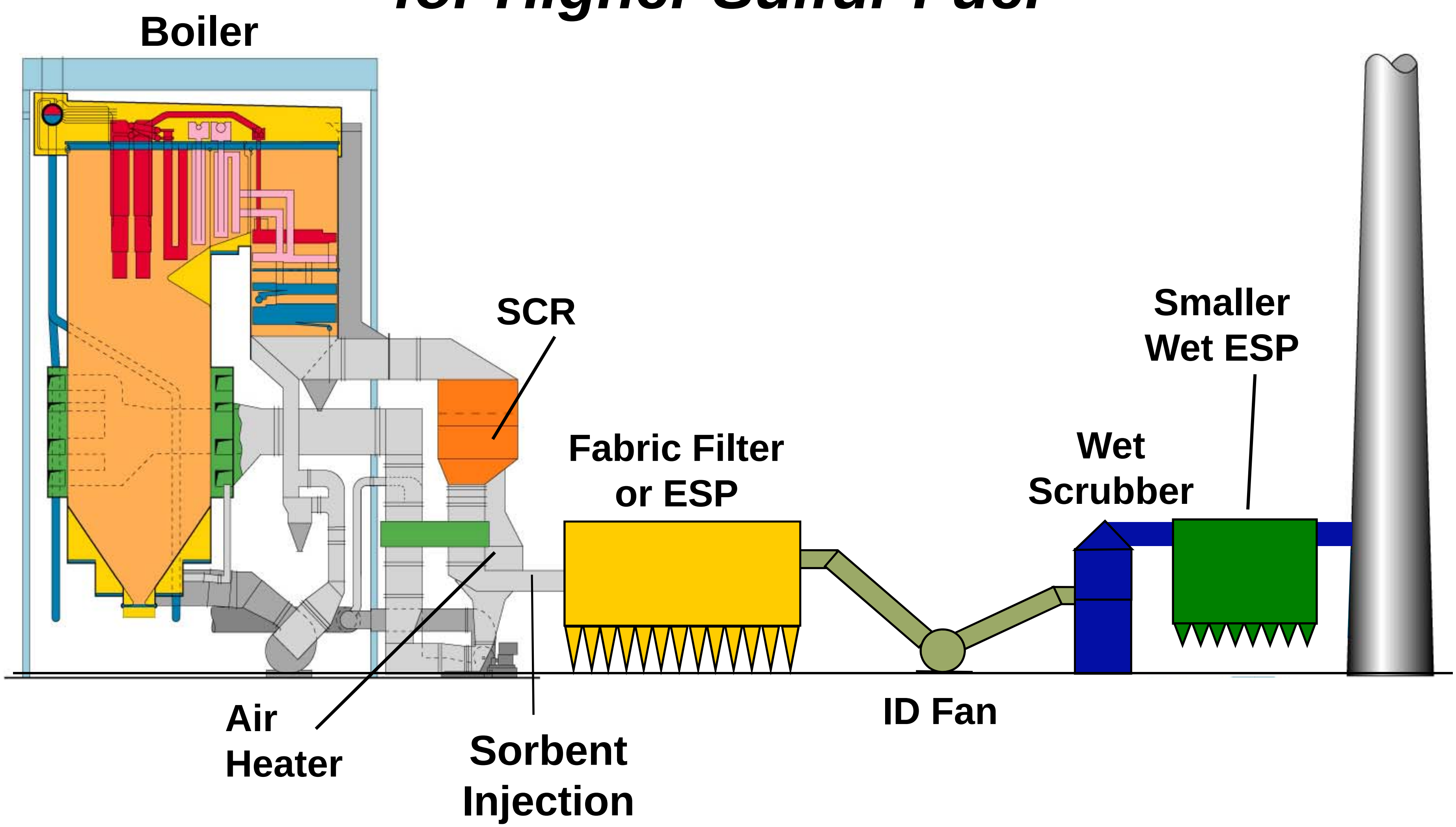
Advantages

- **Exceptionally good device for collection of fine particulate (acids, condensed matter, fine solids)**
- **Not only collects acid but scrubber carryover and ash**
- **O&M cost low**
- **Potential capture of hazardous pollutants**

Disadvantages

- **Capital cost high**
- **More real estate required**

Lowest SO_3 Emission Arrangement for Higher Sulfur Fuel



Conclusions

- **There are many sorbents that are effective in mitigating SO_3**
- **A Wet ESP may be required by permit for new plants**
- **When designing a SO_3 mitigation system, a system approach based on plant specific conditions will reduce the overall cost of mitigation equipment and sorbent usage**

Thank you.