

REINHOLD ENVIRONMENTAL Ltd.



**2014 NO_x-Combustion Round Table
& Expo Presentations**

February 10 & 11, 2014, in Charlotte, NC / Hosted by Duke Energy

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Babcock Power



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Fuel Effect on Boiler Maintenance & Catalyst

Reinhold Conference

Charlotte, NC

February 10, 2014

Enrique Vega/William Medeiros

Riley Power Inc.



Fuel Effect on Boiler Maintenance & Catalyst

Objectives

1. Review Coal fuel make-up

- Chemical analysis
- Characteristics
- How does a fuel change affect boiler maintenance?
- Example: Switching to PRB firing

2. Importance of Engineering Studies

3. Impact to Back End Equipment and Catalyst



Boiler System Design

Fuels Directly Impact the Boiler Design

1. Fuels Fired

- Type of Combustion System (Solids, Suspension, liquid, gas)

2. Boiler Design – Coal Firing

- Combustion Characteristics
- Fouling and Slagging Characteristics
- Corrosion and Erosion Characteristics
- Steaming Conditions (Flow, Temperature, Pressure)

3. Emissions Control

- NO_x, CO, Sulfur, Mercury



Fuel Effect on Boiler Maintenance & Catalyst

Fuel Chemical Elements and Typical Effects on Maintenance

Ultimate Fuel Analysis

Analyzed using ASTM D 3174 Procedure

| |
|--------------|
| Moisture %wt |
| Ash %wt |
| Hydrogen %wt |
| Carbon %wt |
| Nitrogen %wt |
| Sulfur %wt |
| Oxygen %wt |
| Chlorine %wt |
| Total %wt |



Fuel Effect on Boiler Maintenance & Catalyst

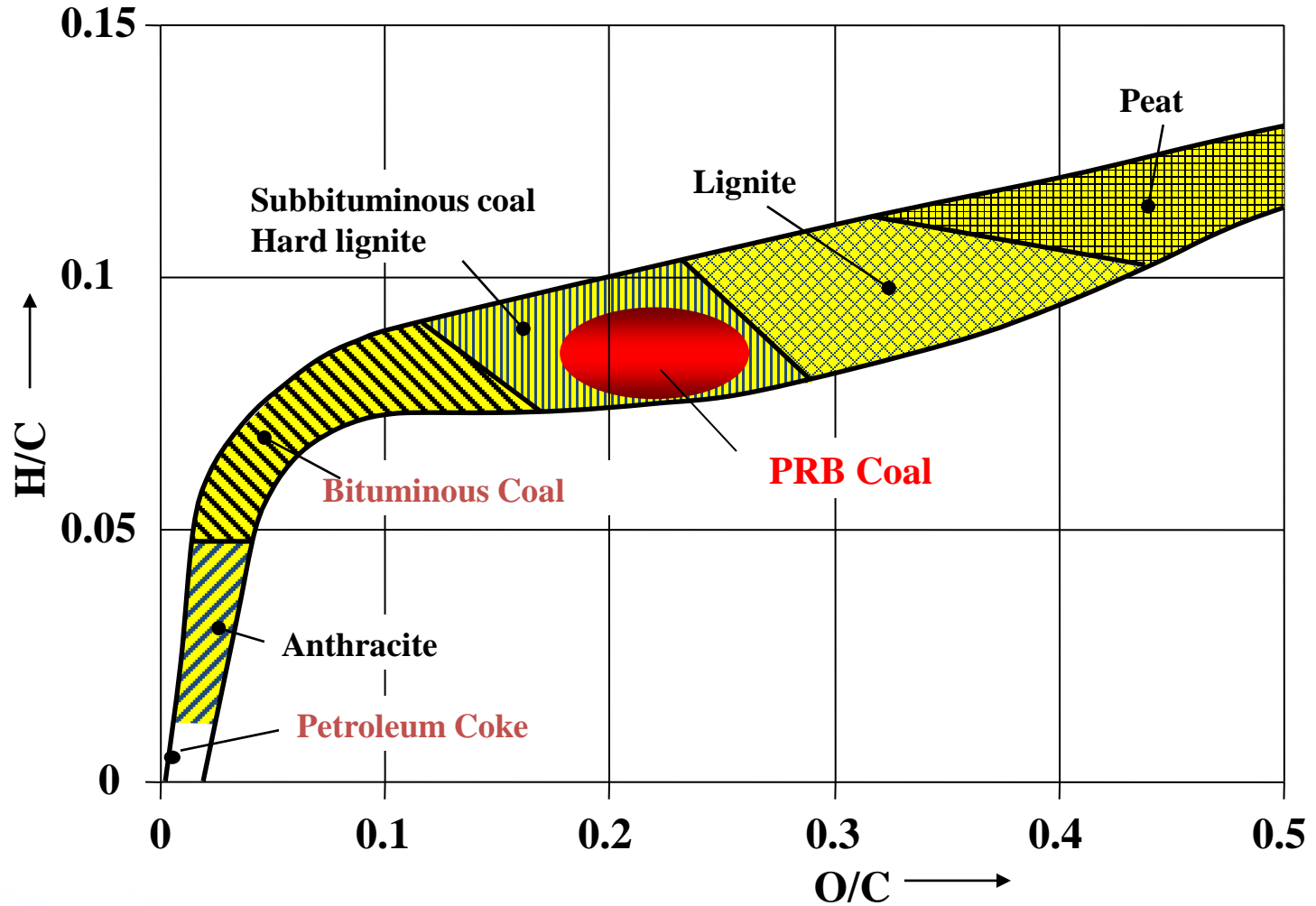
Coal Classification by Rank (ASTM D 338)

| Class | Group | Fixed Carbon Limits, % (Dry, Mineral-Matter-Free) | | Volatile Matter Limits, % (Dry, Mineral-Matter-Free) | | Calorific Values, Btu/lb (Wet, Mineral-Matter-Free) | |
|---------------------------|-----------------|--|-----------|---|--------------------------|--|-----------|
| | | Equal or Greater Than | Less Than | Greater Than | Equal or Greater Than | Equal or Greater Than | Less Than |
| I. Anthracite | Meta-anthracite | 98 | -- | -- | 2 | -- | -- |
| | Anthracite | 92 | 98 | 2 | 8 | -- | -- |
| | Semianthracite | 86 | 92 | 8 | 14 | -- | -- |
| II. Bituminous | Low volatile | 78 | 86 | 14 | 22 | -- | -- |
| | Medium volatile | 69 | 78 | 22 | 31 | -- | -- |
| | High volatile A | -- | 69 | 31 | -- | 14,000 | -- |
| | High volatile B | -- | -- | -- | -- | 13,000 | 14,000 |
| | High volatile C | -- | -- | -- | -- | 10,500 | 13,000 |
| III. Subbituminous | Subbituminous A | -- | -- | -- | -- | 10,500 | 11,500 |
| | Subbituminous B | -- | -- | -- | -- | 9,500 | 10,500 |
| | Subbituminous C | -- | -- | -- | -- | 8,300 | 9,500 |
| IV. Lignitic | Lignite A | -- | -- | -- | -- | 6,300 | 8,300 |
| | Lignite B | -- | -- | -- | -- | -- | 6,300 |



Fuel Effect on Boiler Maintenance & Catalyst

Characterization of solid fuels





Fuel Effect on Boiler Maintenance & Catalyst

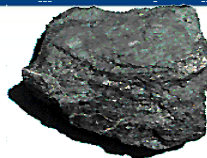
Fuel Analysis Comparison

| | | Bituminous Coal | PRB Sub-Bituminous Coal |
|-----------------------------------|--------|-----------------|-------------------------|
| C | %WT | 69.79 | 47.51 |
| H ₂ | %WT | 4.43 | 3.53 |
| S | %WT | 0.80 | 0.35 |
| O ₂ | %WT | 9.34 | 11.86 |
| N ₂ | %WT | 1.51 | 0.53 |
| H ₂ O | %WT | 6.85 | 30.79 |
| Ash | %WT | 7.28 | 5.42 |
| HHV | Btu/Lb | 12519 | 8115 |
| Ash Softening H=W(Reducing) F° | | 2400+ | 2120 |
| Typical Fouling Tendency | | Med | Med |
| Typical Slagging Tendency | | Med | High |



Fuel Effect on Boiler Maintenance & Catalyst

Coal Comparison

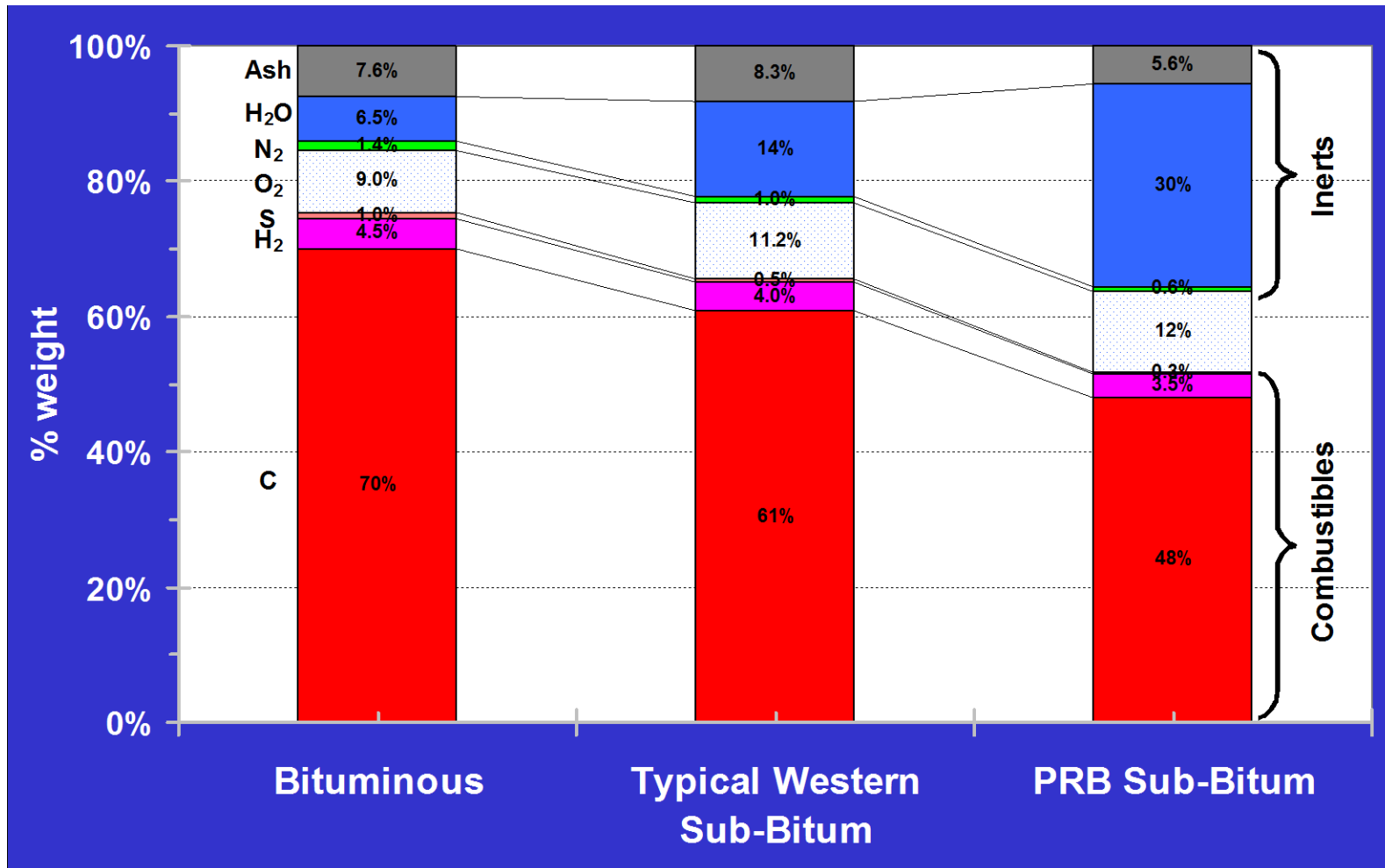


| | | Bituminous | Typical Western Sub-Bituminous | PRB Sub-Bituminous |
|---|---------------|---------------|--------------------------------|--------------------|
| C | % wt | 70 | 61 | 48 |
| H ₂ | % wt | 4.5 | 4.0 | 3.5 |
| S | % wt | 1.0 | 0.5 | 0.3 |
| O ₂ | % wt | 9.0 | 11.2 | 12 |
| N ₂ | % wt | 1.4 | 1.0 | 0.6 |
| H₂O | % wt | 6.5 | 14 | 30 |
| Ash | % wt | 7.6 | 8.3 | 5.6 |
| HHV | Btu/lb | 12,500 | 10,300 | 8,200 |
| Ash Initial Deformation Temp., reducing | F | 2400+ | 2300 | 2130 |
| Typical Slagging Tendency | - | Med | High | Severe |
| Typical Fouling Tendency | - | Med | Med | Severe |



Fuel Effect on Boiler Maintenance & Catalyst

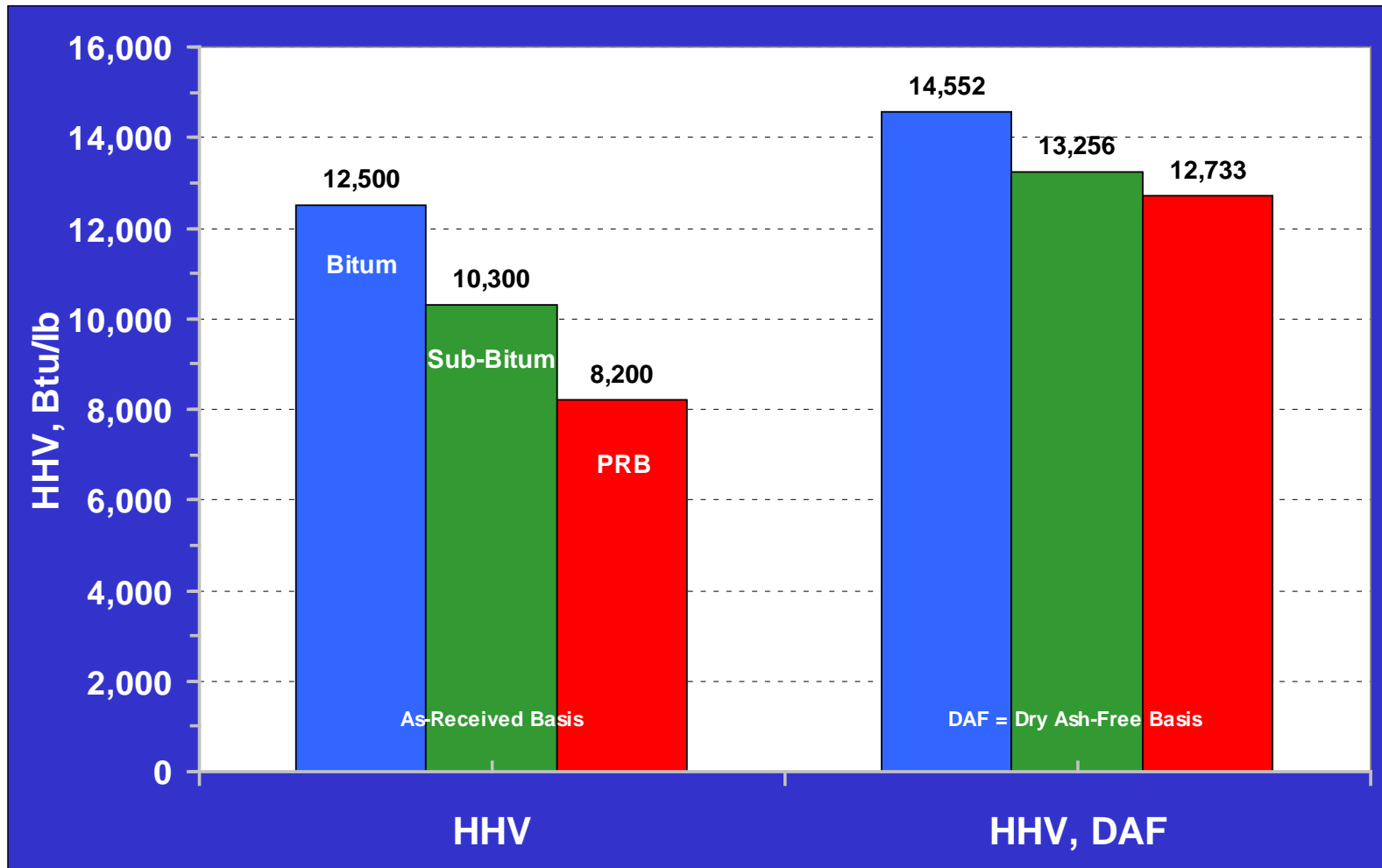
Coal Comparison - Analysis





Fuel Effect on Boiler Maintenance & Catalyst

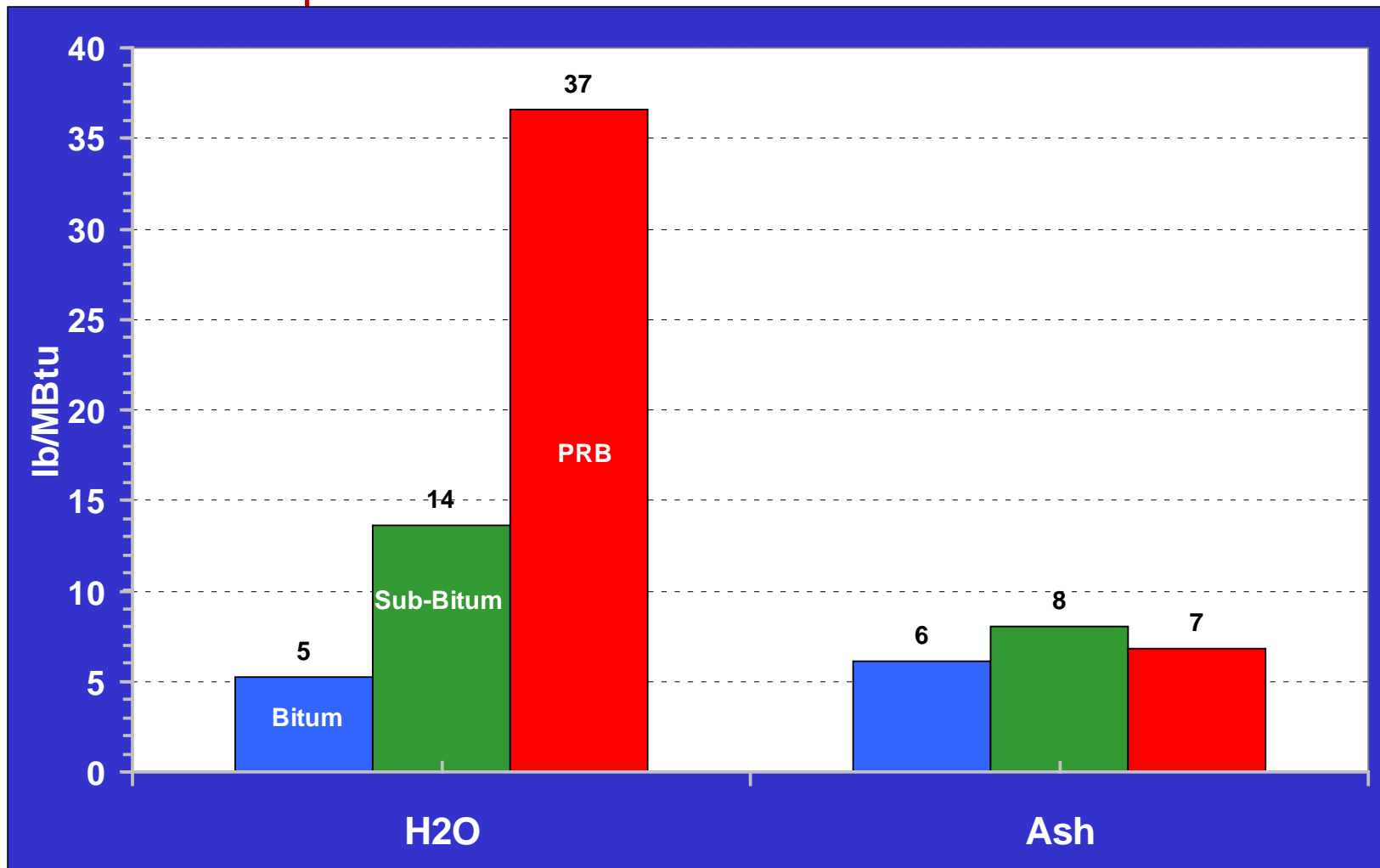
Coal Comparison – Heating Value





Fuel Effect on Boiler Maintenance & Catalyst

Coal Comparison – Moisture and Ash





Fuel Effect on Boiler Maintenance & Catalyst

Fuel Chemical Elements and Typical Effects on Maintenance

Ash Elemental Analysis

Analyzed using ASTM D 3682 Procedure

| |
|---|
| Silicon Dioxide (SiO₂) |
| Aluminum Oxide (Al₂O₃) |
| Ferric Hydroxide (Fe₂O₃) |
| Calcium Oxide (CaO) |
| Magnesium Oxide (MgO) |
| Sodium Oxide (Na₂O) |
| Potassium Oxide (K₂O) |
| Titanium Dioxide (TiO₂) |
| Balance / Others |



Fuel Effect on Boiler Maintenance & Catalyst

Fuel Slagging and Fouling Characteristics and its Effects on Maintenance

Slagging Characteristics

“Slagging is the formation of molten, partially fused or solidified deposits on furnace walls and other surfaces exposed to radiant heat.” *(Steam Its Generation and Use Edition: 41 – Page 21-3)*

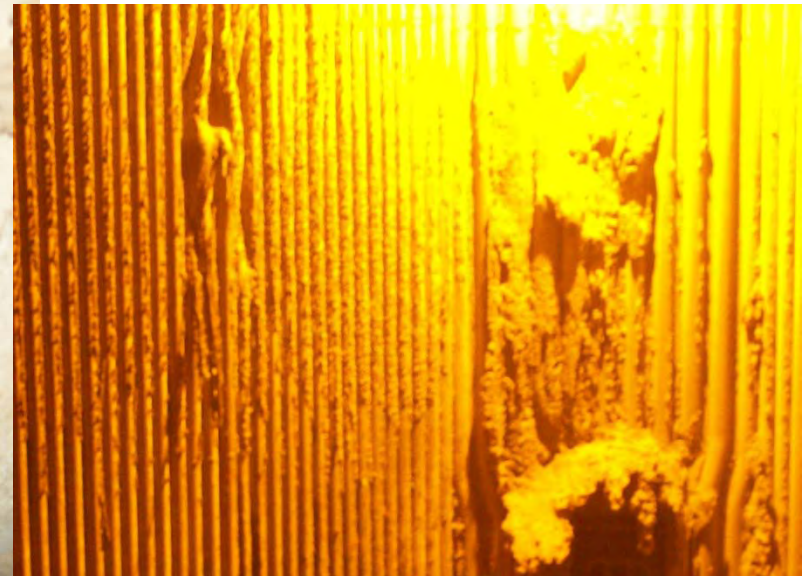
- List of Issues Associated with Furnace Slagging
 - Less Heat Absorption in Furnace
 - Increased Furnace Flue Gas Temperatures
 - Decreased Radiant Superheater/Reheater heat absorption
 - Falling clinkers can cause waterwall tube damage
 - Bridging between radiant pendants can cause gas stratification in the boiler
 - Cleaning slag can cause corrosion on waterwall tubes



Fuel Effect on Boiler Maintenance & Catalyst

Fuel Slagging and Fouling Characteristics and its Effects on Maintenance

Example of Slagging





Fuel Effect on Boiler Maintenance & Catalyst

Fuel Chemical Elements and Typical Effects on Maintenance

Characterizing Slagging and Fouling Tendency

- The Ultimate Analysis, HHV, Ash Elemental Analysis, and Ash softening/melting temperatures are used to characterize the slagging and fouling tendency.
- The fouling and slagging are characterized as:
 - Low
 - Medium
 - High
 - Severe



Fuel Effect on Boiler Maintenance

Fuel Chemical Elements and Typical Effects on Maintenance

Characterizing Slagging and Fouling Tendency

The fouling/slagging effects on a boiler can be defined by how it affects performance.

- In an identical boiler a high slagging coal will have higher furnace exit gas temperatures and lower Radiant SH/RH heat absorption than a low slagging coal.
- A high fouling coal will have less convective heat transfer than a low fouling coal.



Fuel Effect on Boiler Maintenance & Catalyst

Fuel Slagging and Fouling Characteristics and its Effects on Maintenance

Example of Fouling





Fuel Effect on Boiler Maintenance & Catalyst

Fuel Slagging and Fouling Characteristics and its Effects on Maintenance

Fouling Characteristics

“Fouling is defined as the formation of high temperature bonded deposits on convection heat absorbing surfaces, such as superheaters and reheaters, that are not exposed to radiant heat.” *(Steam Its Generation and Use Edition: 41 – Page 21-3)*

List of Issues Associated with Fouling

- Decrease in convective heat transfer
- Less gas free areas can lead to higher flue gas velocity and may cause tube erosion
- Excess sootblowing may cause tube erosion



Fuel Effect on Boiler Maintenance & Catalyst

Maintenance Categories

Erosion

- Erosion is the process where the surface of a tube is worn away by ash in flue gas flow across tube bundles
 - To reduce erosion the maximum velocity of flue gas across tube bundle is limited to 50 ft/s
- Cause
 - High Flue Gas Velocity
 - High Ash Content in Fuel (Ash Loading)
- Solutions
 - Tube Shields
 - Overlay (Inconel/Conforma Clad)



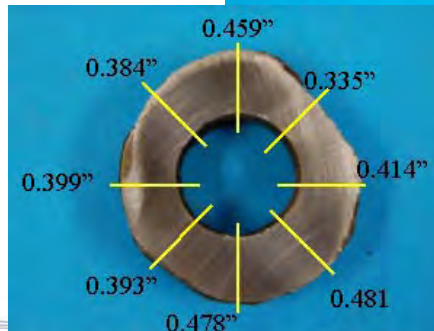
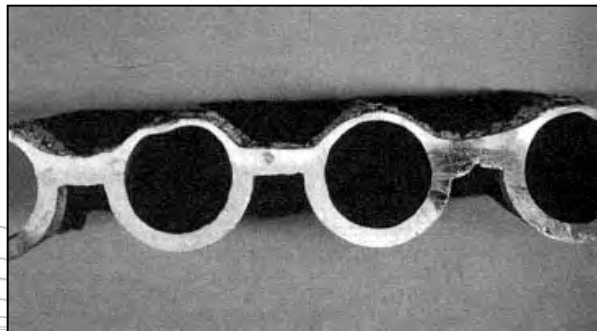


Fuel Effect on Boiler Maintenance & Catalyst

Maintenance Categories

Corrosion

- Corrosion is the process where a solid is eaten away and changed by a chemical action.
- Cause
 - Sulfur and Chlorine Content (From Ultimate Fuel Analysis)
 - High Gas Temperature
 - Low Gas Temperature (Dew Point)
- Solutions
 - Overlay (Inconel/Conforma Clad)
 - Reduced Gas Temperature
 - Upgraded Pressure Part Material





Fuel Effect on Boiler Maintenance & Catalyst

Maintenance Categories

Temperature

- High Flue Gas Temperatures can cause tube metal surface oxidation
- Cause
 - Slagging in furnace will cause higher Furnace Exit Gas Temperature (FEGT)
 - Fouling on convective section will decrease heat absorption
- Solutions
 - Furnace Modifications to reduce FEGT
 - Increased furnace cleaning
 - Increased convective section cleaning.





Fuel Effect on Boiler Maintenance & Catalyst

| Fuel parameter | What does it affect? | Impacted equipment / design |
|---|--|---|
| <ul style="list-style-type: none">• Ultimate analysis• Heating value | <ul style="list-style-type: none">• Air & flue gas flow rates, draft loss• Boiler efficiency, heat rate | <ul style="list-style-type: none">• Flue gas flow area – tube spacing• Duct and flue gas equipment sizing• Fan sizing / margins |
| <ul style="list-style-type: none">• Moisture content | <ul style="list-style-type: none">• Air & flue gas flow rates, draft loss• Boiler efficiency, heat rate• Coal drying in mill | <ul style="list-style-type: none">• Mill capacity / sizing• Mill temperature required |
| <ul style="list-style-type: none">• Sulfur content | <ul style="list-style-type: none">• SO₂ / SO₃ production• Acid dew point temperature | <ul style="list-style-type: none">• Potential for AH / duct corrosion• Desulfurization equipment sizing |
| <ul style="list-style-type: none">• Ash content | <ul style="list-style-type: none">• Ash production• Erosion potential | <ul style="list-style-type: none">• Ash removal equipment• Flue gas flow area / velocity limits |
| <ul style="list-style-type: none">• Ash initial deformation temp.• T₂₅₀ temperature | <ul style="list-style-type: none">• Furnace slagging potential• Furnace efficiency / heat absorption | <ul style="list-style-type: none">• Sootblower / water cannon application• Furnace size / platen surface area |
| <ul style="list-style-type: none">• Ash mineral analysis: Na₂O, CaO | <ul style="list-style-type: none">• Convection pass fouling potential | <ul style="list-style-type: none">• Tube clear space requirements• Sootblower application |



Fuel Effect on Boiler Maintenance & Catalyst

PRB Coal Firing

Benefits/Incentives

- Reduced Fuel Cost
- Reduced Ash Unburned Carbon
- Low Sulfur Content



Fuel Effect on Boiler Maintenance & Catalyst

PRB Coal Furnace Slagging/Fouling

- White Colored Ash, Highly Reflective
- Reduces Furnace Heat Absorption
- Increases Furnace Exit Gas Temperature



Fuel Effect on Boiler Maintenance & Catalyst

Potential Combustion System Modifications

- Coal feeder capacity
- Pulverizer capacity
- Pulverizer motor capacity
- Pulverizer drying capacity (hot primary air)
- Add pulverizer inerting system
- Primary air fan capacity
- Coal pipe velocity / size
- Burner coal nozzle



Fuel Effect on Boiler Maintenance & Catalyst

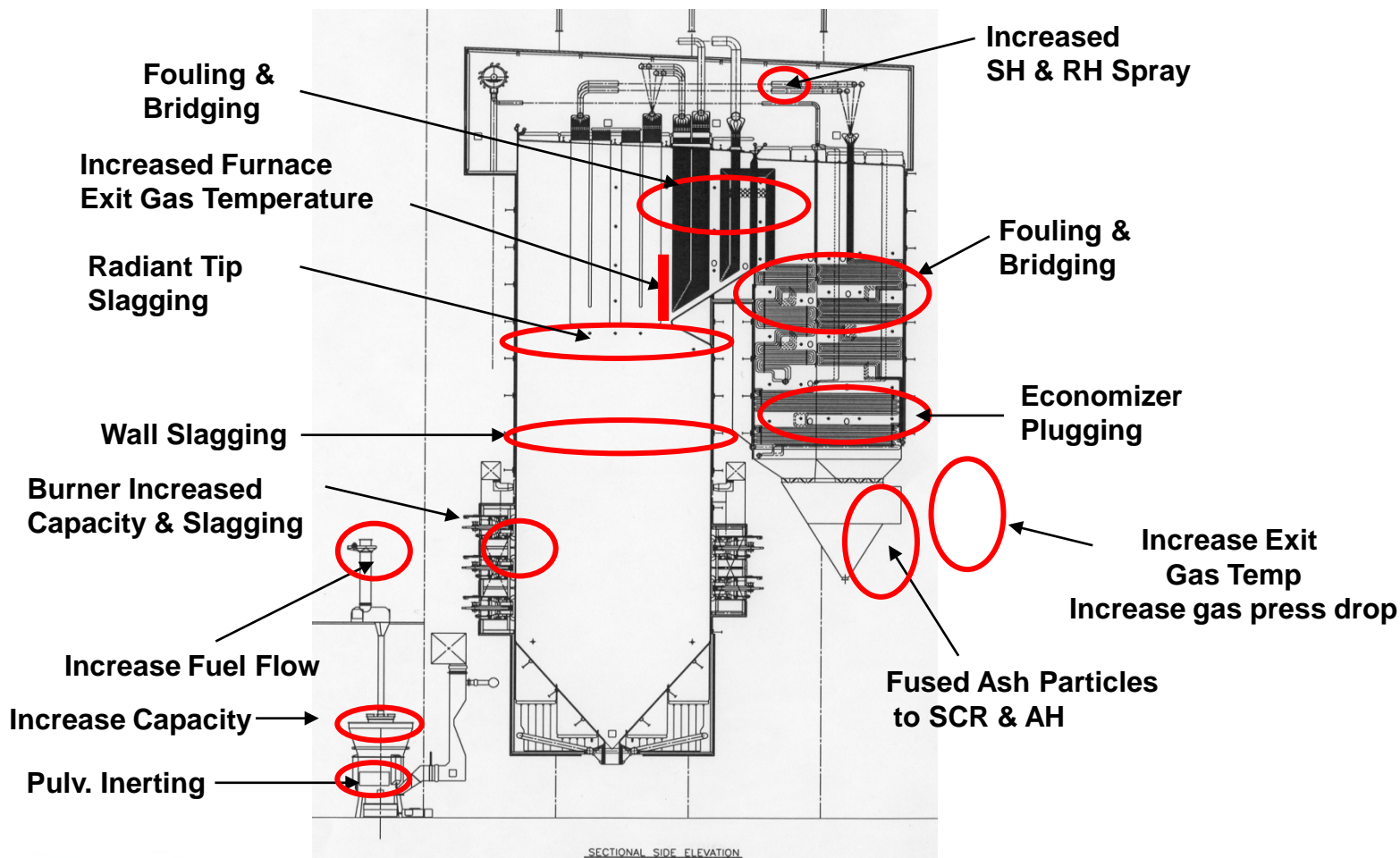
Typical Boiler Problem Areas

- Reduced Furnace Heat Absorption (Reflective Ash Wall Build-Up)
- Increased Furnace Exit Gas Temperature
- Increased Convection Pass Fouling
- Increased LTSH Outlet Steam Temperature
- Increased SH/RH Spray Flow Requirements
- Increased Economizer Exit Gas Temperature
- Increased Coal Flow
- Increased Hot Primary Air Requirements
- Boiler Load Limited to 55%-70% MCR on a Straight Conversion Firing Only PRB Coal



Fuel Effect on Boiler Maintenance & Catalyst

PRB Coal Firing – “Typical Problem Areas”





Fuel Effect on Boiler Maintenance & Catalyst

Approach to Evaluate “PRB” Coal Firing on an Existing Unit

- Record Current (accurate) Boiler, Combustion System Auxiliary Equipment Performance Data (Three Load @60%, 80%, & 100% MCR)
 - Write Testing Procedure
 - Record Data
 - Summarize and Analyze
- Computer Model the Boiler Heat Transfer Performance
 - Calibrate the Model based on Actual Boiler Performance
 - Predict the Boiler Performance, Combustion System Requirements and Auxiliary Equipment firing PRB Coal
- Outline the Problem Areas Firing 100% PRB Coal
 - Boiler Systems
 - Combustion Systems
 - Auxiliary Systems
- Evaluate Options to Address the Problem Areas
- Evaluate Risk and the Most Cost Effective Options



Fuel Effect on Boiler Maintenance and Catalyst

Fuel Characteristics That Affect Catalyst Life and Maintenance

- Catalyst Life
 - Early catalyst replacement
 - Higher ammonia slip

- Downstream Effects

Ammonia salt formation, ABS

- Ammonia Sulfate $(\text{NH}_4)_2\text{SO}_4$ and/or Ammonia Bisulfate, NH_4HSO_4
 - Ammonia Bisulfate Causes Air Pre-heater plugging
 - ABS Dew point, Bulk = F (SO_3 , NH_3 , Moisture)
 - Ash Sales
- Lower SO_3 dew point temperature



Fuel Effect on Boiler Maintenance and Catalyst

Fuel Characteristics That Affect Catalyst Life and Maintenance

- Off design
 - Major Fuel / Design Modification
 - Reduced Catalyst Life
 - Increase or decrease in minimum operating temperature
 - Increased SO₂



Fuel Effect on Boiler Maintenance and Catalyst

Off Design - Terminology

Catalyst Potential

$$P = K/Av = -\ln(1-\eta)$$

P = Catalyst Potential

Av = Area Velocity, Nm/hr

(Normal gas Flow Nm³/hr divided by the total installed catalyst surface area, m²)

η = Nox Removal, Fraction

K = (Catalyst Activity, Nm³/m² hr, or Nm/hr) = F (Temperature, NO_x, O₂, H₂O)

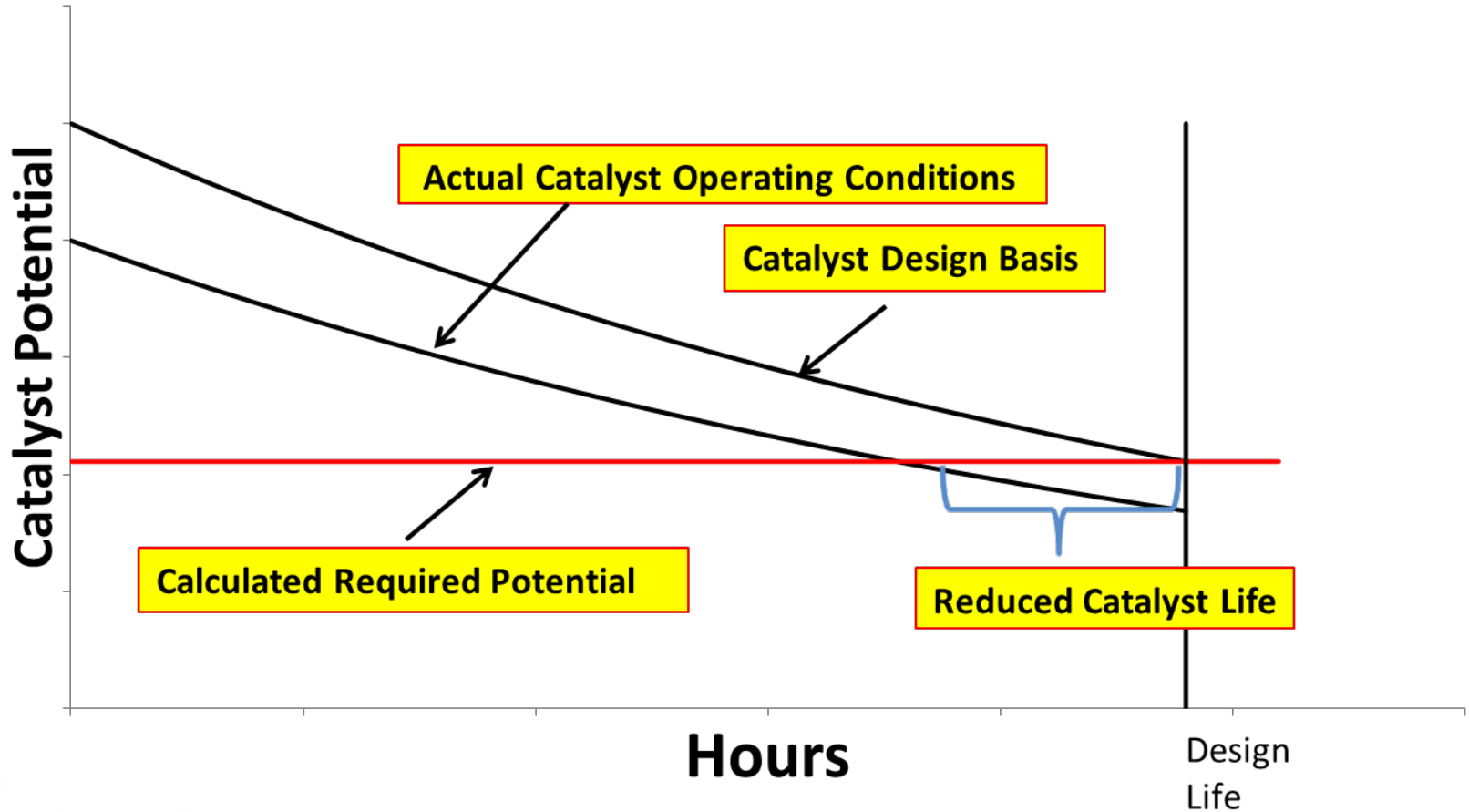
SO₂ to SO₃ Conversation Rate

= F(Av, Temperature, SO₂, O₂, H₂O)



Fuel Effect on Boiler Maintenance and Catalyst

Off Design Condition





Fuel Effect on Boiler Maintenance and Catalyst

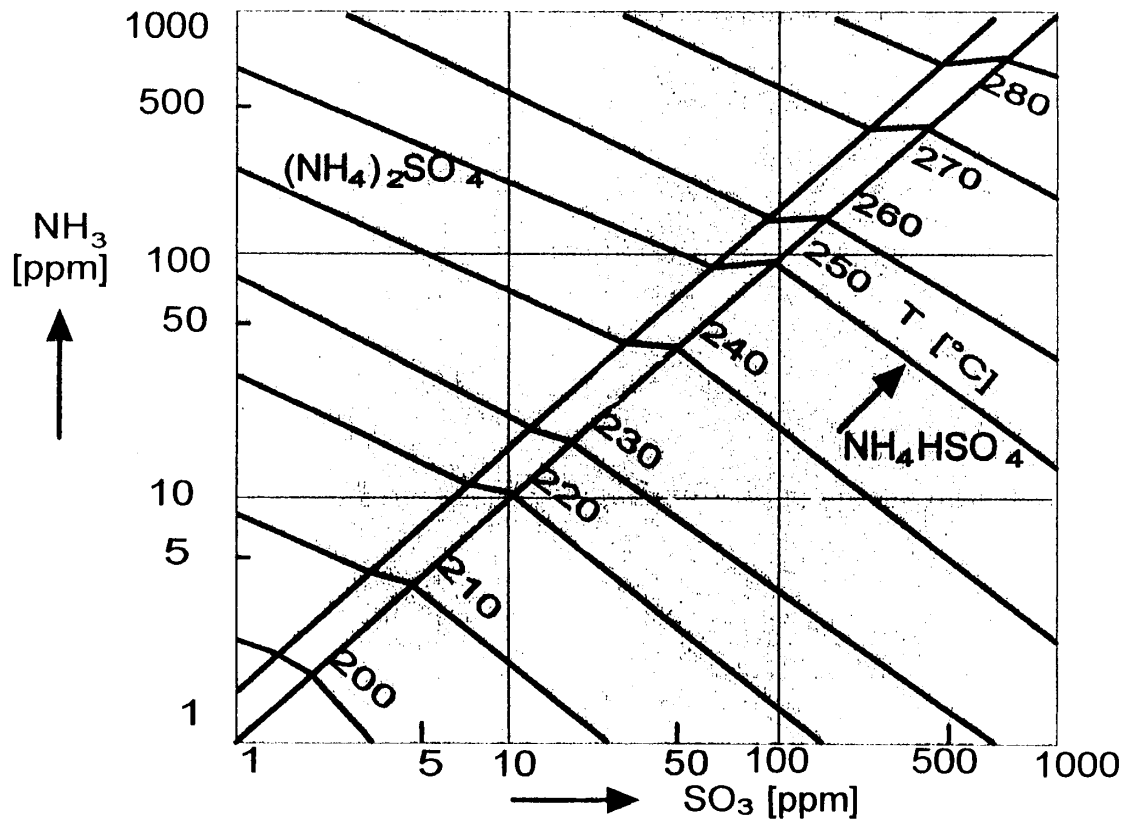
Off Design Conditions

- Catalyst Flue Gas Design Parameters
 - Gross changes to design parameters
 - Higher Reactor Inlet NO_x
 - Inadequate amount of catalyst potential
 - Temperature
 - Lower Temperature – Decrease in catalyst potential
 - Decrease in expected life
 - Increase in minimum load
 - Higher Temperature – Increase in SO₂ to SO₃ Conversion
 - Downstream effects
 - Possible decrease in life - Sintering



Fuel Effect on Boiler Maintenance and Catalyst

Catalyst – Minimum Continuous Operating Temperature (T_{mcoT})





Fuel Effect on Boiler Maintenance and Catalyst

Off Design Conditions (Continued)

- Catalyst Flue Gas Design Parameters
 - Flue gas volume flow rate changes
 - Higher volume flow – Inadequate amount of catalyst potential
 - Lower volume flow - Increase in SO_2 to SO_3 conversion
 - Increase in SO_3 concentration
 - Higher sulfur
 - High vanadium/ Iron – Boiler or catalyst
 - Significant Change Fuel



Fuel Effect on Boiler Maintenance and Catalyst

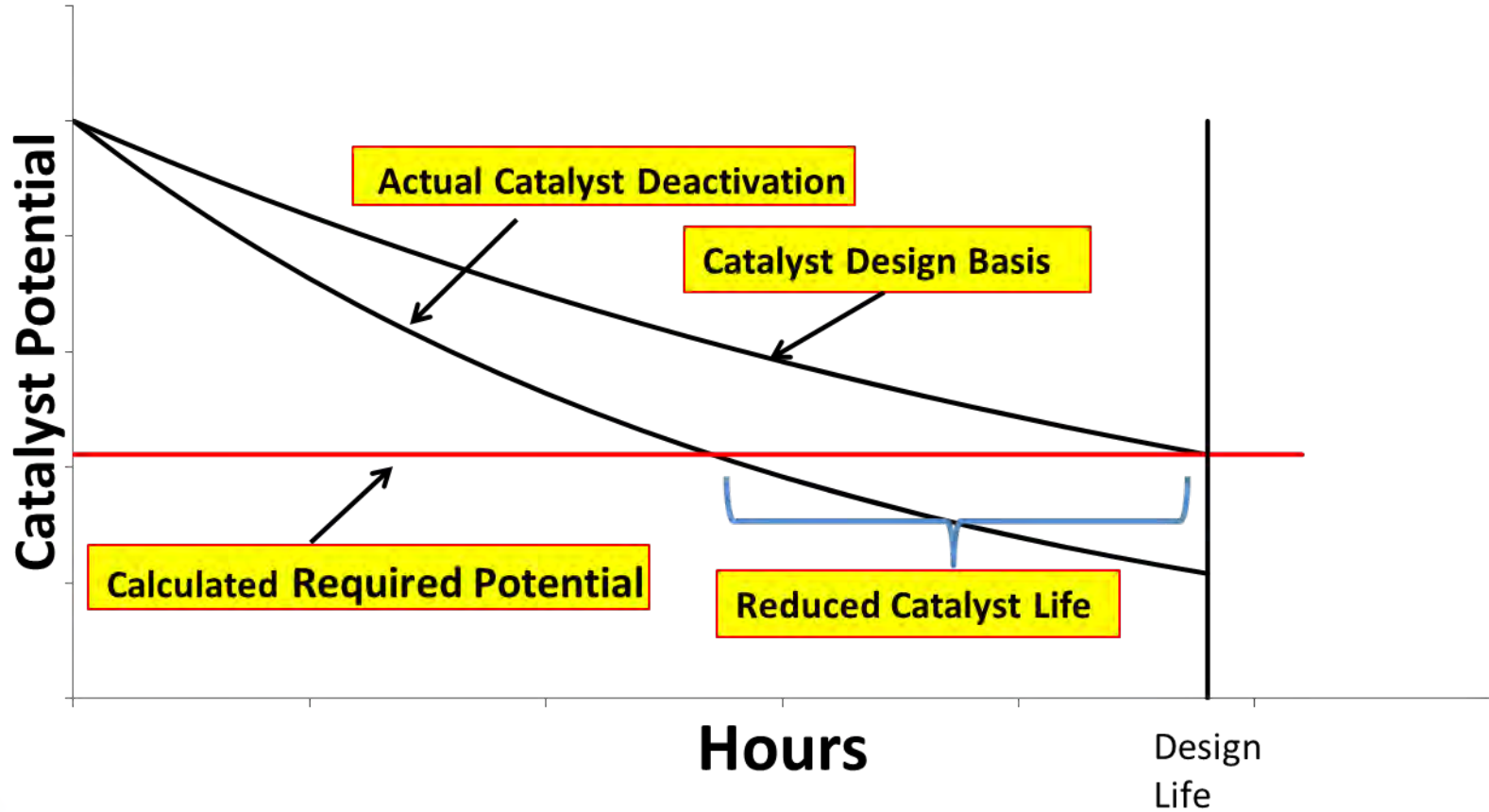
Fuel Characteristics that Affect Catalyst Life and Maintenance

- Irreversible - Can't Be Regenerated
 - Large Particle Ash (LPA)
 - Gross plugging
 - Erosion
 - Unburned Carbon (LOI)
 - Fire
- Reversible – Can Be Regenerated
 - Poisoning
 - Fouling



Fuel Effect on Boiler Maintenance and Catalyst

Deactivation

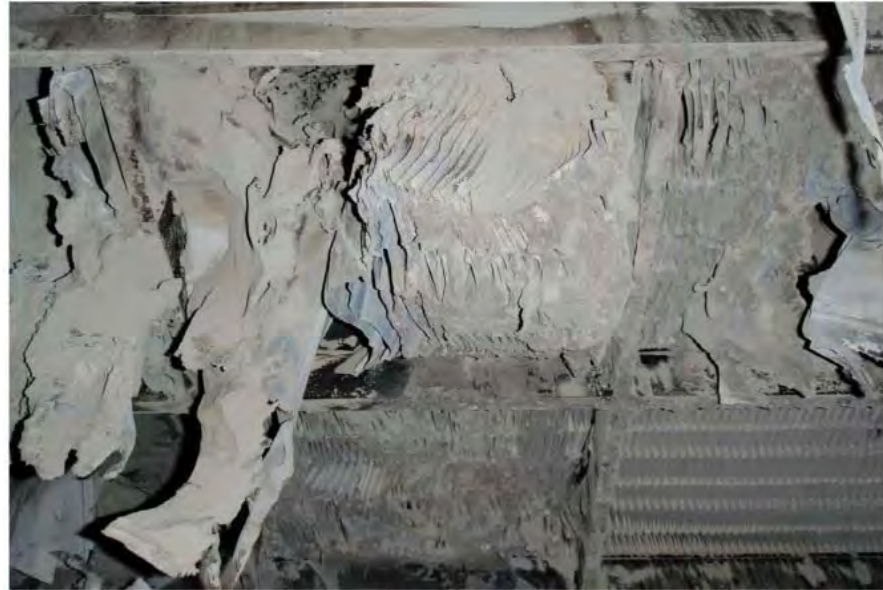




Fuel Effect on Boiler Maintenance and Catalyst

Fire

- Plate Catalyst – Catastrophic
- Honeycomb – Can be localized at leading edge of catalyst
- Sintering of any catalyst results in loss of pore structure that can't be regenerated
- Issue in the 15% to 20% LOI range



'Catalyst Management Strategy Improvements', C. P. Lin, Feb. 8 1010 .
Reinhold NOx-Combustion Conference



Fuel Effect on Boiler Maintenance and Catalyst

Large Particle Ash (LPA)

- LPA Properties
 - Size >4.0 mm
 - Density 0.7 to 1.25 g/cc
 - Sphericity 0.7 to 0.99
 - Coefficient of Restitution 0.15 to 0.2
 - Fuel Dependent

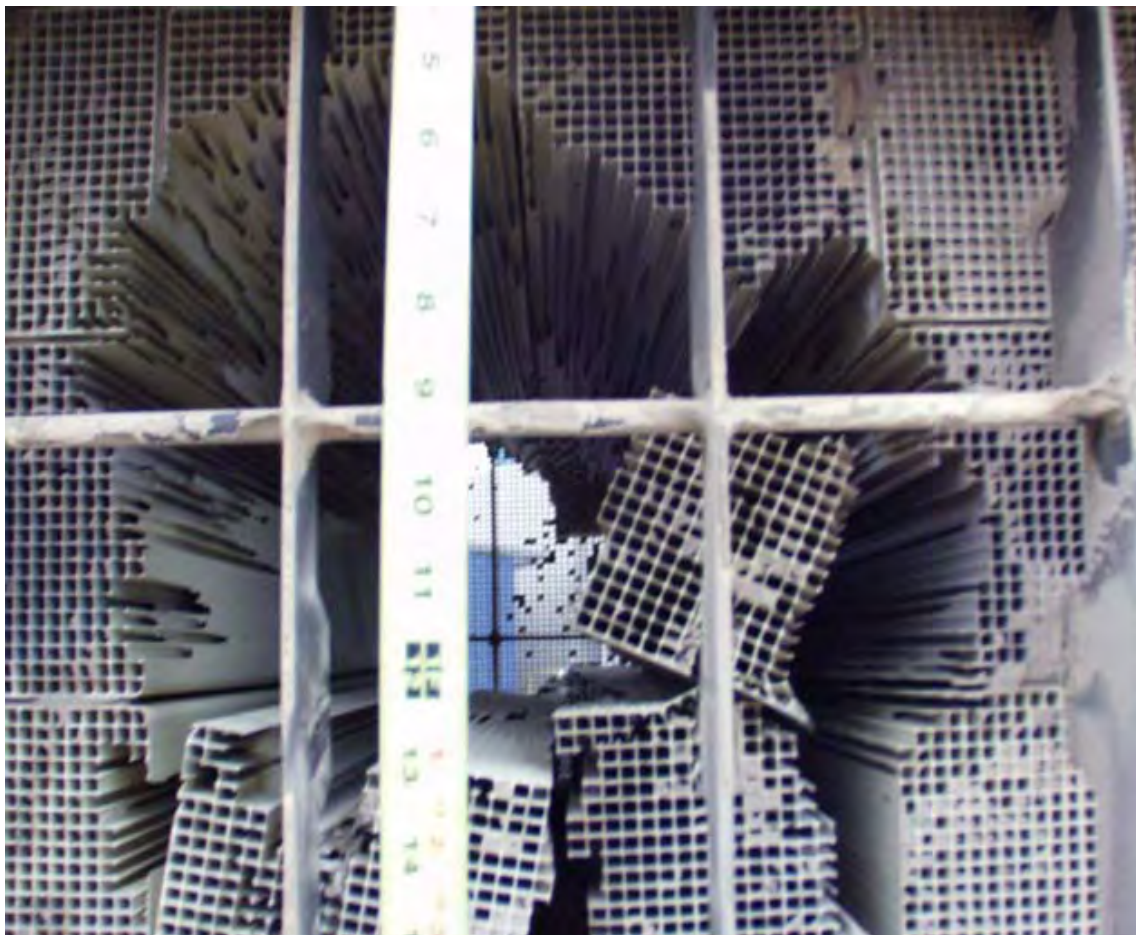


- Screen Design Important
- Pluggage
- Erosion
- Fuel is a factor in formation of LPA, but unpredictable,



Fuel Effect on Boiler Maintenance and Catalyst

Erosion From Large Particle Ash Plugging

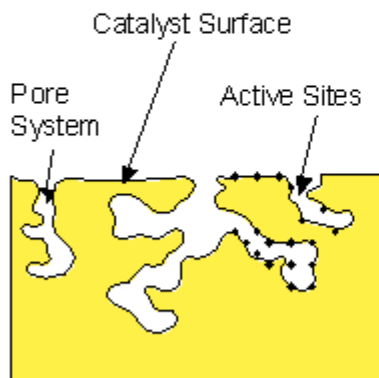




Catalyst - Deactivation

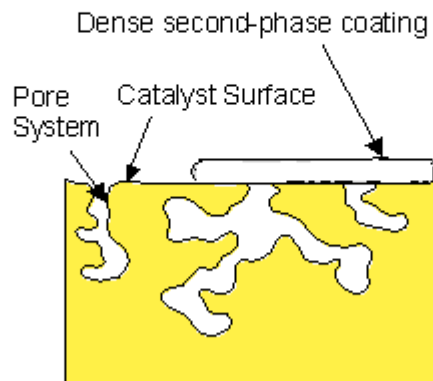
Poisoning:

Deactivation of active catalyst sites by chemical attack



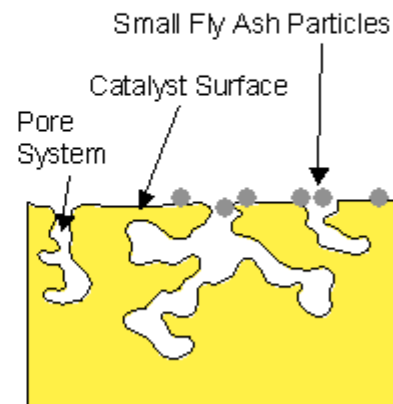
Masking:

Macroscopic blockage of catalyst surface by dense second-phase coating



Plugging:

Microscopic blockage of catalyst pore system by small fly ash particles





Fuel Effect on Boiler Maintenance and Catalyst

Deactivation – Maintenance

- Fine Particulate
 - $\text{CaO}, \text{Na}_2\text{O}, \text{K}_2\text{O}$ Reacting on Catalyst Surface
- Alkaline Metals
 - Sodium, Potassium
- Alkaline Earth Metals
 - Sodium, Magnesium, Calcium, Magnesium, Barium, Strontium, Phosphorus
- Halogens
- Heavy and Base Metals
 - Arsenic, Antimony, Chrome, Cooper, Lead, Mercury, Nickel, Tin, Zinc, Vanadium



Fuel Effect on Boiler Maintenance and Catalyst

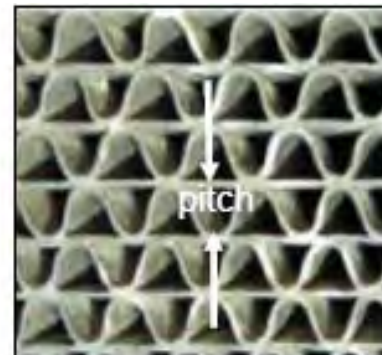
Deactivation - Maintenance

- Specific Fuels
 - Bituminous Coal – Arsenic, SiO_2
 - Sub-Bituminous Coal – CaO , Na_2O , P_2O_5
 - Ash loading - Pitch
 - Lignite – Sulfur, Iron
 - Iron Increase in SO_2 conversion
 - Ash loading - Pitch
 - Biomass - CaO , K_2O , P_2O_5
 - Pet Coke – Vanadium
 - Increase in SO_2 conversion



Fuel Effect on Boiler Maintenance and Catalyst

Catalyst Pitch Selection



- High Dust Honeycomb (Bituminous)
 - 7 mm pitch - 500 m²/m³
 - 6.9 mm to 7.4 mm
- High Dust Honeycomb (Sub-Bituminous)
 - 8.2 mm pitch - 420 m²/m³
 - 7 mm to 9 mm
- Low Dust Coal
 - 5.9 mm Pitch - 580 m²/m³
- Plate
 - 5.6 pitch - 350 m²/m³



Fuel Effect on Boiler Maintenance and Catalyst

Coal Monitoring

- Proximate Analysis, ASTM D-3172
- Ultimate Analysis, ASTM D-3176
- Fuel Trace Analysis, ASTM D-3683-9, ASTM D-6357
- Fly Ash, D-ASTM 3682-94

| |
|----------------------------------|
| SiO ₂ % |
| Al ₂ O ₃ % |
| Fe ₂ O ₃ % |
| CaO |
| MgO % |
| TiO ₂ % |
| MnO % |
| V ₂ O ₅ % |
| Na ₂ O ₂ % |
| K ₂ O ₅ % |
| P ₂ O ₅ % |
| SO ₃ % |
| LOI |



Fuel Effect on Boiler Maintenance and Catalyst

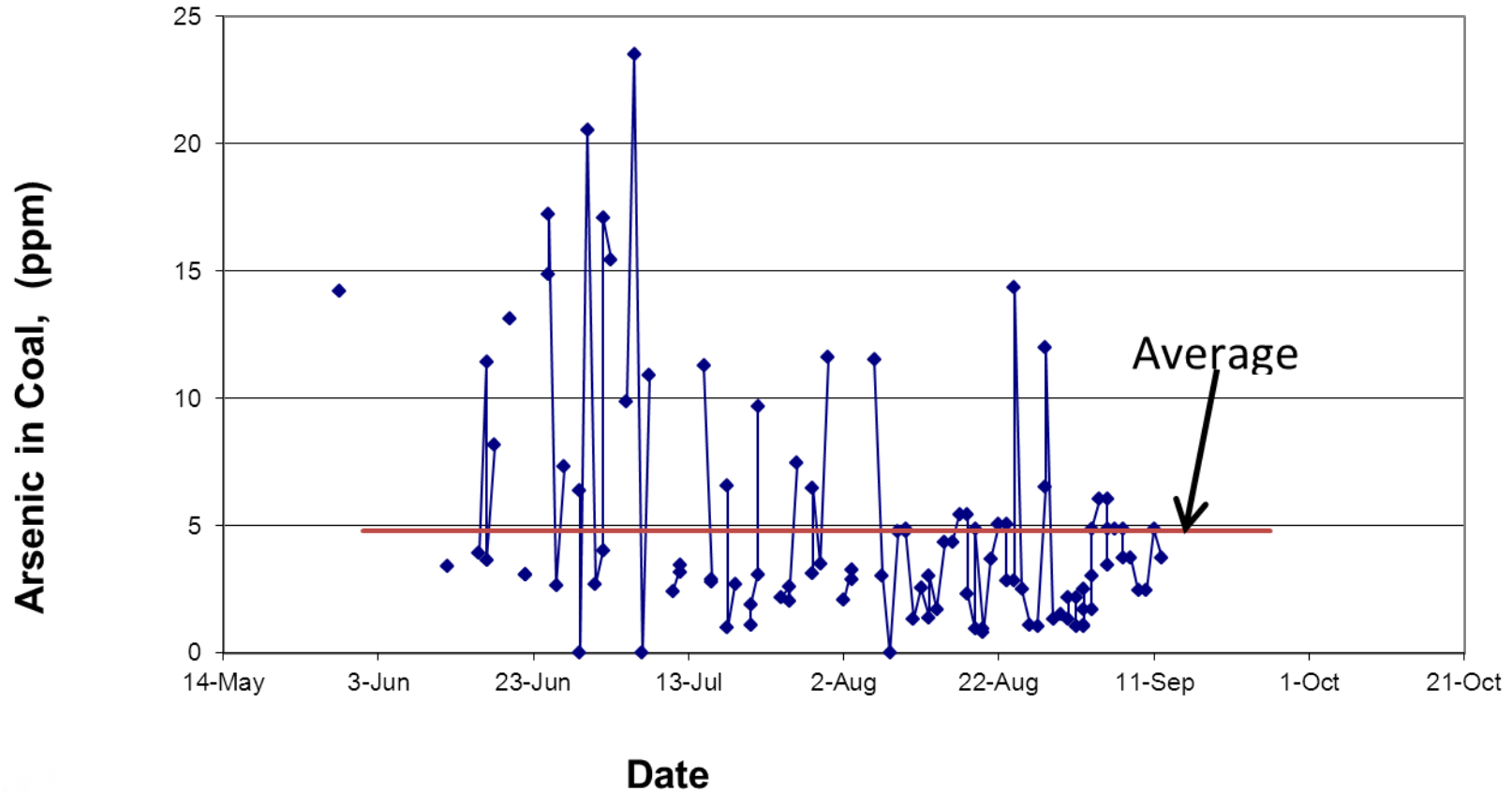
Coal Monitoring (Continued)

- Hourly DCS Monitoring
 - Pressure drop
 - Catalyst
 - Airheater
 - Ammonia consumption
 - Flue Gas Process Conditions
 - NOx in, NOx out, SCR temperature, etc.
- Daily – Weekly
 - Coal Sampling
 - Ash Sampling
 - NH3 in Fly Ash
- Annually
 - Direct measurement of slip
 - Catalyst test sample
 - Ammonia tuning



Fuel Effect on Boiler Maintenance and Catalyst

Coal Property Variability

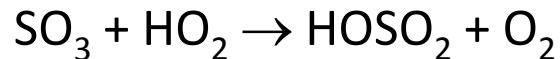




Fuel Effect on Boiler Maintenance and Catalyst

SO₃ Formation in Boilers

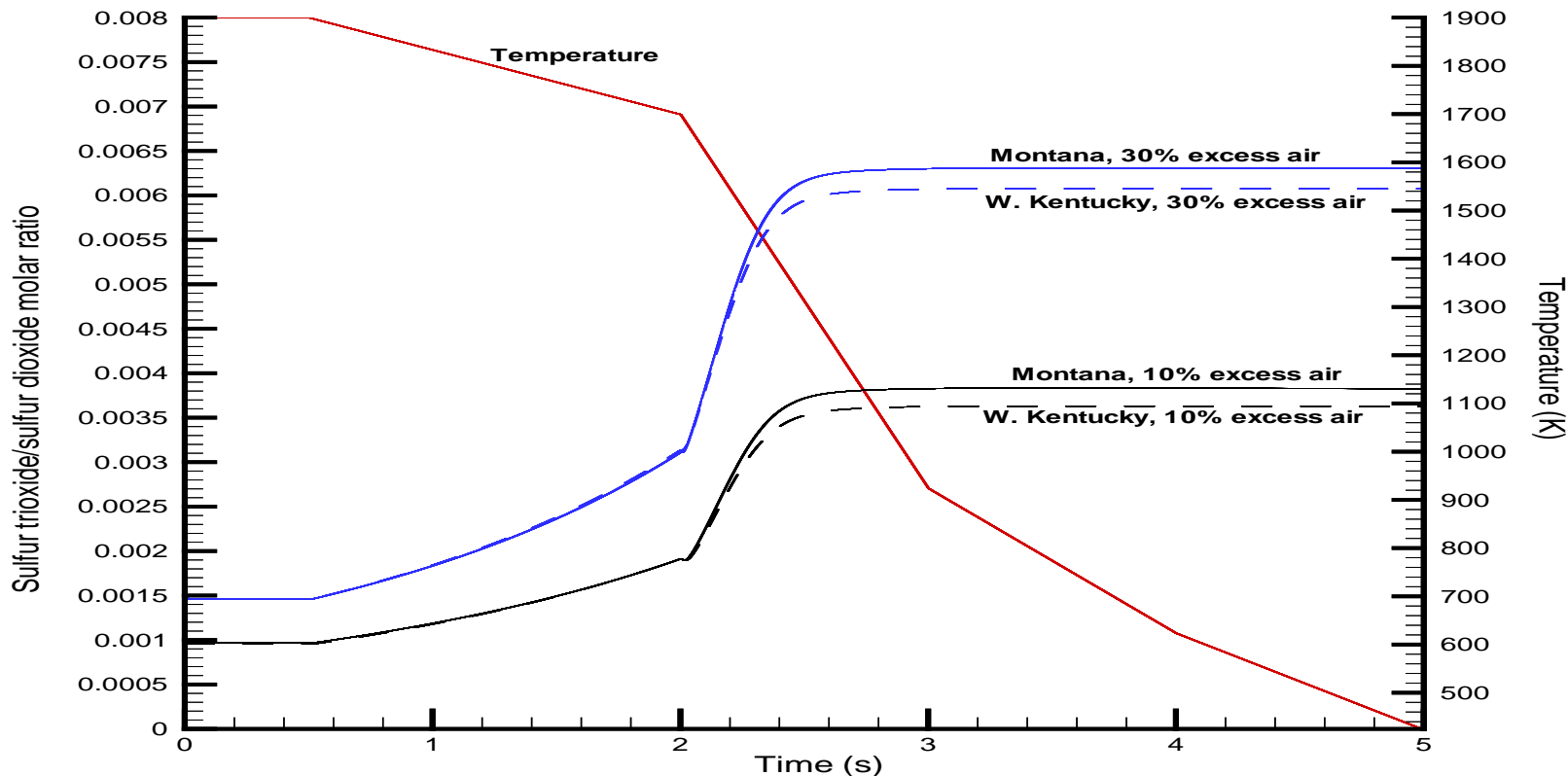
- During combustion, coal sulfur rapidly oxidizes to either SO₂ or SO₃
- Combustion oxidization mainly forms SO₂
- High temperature SO₃ kinetics (principal reactions):





Fuel Effect on Boiler Maintenance and Catalyst

Formation in Boilers





Formation in Economizers

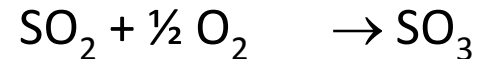
- Oxidation of SO_2 via O_2 catalyzed by iron oxides present in both ash and tube surfaces; temperature range of 1100-800 °F (593-427 °C)
- Depends on SO_2 concentration, ash content and composition, convective pass surface area, gas and tube surface temperature distributions, and excess air level; very site-specific
- Data suggests furnace/economizer conversion to be approximately 0.8 to 1.6% for bituminous and 0.05 to 0.1% for subbituminous coals



Fuel Effect on Boiler Maintenance and Catalyst

Formation in SCR Reactors

- SCR oxidizes a small fraction of SO₂ in the flue gas to SO₃:



- Conversion rate depends primarily on the vanadium content of the catalyst, and is linearly proportional to catalyst wall thickness
- Generally, oxidation can range from 0.25% to 0.5% of SO₂ per layer of catalyst in bituminous and 0.75 to 1.25% per layer in low-sulfur subbituminous coal applications.
- Potential for significant increase in SO₃ concentration



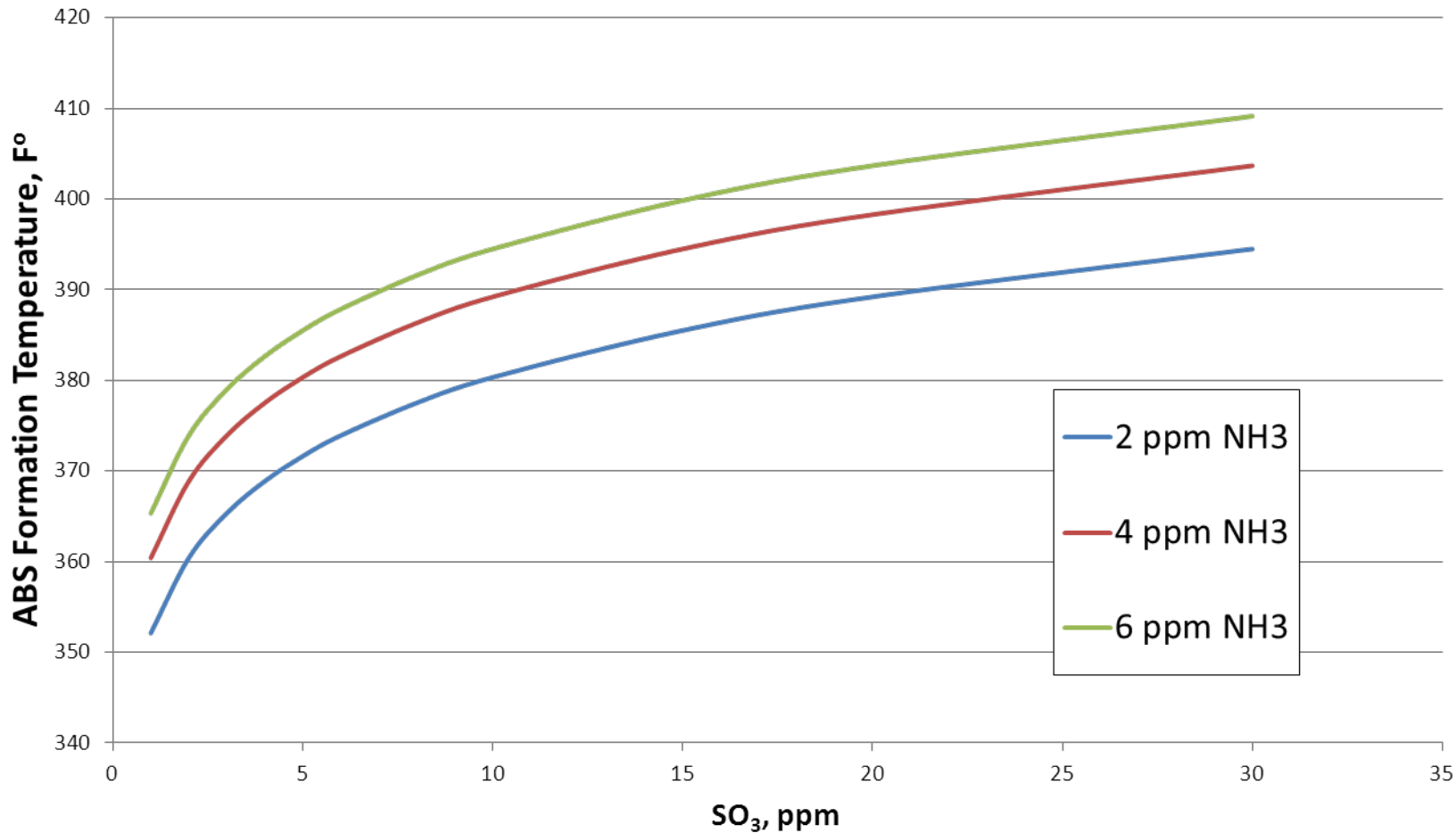
Fuel Effect on Boiler Maintenance and Catalyst

- SO_3 absorbs vapor-phase moisture at temperatures above its dew point to form H_2SO_4 vapor. Virtually all SO_3 converts to H_2SO_4 at temperatures of 400 °F or less.
- If local metal temperatures in the APH flow passages drop below the acid dew point (ADP), some H_2SO_4 condenses on these surfaces as liquid droplets (aerosol); regenerative vs. tubular APH
- Ammonia slip from SCR can react with SO_3 to form sulfates and bisulfates



Fuel Effect on Boiler Maintenance and Catalyst

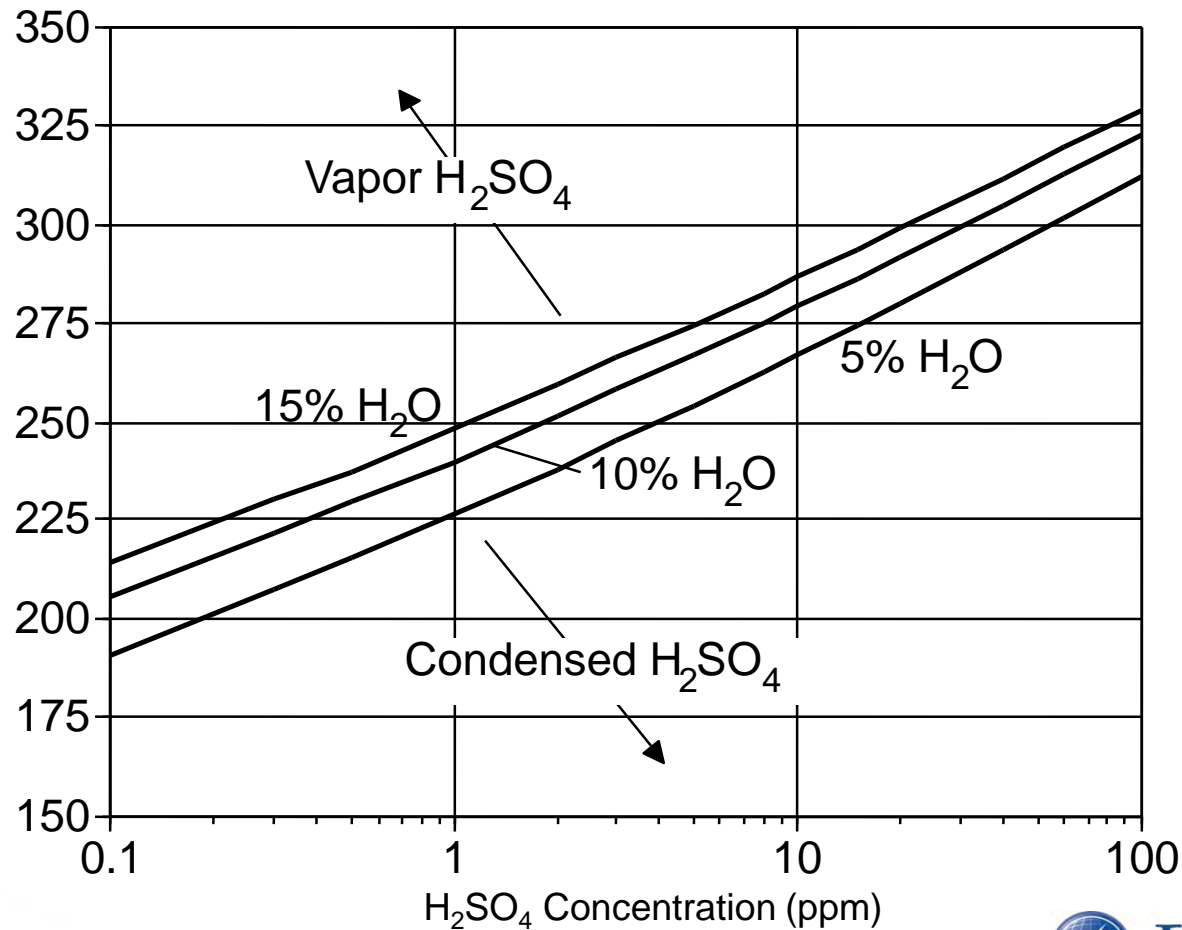
ABS Formation in Downstream





Fuel Effect on Boiler Maintenance and Catalyst

Condensation Between APH and PM Control





Fuel Effect on Boiler Maintenance and Catalyst

Removal in PM Control

- Adsorption rate dependant on fly ash properties
- Fly ash alkalinity main factor
- Adsorption rate dependant on flue gas temperatures
- Condensed SO_3 removed with fly ash
- Adsorption depends on equipment type; baghouses more efficient than ESP's
- SO_3 competes with mercury absorption in activated carbon

