Outline

• What is SO3 FGC
• Basics of an Electrostatic Precipitator
• Ash Resistivity
• SO3 Process
• Design Principles
SO3 FGC Background

- Sulfur Trioxide Flue Gas Conditioning
- Corrects Ash Resitivity to Improve performance of Electrostatic Precipitators (ESPs)
- Small amount injected upstream of ESP
- Approximately 1500 units worldwide
- Commercialized by Wahlco in early 1970’s
Fuel Switch

- Enlarge Electrostatic Precipitator: $20-30
- Flue Gas Conditioning (FGC): $1-3
- Construct New Electrostatic Precipitator or Fabric Filter: $30-40

Regulatory Compliance Alternatives

Approximate Cost Per Kilowatt-Hour (U.S. Dollars)
# Sulfur Emissions

## Typical Sulfur Oxide Emissions from Coal-Burning Boilers

<table>
<thead>
<tr>
<th>Sulfur Oxides PPMV</th>
<th>3.5% Sulfur Content</th>
<th>0.5% Sulfur Content</th>
<th>0.5% Sulfur &amp; FGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entering Precipitator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SO}_2$</td>
<td>2600</td>
<td>370</td>
<td>371</td>
</tr>
<tr>
<td>$\text{SO}_3$</td>
<td>26</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Entering Stack</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SO}_2$</td>
<td>2600</td>
<td>370</td>
<td>375</td>
</tr>
<tr>
<td>$\text{SO}_3$</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Flue gas conditioning does not increase emission levels of sulfur oxides ($\text{SO}_2$ or $\text{SO}_3$).
Sulfur Trioxide

- Toxic highly reactive gas
- Combines with water vapor to form sulfuric acid mist
- Gas above 500 deg F
- Generally produced by burning sulfur and catalytic oxidation of Sulfur Dioxide gas
- Typical inject 5 to 15 ppm in Flue Gas ~ 20 to 300 lb/hr sulfur - 50 to 800 mW
Typical ESP

(a) Cold-Side Electrostatic Precipitator

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ESP Principles

• Charge the Particles
• Migration of Charged Particles to Collecting Plates
• Move the Collected Material to the Hopper for Removal
Dust Layer on Plates

DUST RESISTIVITY EFFECTS

CURTAIN

DUST LAYER

V = Volts Across Dust
\[ V = i \rho l \]

i = Current Density
\[ i \]

\rho = Resistivity
\[ \rho \]

l = Layer Thickness
\[ l \]
Sulfur Trioxide FGC

- SO3 Reacts with moisture in flue gas
- Absorbed on surface of fly ash
- Improves surface conductance of ash
- Lowers the surface resistivity
Ash Resistivity

- Surface Conduction
- Volume Conduction
- Optimum is between
  - $1 \times 10^8$ ohm-cm
  - And
  - $1 \times 10^{10}$ ohm-cm
- Ash measured in Laboratory in Oven and High voltage Cell
- Computer model developed based on Ash Analysis
VI Curves

High Resistivity

Voltage kV

Current mA

1st Field
2nd Field
3rd Field
VI Curves

Normal Resistivity

Current mA

Voltage kV

1st Field

2nd Field

3rd Field
ESP Efficiency vs. Resistivity for SCA 325 ft²/1000 acfm
Precipitator Efficiency vs. SO$_3$ for ESP of 325 SCA
Precipitator Efficiency vs. Power

![Graph showing precipitator efficiency versus power consumption. The graph plots precipitator efficiency (%) on the y-axis against watts per 1000 ACFM on the x-axis. The graph shows a curve that levels off at approximately 99.72% efficiency at higher power levels.]
PRB

EXPECTED RESISTIVITY

TVA – Johnsonville
PRB -- Average

Ash Spectrographic Analysis

LI2O=
K2O=1.
CAO=
AL2O3=1
TIO2=1.
SO3=20.
NA2O=0.
MGO=3.
FE2O3=7
SIO2=28
P2O5=0.

No SO3
Predicted Coal SO3
1 PPM SO3
4 PPM SO3
10 PPM SO3
Dual FGC
Appalachian ‘Average’

TVA -- Johnsonville
100% Eastern Appalachian -- Average

EXPECTED RESISTIVITY

OHM-CM

TEMPERATURE DEG FAHRENHEIT

Ash Spectrographic Analysis

Li2O =
K2O = 2.
CaO =
Al2O3 = 2
TiO2 = 1.
SO3 = 1
Na2O = 0.
MgO = 1
Fe2O3 = 6
SiO2 = 57
P2O5 = 0.

No SO3
Predicted Coal SO3
1 PPM SO3
4 PPM SO3
10 PPM SO3
Low Alkali

![Graph showing the relationship between temperature (in degrees Fahrenheit) and ohm-cm for different SO3 concentrations: No SO3, Predicted Coal SO3, 1 PPM SO3, 4 PPM SO3, and 10 PPM SO3. The graph indicates a decrease in ohm-cm with increasing temperature, with different lines for each SO3 concentration, showing varying levels of ohm-cm at different temperatures.]
Dual Conditioning

• Inject both SO3 and Ammonia independently
• Ammonia improves attachment of SO3
• Extend performance at higher temperatures
• Reduces precipitator ash reentrainment
Nanticoke Dual FGC Results

- SO3 – Opacity reduced from 22 to 15%
- With Dual FGC opacity 8%
- Substantial increase in Particle Size
- Dramatic reduction in rapper spikes
- Reduction in opacity baseline
- No hopper ash removal problems encountered
Nanticoke Regular Coal – No FGC
NANTICOKE UNIT 2 OPACITY

LOW SULFUR 50/50
TEST 43
SO3 OFF
NH3 OFF
NANTICOKE UNIT 2
OPACITY

LOW SULFUR 50/50
TEST 35
SO3 5.5 ppm
NH3 OFF
NANTICOKE UNIT 2
OPACITY

Nov 15, 1988
512 Mw
NH$_3$ - 17 ppm
SO$_2$ - 17 ppm

LOW SULFUR 50/50
TEST 33
SO$_3$  17 ppm
NH$_3$  17 ppm
Equipment Design Issues
SO3 Flue Gas Conditioning
Critical Design Principles

• Injection into Flue Gas
  – Must remain above Dew Point
    • Piping Heat Loss Issues
    • Energy Consumption
  – Proper Distribution

• SO3 Converter Inlet Temperature
  – Conversion Efficiency
  – Catalyst Life

• Burner Issues
  – Sulfur Purity
  – Complete Combustion
Injection Location Criteria

- Achieve $>1$ second residence time
- Nozzle Spacing $<\frac{1}{10^{th}}$ Mixing Distance
- Hot Gas Piping not excessive length
- Accessible Location
- Hot Side / Cold Side
Injector Sizing Principles

- Achieve Uniform Distribution
- Mixing
- Maintain Adequate Injection temperatures
- Maintain Injection velocities
Injector and Nozzle Spacing

- Inject into Centroid of Square Equal Areas
- Adequate Injection Points
- Minimize Number of Injectors
- Injectors Usually about 3 feet apart
Square Duct Injector Spacing
Rectangular Duct Injector Spacing
Improper Nozzle Spacing
Hot Side Injector
Injector Plugging Factors

- Injector Gas Flow
- Injector Temperature
- Duct Temperature
- Injector Length
- Injector Type
- Number and Size of Injector Nozzles
Improvements in Design

• Less nozzles
• Larger nozzles
• Improved Purging
• Nozzle at End of Injector
• Clean Out Path
New Design

COLD SIDE PROBE DETAIL

PLAN

INTERNAL PIPE REDUCTION

SEE DETAIL "A"

REMOVABLE THERMOWELL

ELEVATION

END MOUNTED INJECTION ORIFICE

DETAIL "A"
Design Improvements
Equilibrium Conversion for SO2 Oxidation

% Conversion

Temperature Deg F

2% SO2
4% SO2
8% SO2
High Efficiency Converter

• Low SO2 Gas Concentration
  – Improved Equilibrium Conversion
• Design Converter Gas Velocity Low < 3 fps
• High Activity First Catalyst Layer
  – Lower Light off temperature
  – Lower Outlet Temperature
  – Higher Conversion
• Second Layer Conventional Catalyst
SO3 System in Enclosure
Air Heater Features

• Over sized air Heaters
• Rapid Startup
• Operating watt density less than design of 20 watts/ sq in
• Small easy to handle modules
• Vertical design assures good air distribution
Molten Sulfur Storage Tanks

- Typical 14 to 30 days storage at 20 ppm
- Tanks complete with platforms, and instrumentation
- Redundant steam coils – fast melt design
- Steam heated penetrations
- Single vent
- Single tank can feed multiple units
Advanced Ring Main Sulfur Pumping System

- Constant speed centrifugal pumps
- Robust low maintenance design, highly reliable, industry standard
- Redundant sulfur pumps
- Sulfur metered with Coriolis Flow Element
- Controlled at each sulfur burner with flow control valve
Hot Side Injection

- Increased SO3 Residence time
- Minimal Injector Plugging
- Improved SO3 Distribution
- SO3 always above dewpoint – no injector corrosion
- Ideal for Tubular Air Heaters
- Enables control of SO3 / Ammonia Ratio
Low Energy Consumption Design

- Significant Energy Savings
- Air Flow Varies with Sulfur Rate
- High Gas Volume for Rapid Startup
- Air Heater off at about 60% of Design
- No Blower Speed Control
Sulfur Burner 500 MW
Injection Rate vs. Power

Power [kW] vs. SO3 Injection Rate [ppmv]
Advantages of Molten Sulfur Feed

- Molten Sulfur $\frac{1}{5}$ to $\frac{1}{2}$ Cost
- Less Manpower Intensive
  - 20 tons unloaded in half hour
  - No Silo to Maintain
- Lower Energy Consumption
  - Sulfur is delivered molten
- More tolerant of Impurities
  - Large settling capacity of Tank
Advantages of Molten Sulfur Feed

• More tolerant of Impurities
  – Large settling capacity of Tank
• Safer
  – No sulfur dust hazards
• Molten Sulfur Readily Available
• Less Mechanical Equipment
• Hybrid Design has worst of both designs
Sulfur Properties

• Heat of Fusion ~ 17 Btu/lb
• Specific Heat 0.16 Btu/lb/deg F
• Molten Sulfur Viscosity of Wide Temperature Range
• 3952 Btu/lb
Sulfur Viscosity

![Graph showing sulfur viscosity versus temperature. The viscosity decreases with increasing temperature until a sharp increase at around 310°F.]
Typical Molten Sulfur Specification

- Sulfur 99.9570%
- Ash 0.0007%
- Organic 0.0036%
- Moisture 0.0872%
- Selenium < 1 ppm
- Tellurium < 1 ppm
Summary

• Approximately 1500 FGC units installed worldwide
• Refined over 30 years
• Many units over 25 years still operating
• New systems use only 10% of the energy of older system
• Application of the technology is predictable
• Successful and competitive ash resistivity correction