REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table & Expo Presentation

February 19-20, 2018, in St. Louis, MO / Hosted by Dynegy

Performance Improvements through Targeted Hydrated Lime Injection

MISSISSIPPI® LIME

Discovering what's possible with calcium

February 20, 2018
Reinhold NOx Conference
St. Louis, MO

Historical Plant Data Analysis

What's Immediately Possible Today?

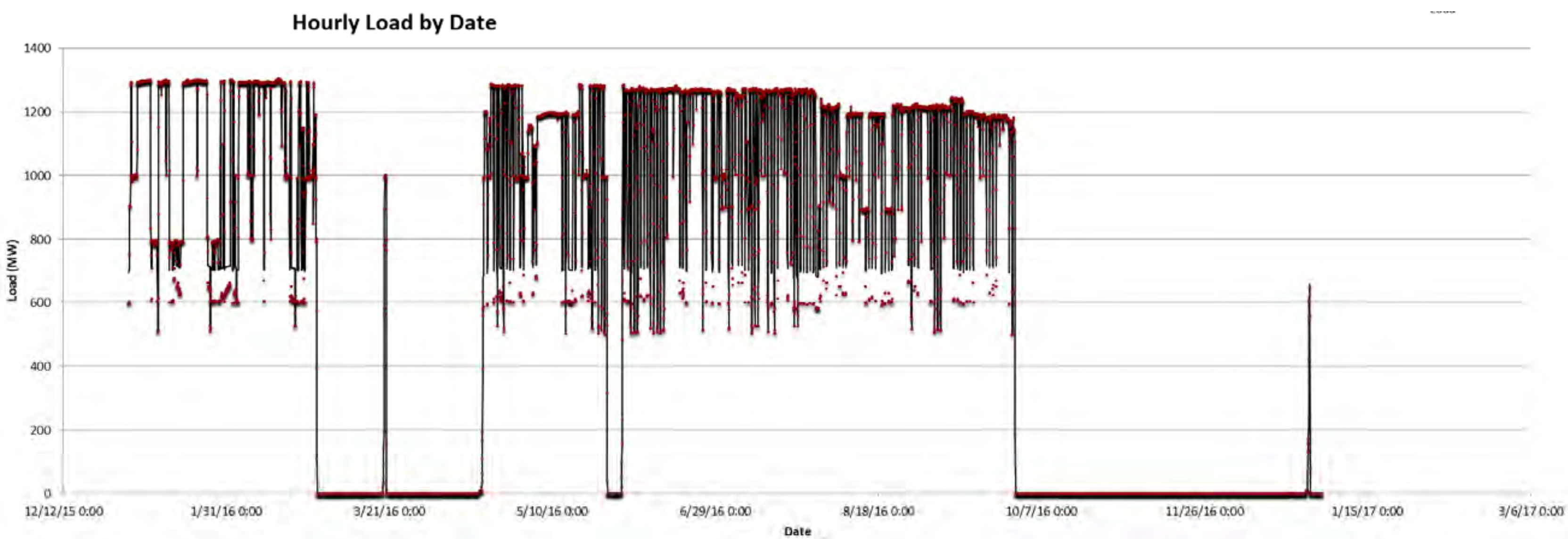
Data Sources & Availability

- Data for this analysis comes from:
  - EPA 2016 Acid Rain Database (AMPD)
  - EIA923 – 2016 Fuel Use and Generation Report
  - Plant Data supplied by Plant Engineering

High Level Fuel Analysis

• Total Coal mmBTU Consumed	53,583,133
• Net Generation (MWHr)	5,634,455
– Average Net Heat Rate	9,510 BTU/kWHr
• Coal Composition	
– HHV	12,312 BTU/Lb.
– Sulfur %	2.88%
– SO2 Release	4.67 Lb./mmBTU
– Ash %	6.94%

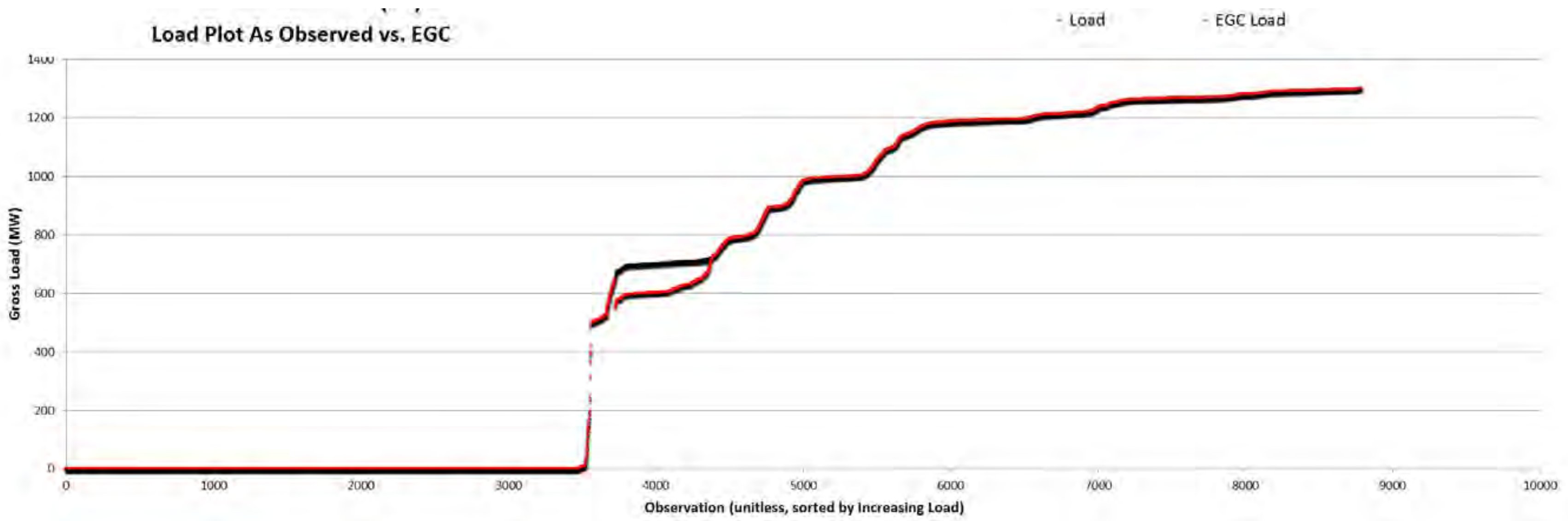
Hourly Load Profile for 2016



What can we see from this:

- Unit Capacity Factor for the year is under 50%
- Unit has difficulty maintaining full load at end of summer run
    - Could be AH fouling, or
    - Could be Condenser water temperature

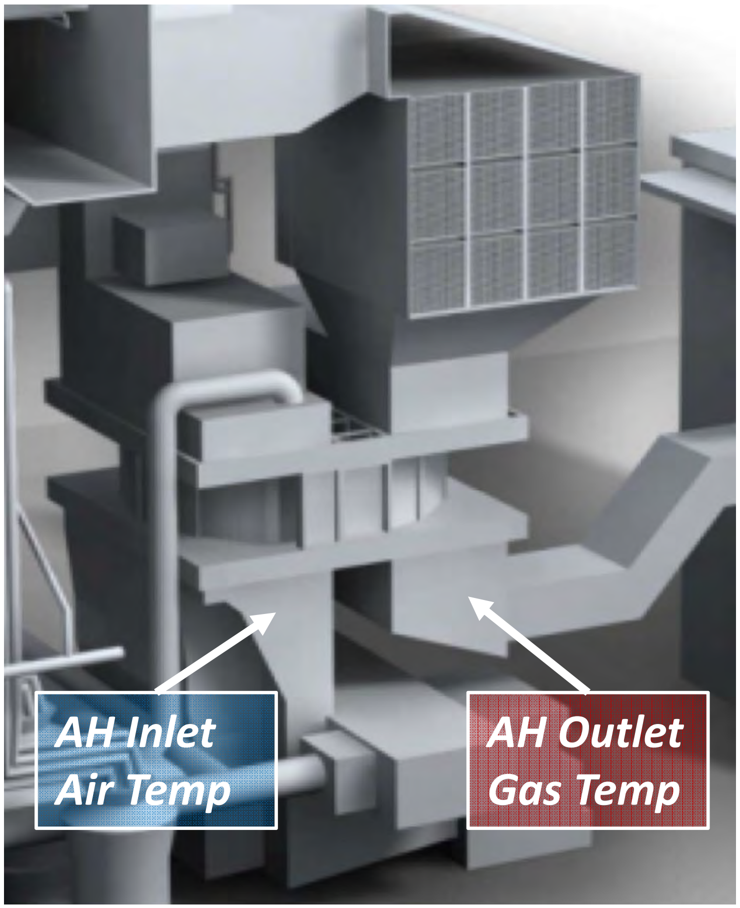
Load Distribution Plot - 2016



- Unit has a fundamental minimum load of 700 MW but has flirted with 500.
- Unit ran roughly 1000 hours at Minimum load but might have wanted more if MOT was lowered (vs. shutting unit down)
- Unit runs half of its actual operating time at, or near, full load
- Unit currently injects High Reactivity Hydrate (HRH) at the ESP Inlet and/or SCR Outlet

Air Heater Based Injection Location Impacts

Air Heater – Steam Coil Impact

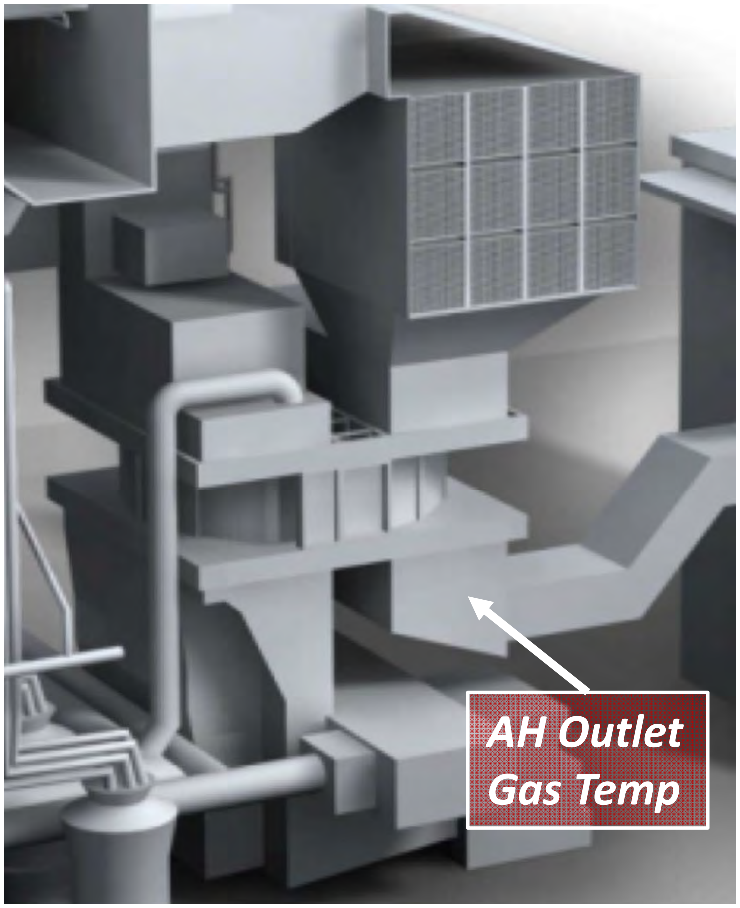


AH Outlet Gas Temp is Key

- Inlet air temp is adjusted via Steam Coils to maintain a desired AH Outlet gas temp
- Outlet gas temp is set to avoid condensable fouling
- It takes 0.24 BTU to raise 1 Lb of Inlet air by 1 degree F

Eliminating condensable material via hydrated lime injection eliminates the need for steam coils

Air Heater – Outlet Gas Temp Impact

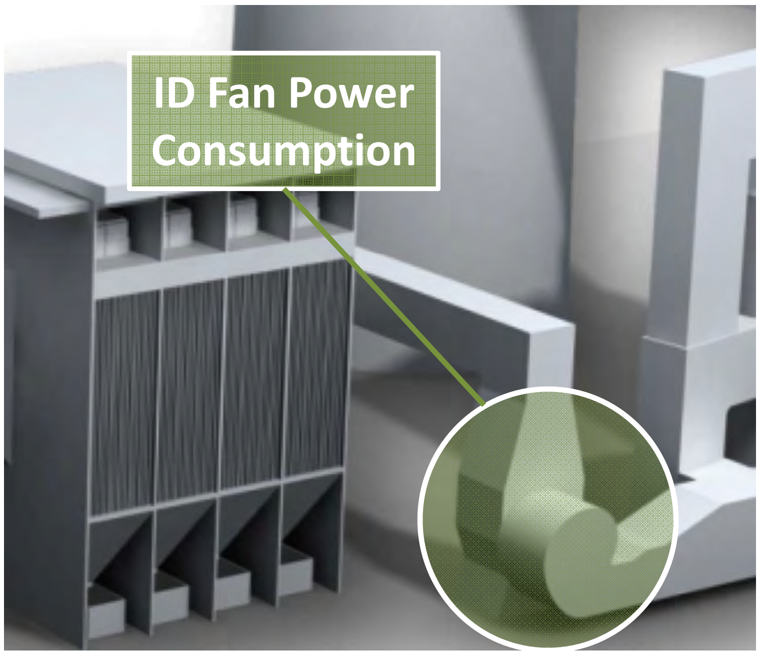


AH Outlet Gas Temp HR Impact

- After Steam Coil power is eliminated, every Lb of air at the AH outlet that is 1 degree higher than necessary is 0.24 BTU wasted
- It takes 14 Lb of Air to Burn 1 Lb of Coal (on average)
- Allowing for 6% - 8% AH leakage impact, 30F of unneeded gas temp at the AH outlet requires 1% unneeded fuel input (this is 1% in Heat Rate)

If Hydrated Lime eliminates AH Condensable Fouling, any process improvement that lowers the AH Outlet Gas temperature provides a permanent Heat Rate Improvement to the plant.

Air Heater – ID Fan Power Impact

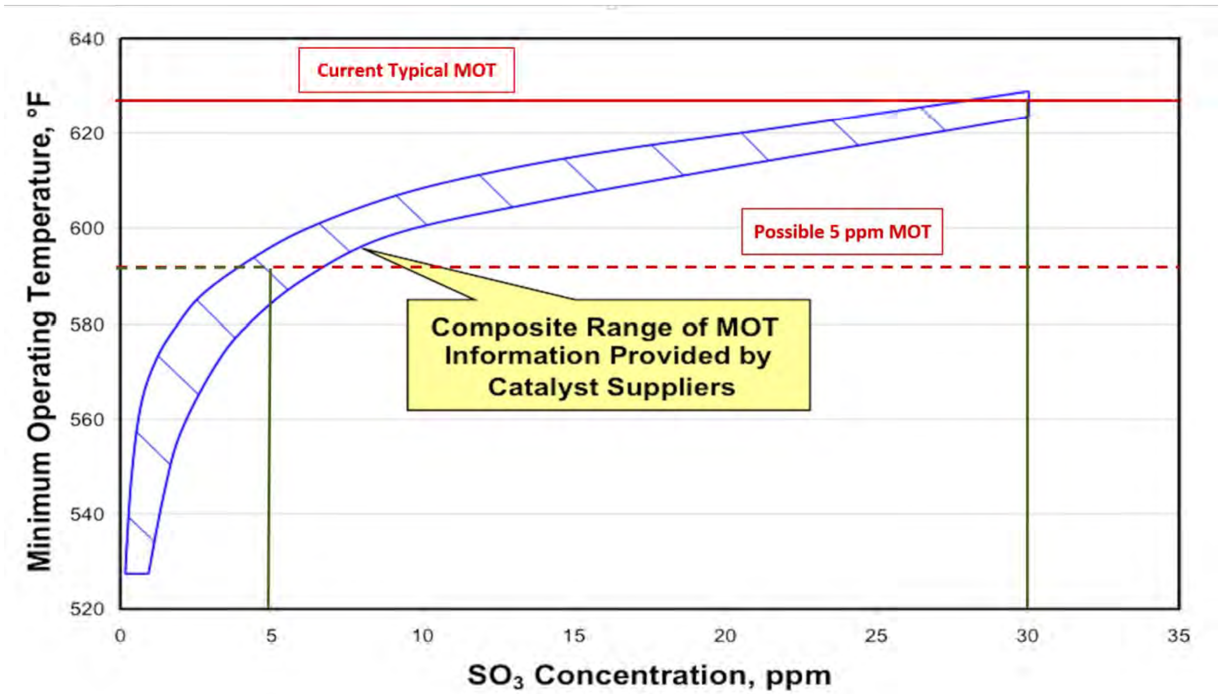


<u>AH Differential Pressure Impact on ID Fan Power</u>

- Every Inch of average increase in AH Differential Pressure (DP) due to condensate fouling results in roughly 6 BTU/kWHr of increased ID Fan Power Required
- For a nominal Heat Rate of 10,000 BTU/kWHr, 6 BTU=.06% in Heat Rate
- If, for example, an AH climbs from 6" DP to 14" DP before cleaning is required, the 8" differential can be viewed as 4" on average.

Simply, every 1" of differential between the Min and Max pressure drop across an AH can be viewed as 0.03% in Heat Rate

SCR Minimum Operating Temperature

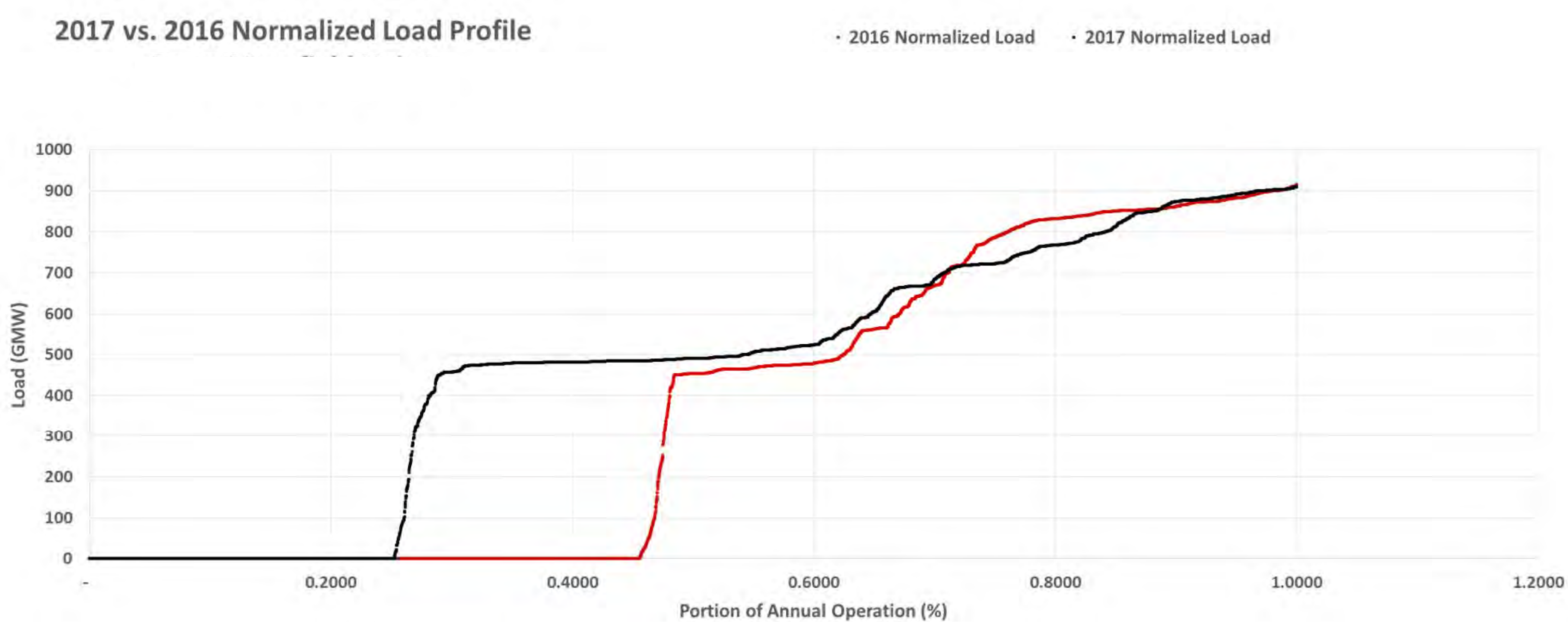


For a quick estimate of SCR MOT reduction value, we assume that a reduction in SO_3 from its native level to 5 ppm will eliminate SCR MOT constraints and will provide a 30F reduction in desired SCR Inlet temperature

The actual relationship between SCR Inlet SO_3 (ppm) and the SCR Minimum Operating Temperature (MOT) is very plant specific. The design curve from the catalyst supplier is required to determine the true potential impact of SCR Inlet SO_3 reduction.

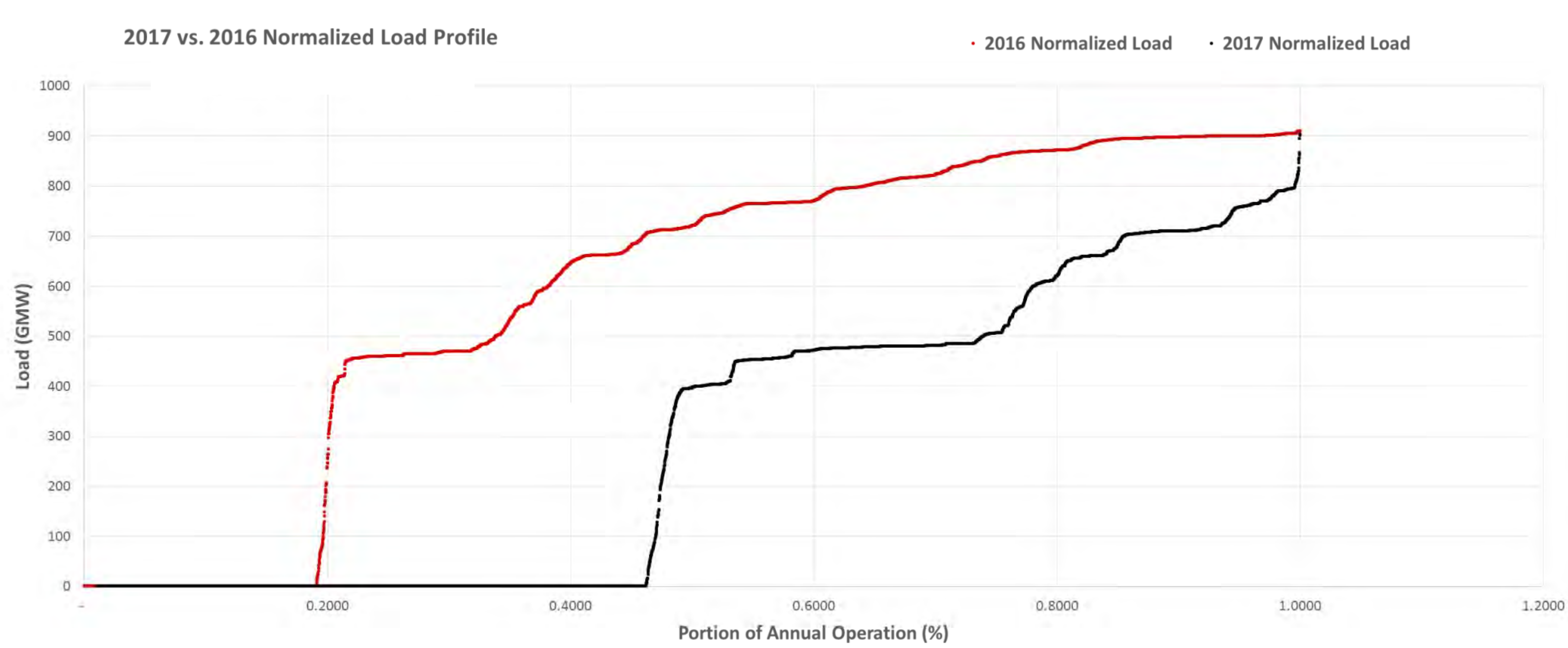
We'll Detail This Later in the Talk

Unit 1 Load Comparison



In 2017 Unit 1 operated significantly more than in 2016 with most of the added run time being at minimum load

Unit 3 Load Comparison



In 2017 Unit 3 operated significantly less than in 2016 but almost half of its operating time was at minimum load

Injection Location Summary

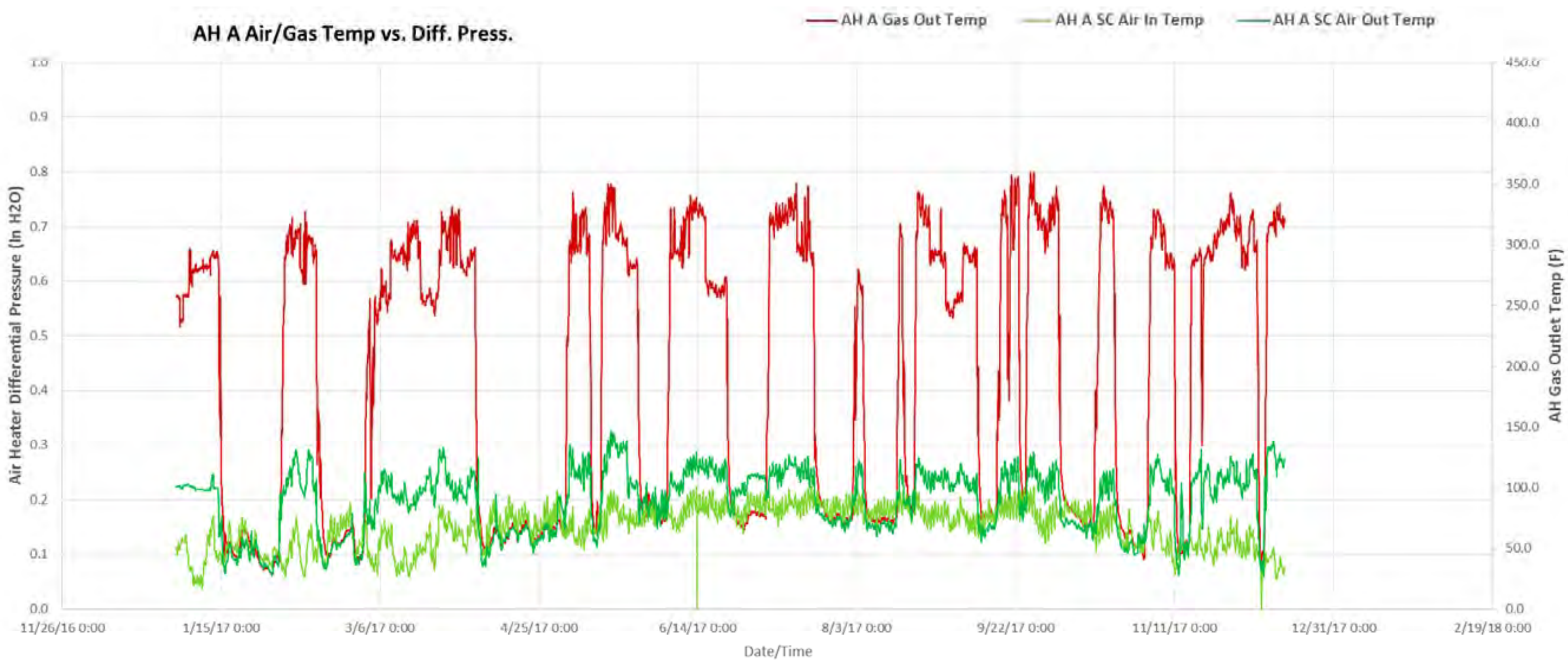
Calculations	Coal $/mmBTU	Total mmBTU	Total MWHr	Avg HI/MWHr	Total Steam Coil Power (mmBTU)	Min AH DP	Max AH DP	total ID Fan Loss (mmBTU)	Min Load	Proj Min Load	Hrs. at Min Load
d 1 - 2016	$2.25	28,662,782	3,211,338	8.925	417,776.00	6	14	68,791	425	350	1230
d 1 - 2017	$2.25	36,529,196	4,067,175	8.981	529,115.27	6	14	87,670	425	350	2278
d 3 - 2016	$2.25	46,080,751	5,169,148	8.915	498,344.59	4	14	138,242	440	350	1054
d 3 - 2017	$2.25	22,215,537	2,492,047	8.915	240,252.00	4	14	66,647	440	350	2102
s 1 - 2016	$2.25	35,583,317	4,129,230	8.617	98,805.00	6	8	23,618	350	250	990
s 1 - 2017		30,160,977	3,500,000	8.617							

Summary	AH mmBTU Shed	AH $ Value	MOT MWHr Shed	MOT mmBTU Shed	MOT $ Value	Injection Loaction Total $
- 2016	486,567	$1,094,775	92,232	823,216	$1,852,237	$2,947,012
- 2017	616,785	$1,387,767	170,820	1,534,214	$3,451,982	$4,839,749
- 2016	636,587	$1,432,320	94,867	845,701	$1,902,826	$3,335,147
- 2017	306,899	$690,522	189,216	1,686,780	$3,795,255	$4,485,777
- 2016	122,423	$275,452	99,000	853,125	$1,919,531	$2,194,982

Opportunities for Operational Benefits vary unit to unit based on the operating profiles, fuel cost and desired modifications

So What Is Currently in There?

A Duct AH Temps

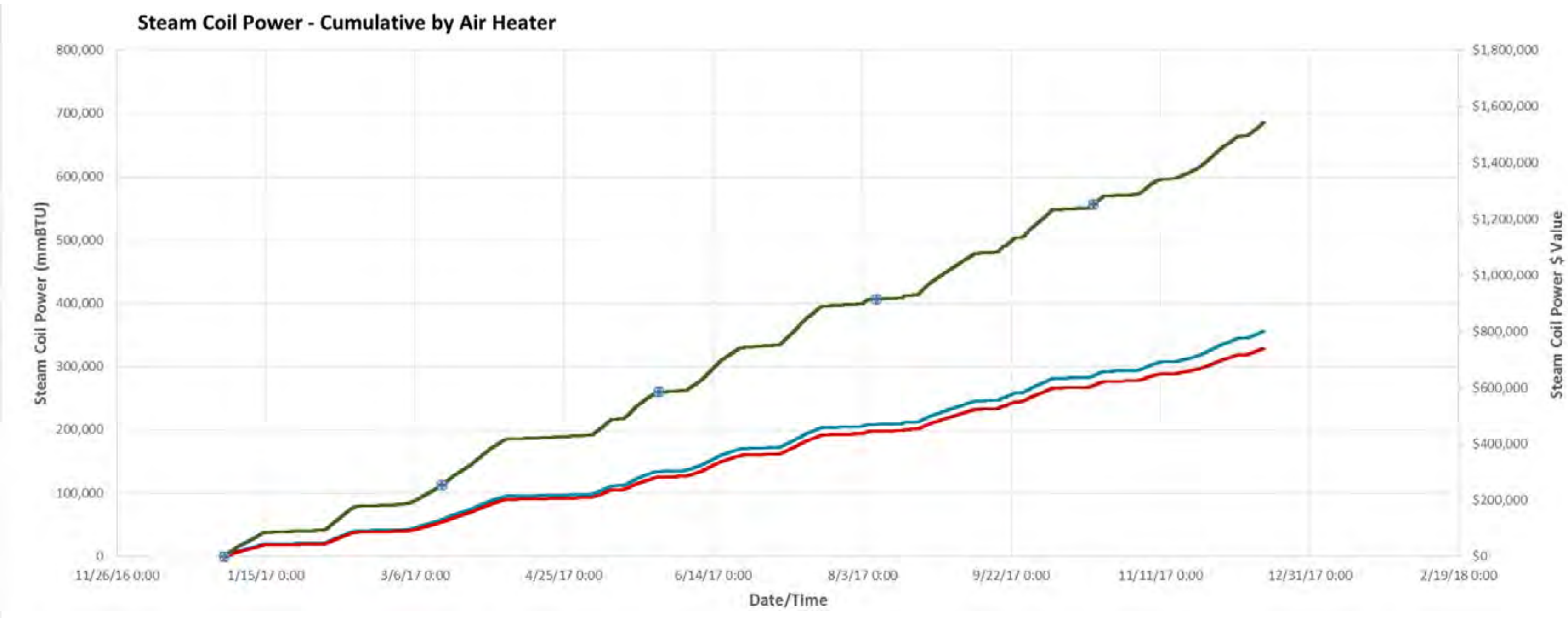


A Duct Avg. Gas Out – 320F to 350F.

B Duct AH Temps

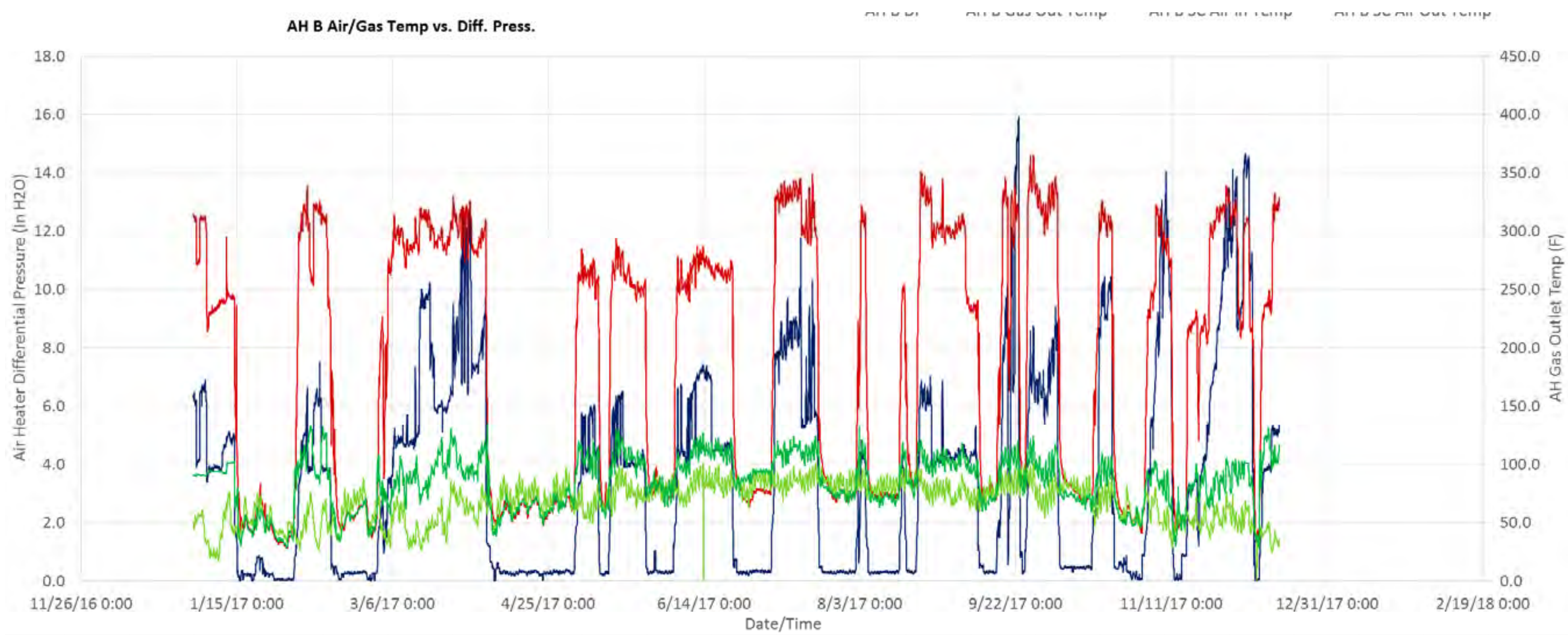
B Duct Avg. Gas Out – 320F to 340F, slightly cooler than A Duct.

Cumulative Power Loss to Steam Coils



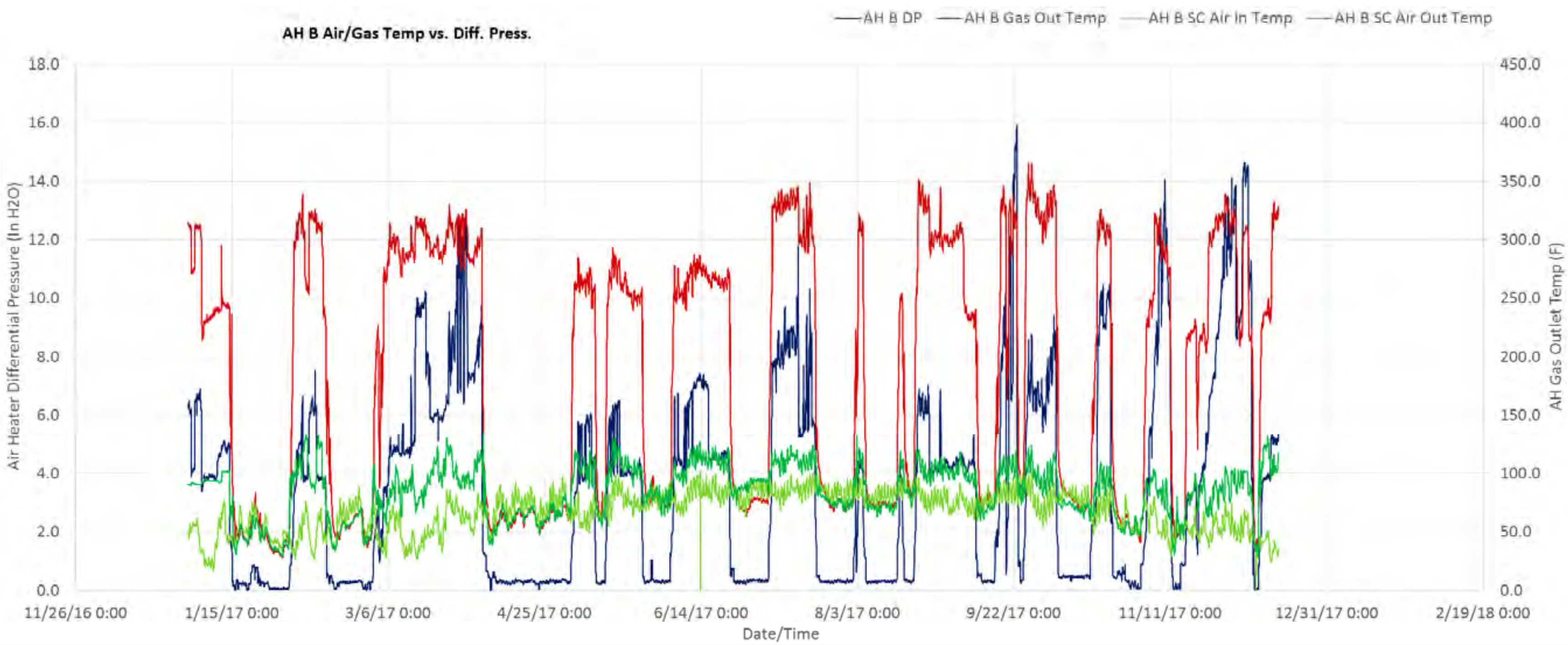
But why are AH Temperatures elevated to begin with?
To avoid Air Heater Differential Pressure buildup.

A Duct AH Temps



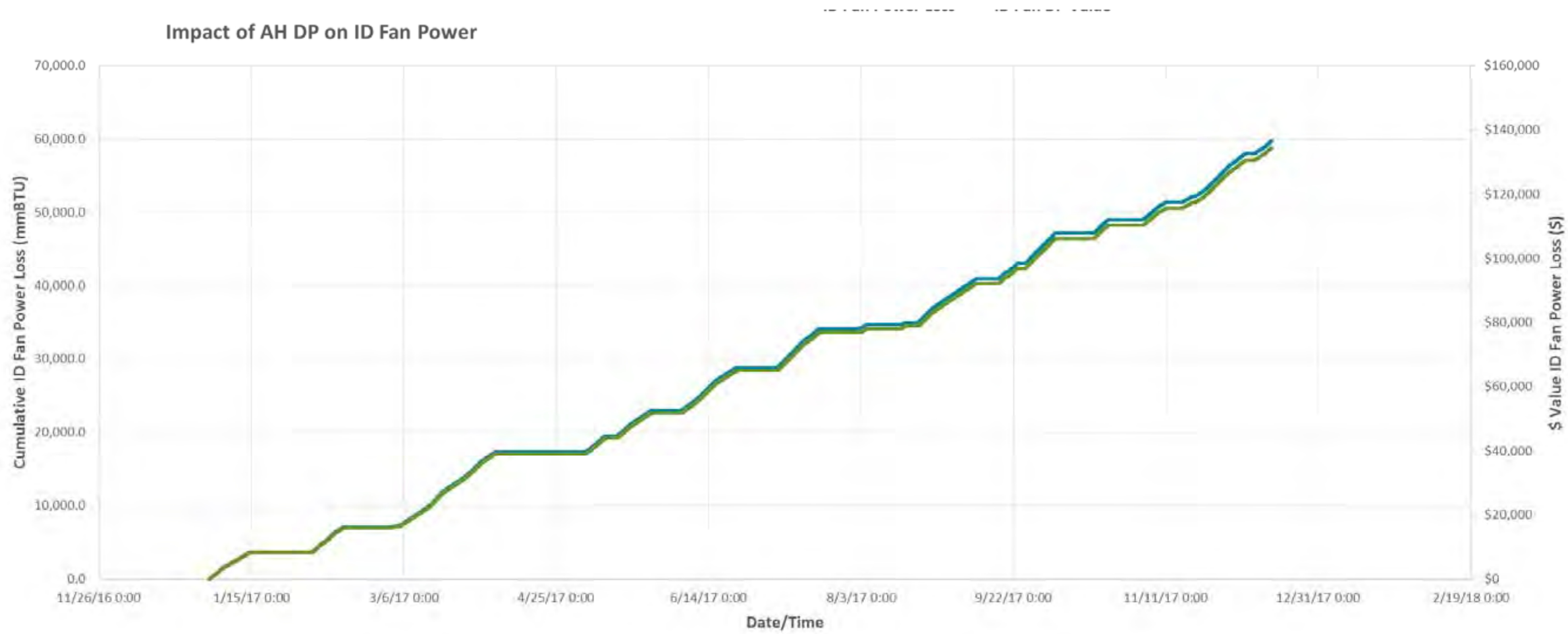
Differential Pressure increase of 8”, avg. over period = 4”

B Duct AH Temps



Differential Pressure increase of 8”, avg. over period = 4”

ID Fan Loading



AH Condensable Impact Savings

- Power Loss to Steam Coils
  - $1,500,000/Yr.
- Average Steam Coil temperature rise:
  - Summer 30F
  - Winter 60F
- Potential to drop AH Outlet Gas temps by 30F overall is very high. 30F drop in AH Outlet Gas temp yields 1% reduction in fuel use:
  - 1% of 28,179,238 = 281,792 mmBTU
  - @ $2.25/mmBTU = $634,000
- Total Savings from Improved AH Performance > $2,000,000

Unit Turndown Considerations?

What is MOT

EPRI Ongoing Work

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Update on SCR Operation During Reduced Load

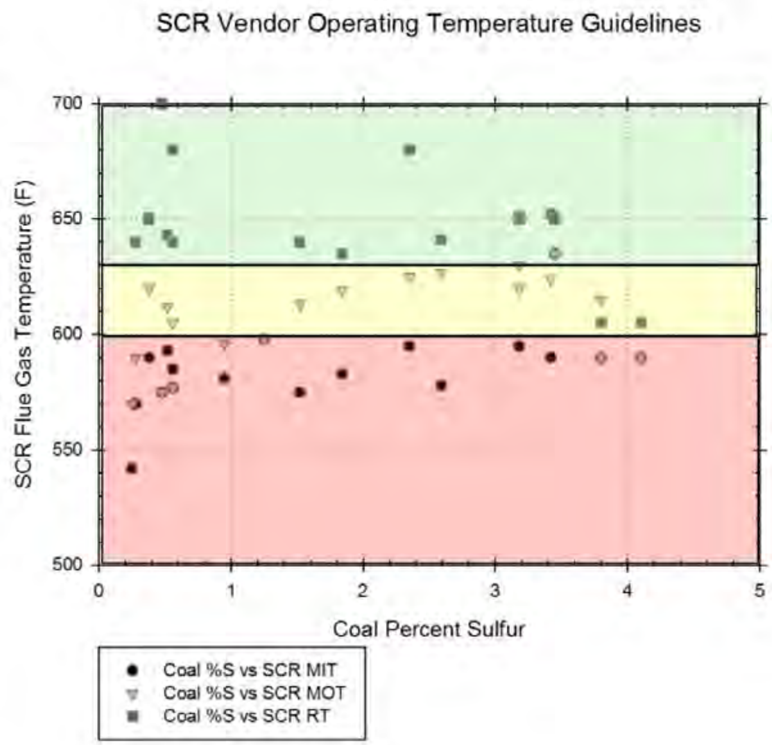
Richard Himes, P.E.
EPRI Technical Executive

Reinhold 2017 NOx-Combustion Conference
February 27, 2017

Current MOTs are Likely Conservative

Range of SCR MOT Guidance Provided to SCR Operators

- Range of factors influence SCR MOT
  - Coal sulfur and SCR inlet [SO_3] variability
  - SCR inlet NH_3 variability
  - SCR NOx reduction requirement
  - SCR inlet temperature non-uniformity
- Informal survey suggested utility guidance tended to be inconsistent
- Static SCR MOT value
- MOTs appear overly conservative based on more accurate ABS formation temperature



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Case Study on MOT Reduction

Case Study 1 – SCR Inlet Conditions vs Load

April 2014 Baseline Tests

	Load (MW)		
	1300	600	500
O_2 (%)	5.77 +/- 15%	9.33% +/- 4%	10.08% +/- 5%
NOx (ppmc)	410 +/- 9%	378 +/- 4%	377 +/- 4%
NOx (ppm)	346	244	227
Temp (F)	667 +/- 3%	570 +/- 3%	561 +/- 3%
SO_3 (ppm)	11.5	15.3	14.0
$[NH_3]$*$[SO_3]$	3,583	3,354	2,861
Bulk ABS Temp (F)	527	526	522

* NH_3 based on 90% ΔNOx

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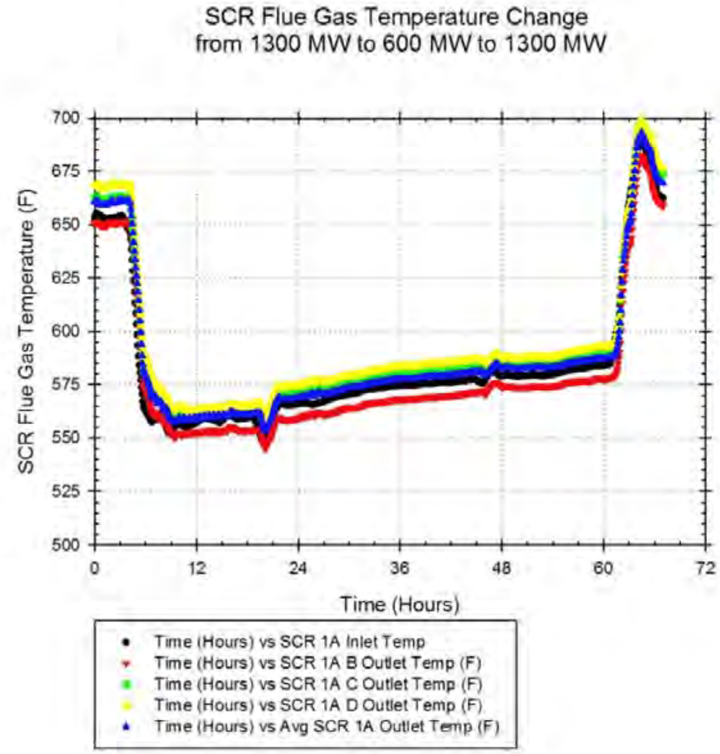
Protocol Definition

SCR Inlet Temperature

- Initial 600 MW tests conducted following unit outage with cleaning of back pass
  - Typical 50 F range in flue gas temperatures for given load
- During 54 hour 600 MW reduced load test in May 2014, flue gas temperatures ranged from 550 – 590 F
  - No soot blowing during reduced load operation
- During 54 hour 500 MW reduced load test in September 2014, flue gas temperatures nominally 20 F higher due to dirty furnace and back pass



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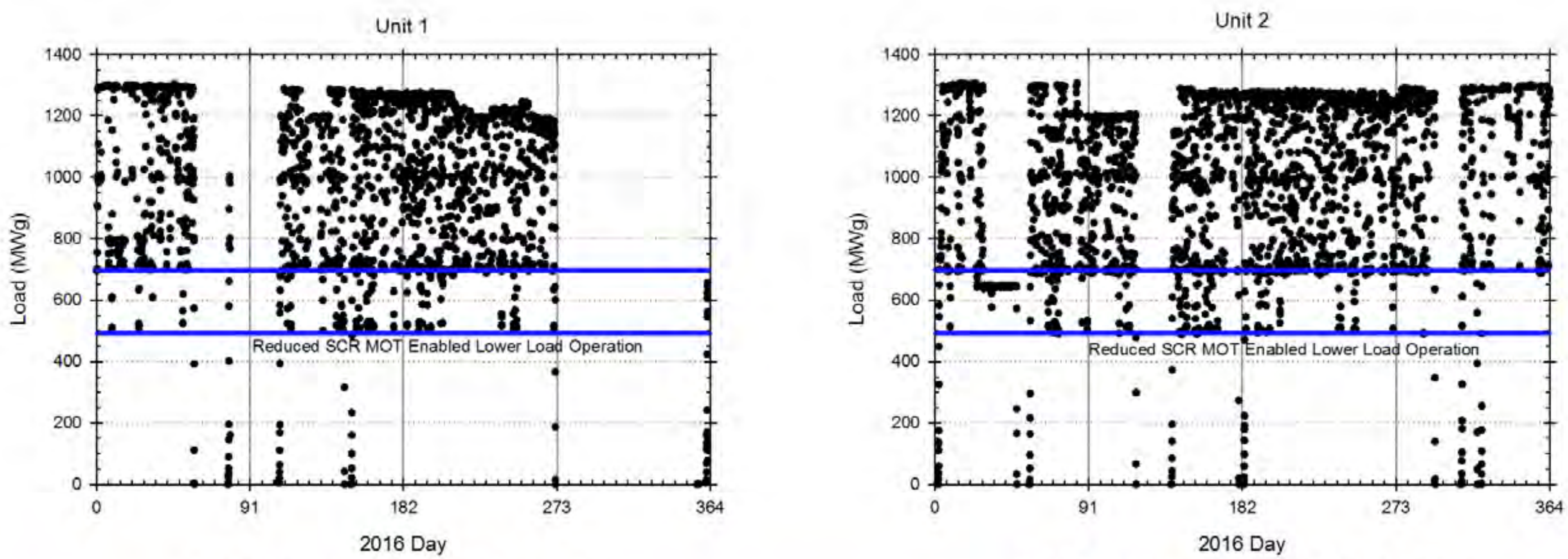
200 MW Drop in Min Load

Subsequent 2016 Unit Annual Load Profile



293 hours ; NOx < 0.075 lb/MBtu

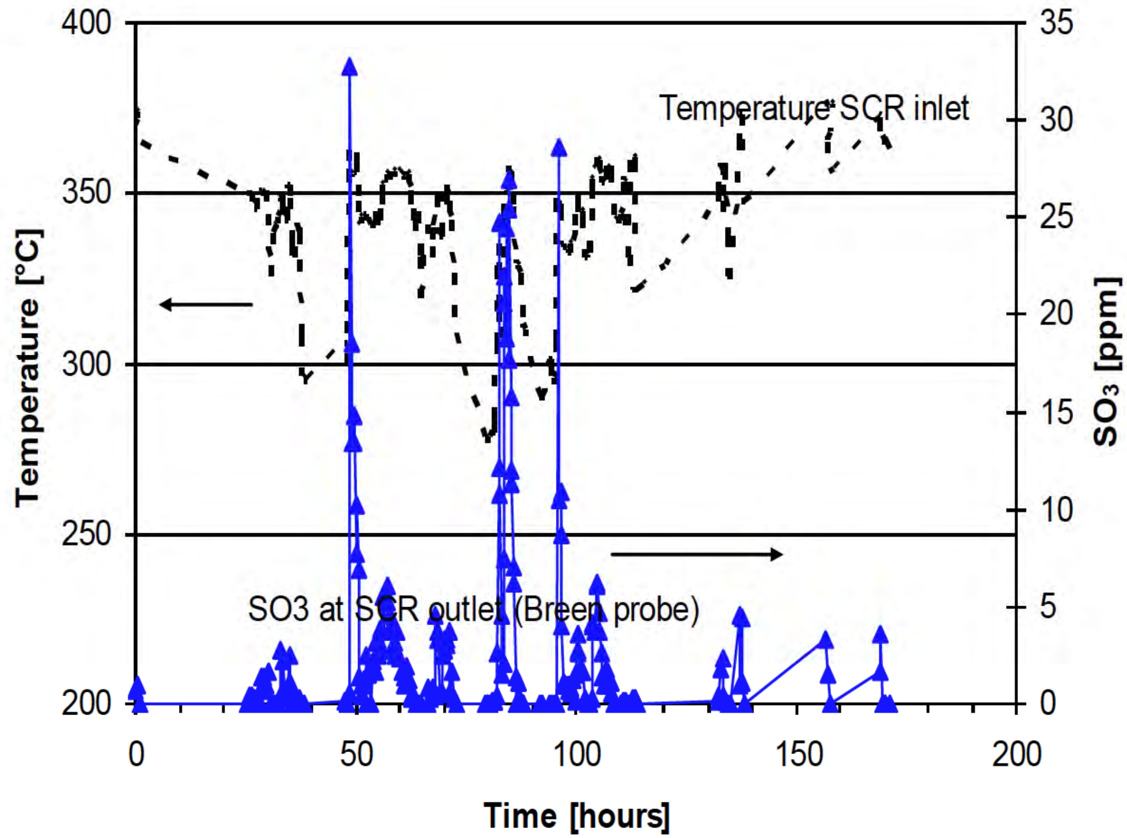
1,032 hours ; NOx < 0.075 lb/MBtu

Increased unit turndown 200 MW following SCR MOT demonstration project

Some Haldor Topsoe Thoughts

Reduced load at Studstrup

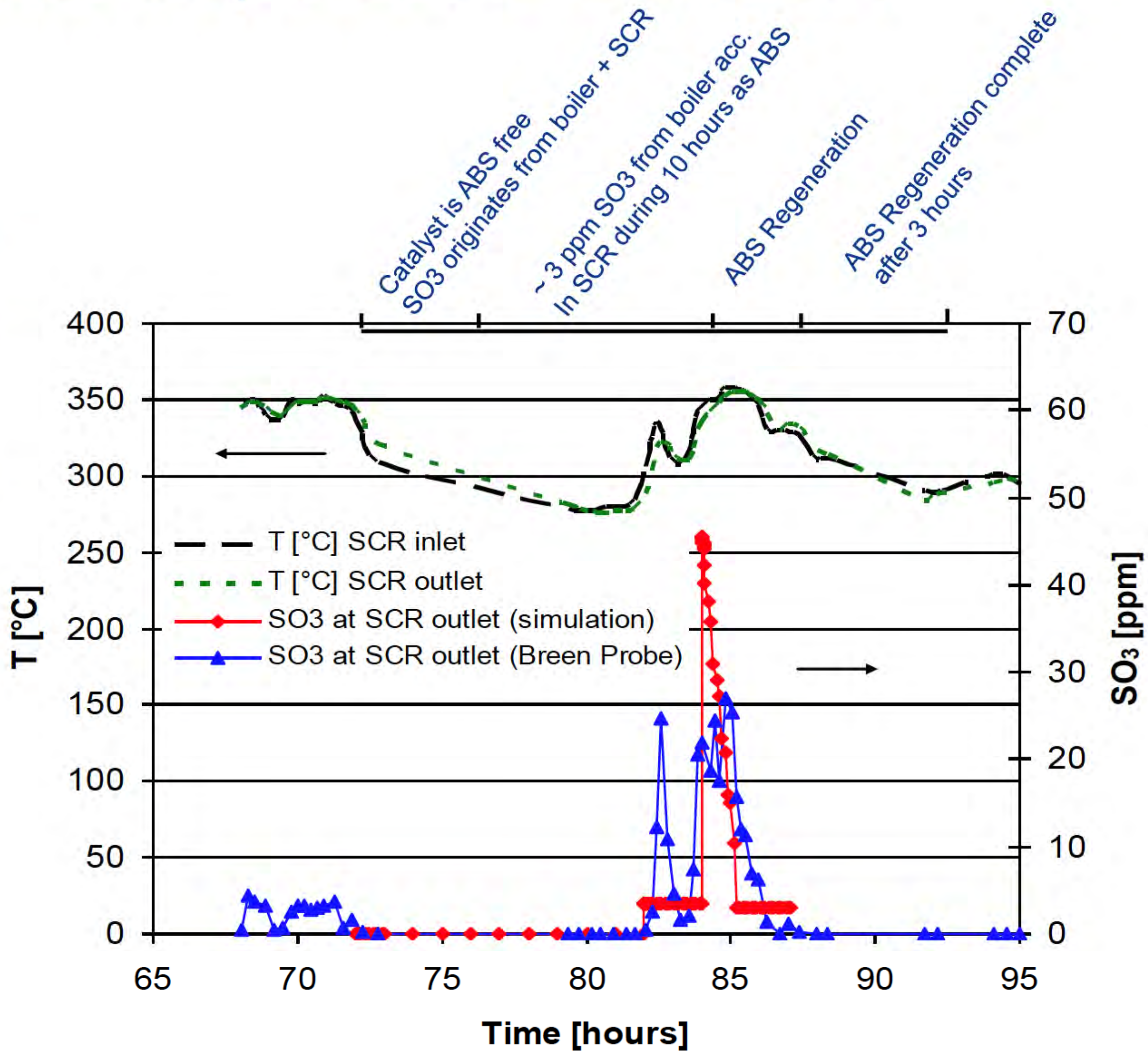
- 350 MWt power plant unit.
- ~ 3 ppm SO_3 at SCR inlet.
- Reduced load operations in the range 280 - 300˚C for 10 hours followed by heating to 350˚C.
- SO_3 measured at SCR outlet using a Breen probe.



Ref: Dong Energy

Breen Probe and Topsøe ABS model

- Regeneration experiment
  - Baseline operation
  - ABS accumulation
  - Regeneration
- 3 ppm SO_3 from the boiler.
- After 10 hours 0.007 ml/gcat ABS is accumulated.
- ABS regeneration complete after 3 hours



Some Cormetech Thoughts

CORMETECH

Method for Enhanced Low Load SCR Operation

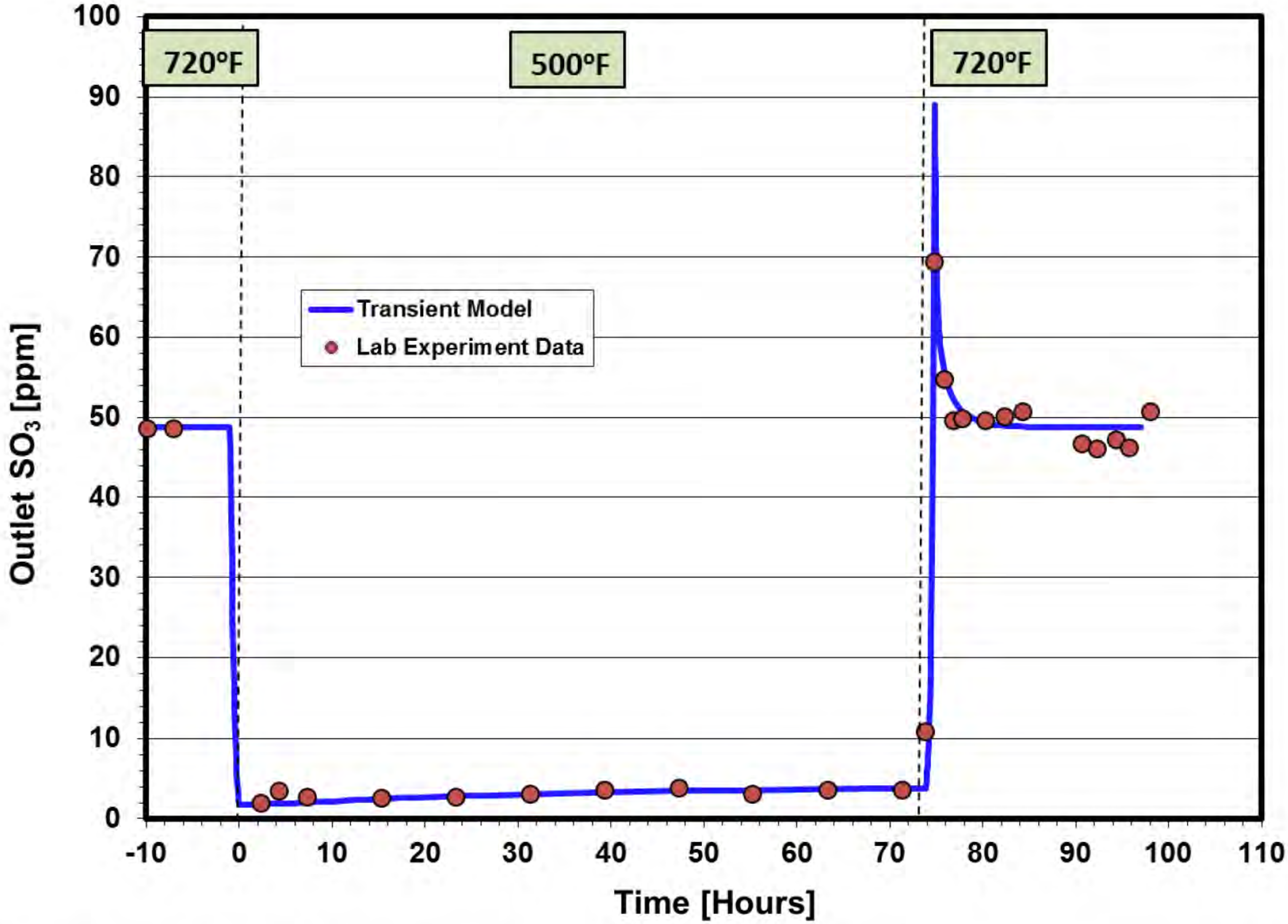
Christopher J. Bertole, Ph.D.

Extended Abstract #81

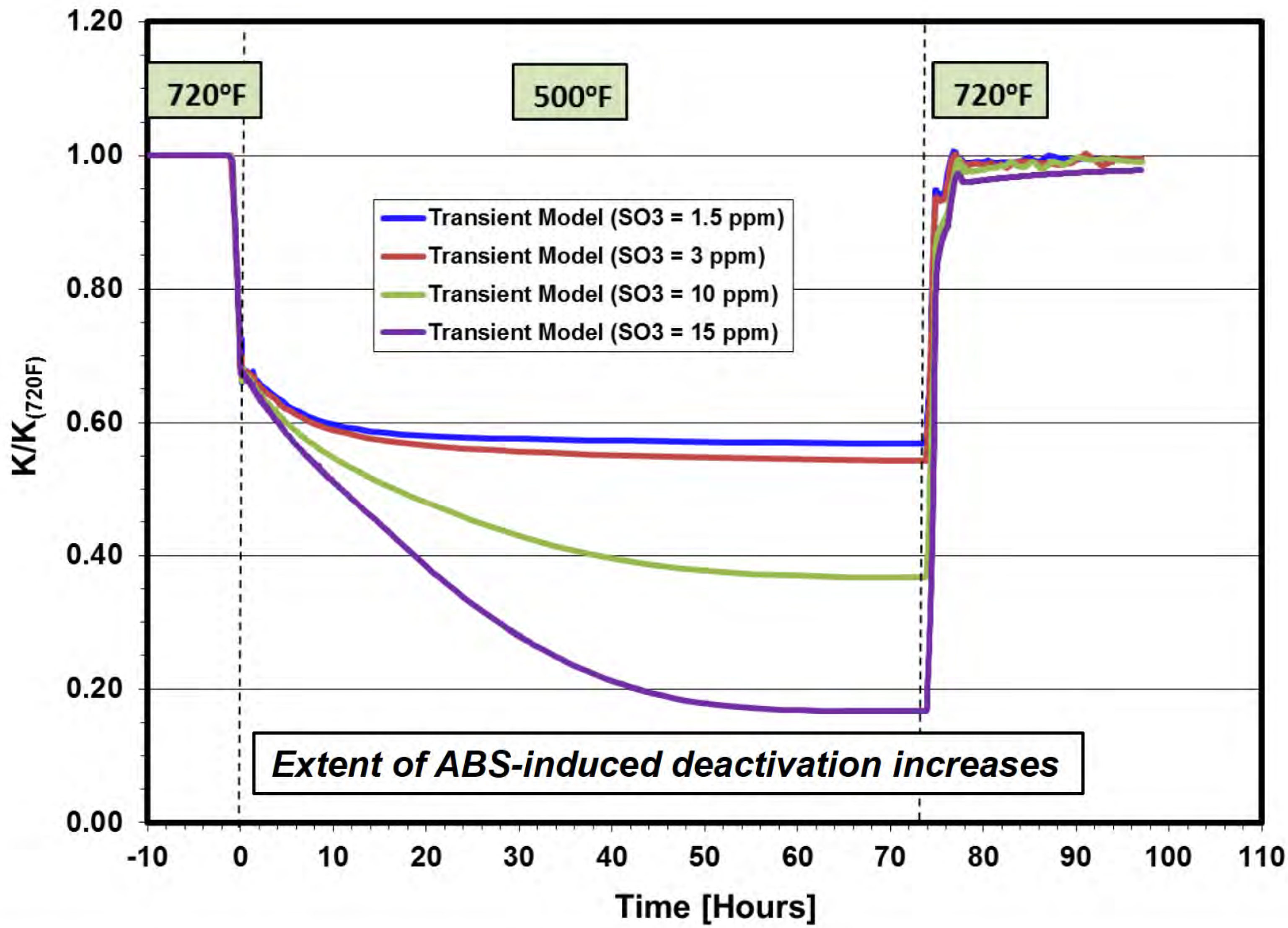
Power Plant Pollutant Control and Carbon Management "MEGA" Symposium

August 16-18, 2016

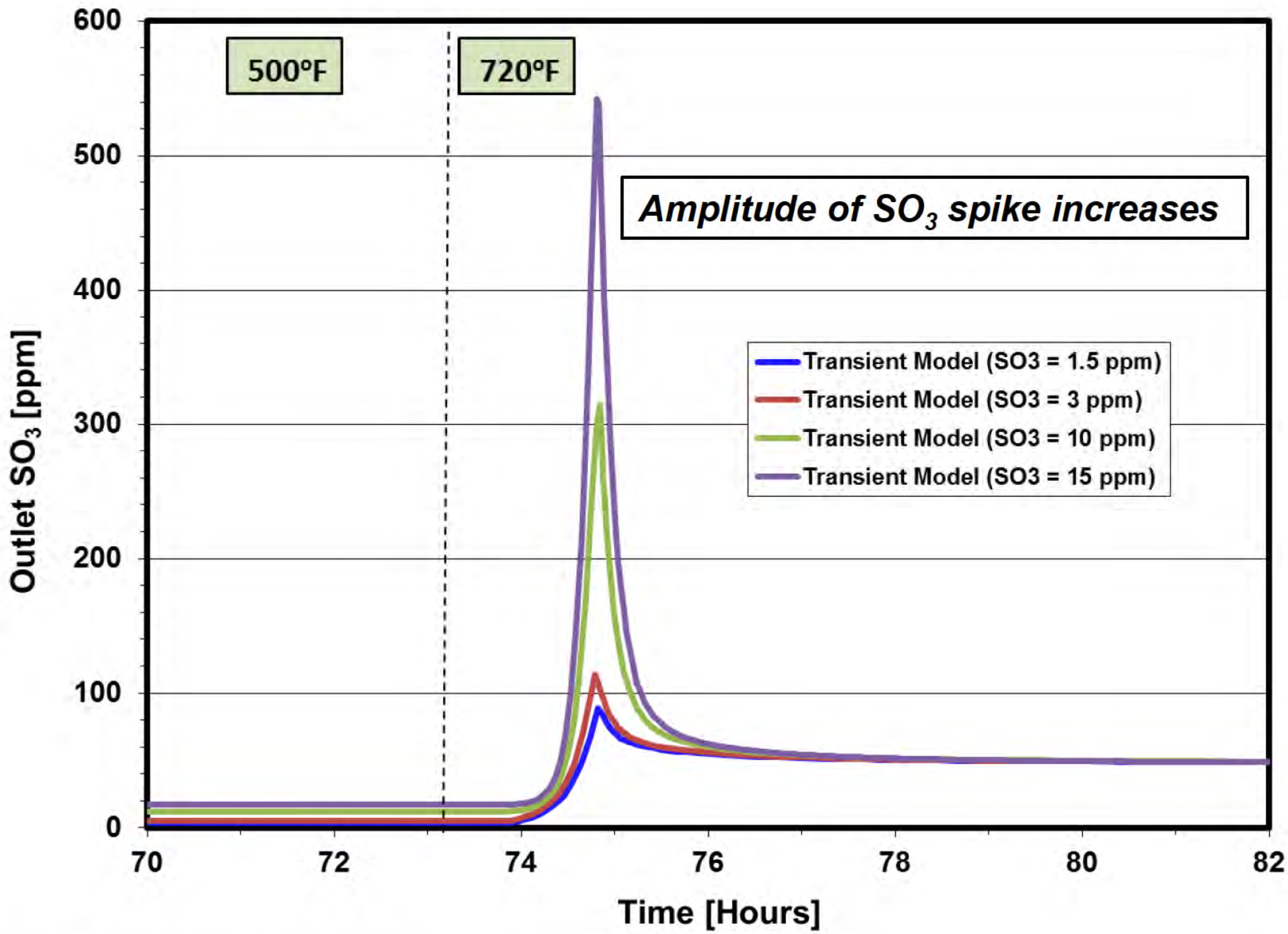
Model Fit: Outlet SO_3



What if Actual Inlet SO_3 is Higher?

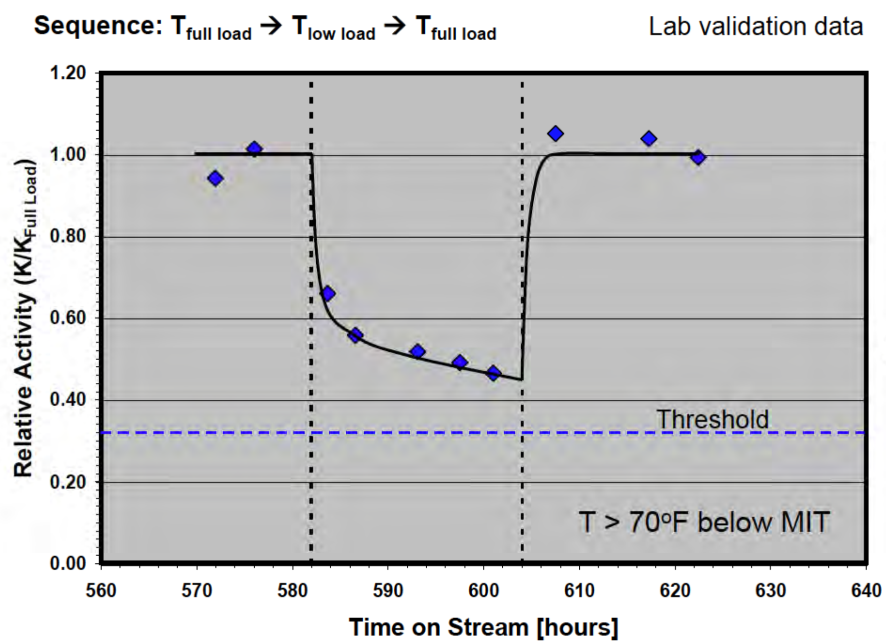


What if Actual Inlet SO_3 is Higher?



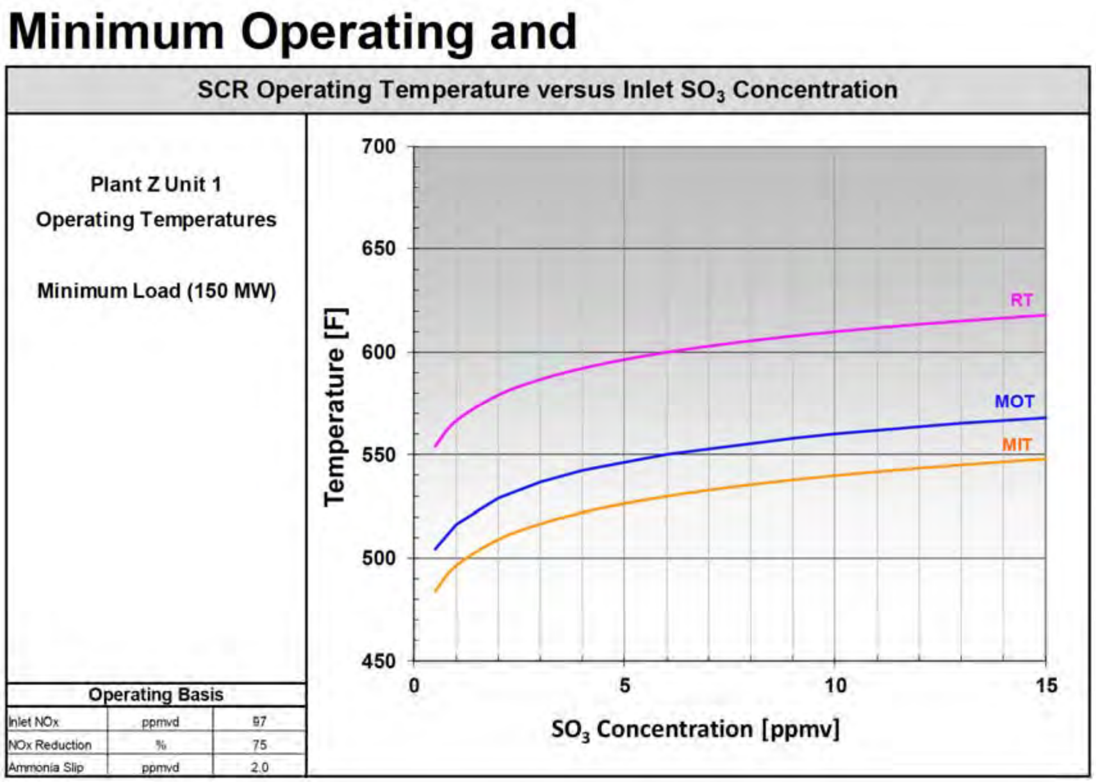
During Low Load Operation

- **DeNOx and NH_3 slip performance cannot be met if:**
  - $K/K_{full\ load}$ decreases below $AV/AV_{full\ load}$ (i.e., below threshold)
  - **Options to consider to mitigate:**
    - Increase NH_3 slip, or reduce DeNOx efficiency
    - Settle at a higher low load temperature (don't go as low!)
    - Reheat catalyst above recovery temperature



Scenario OK!

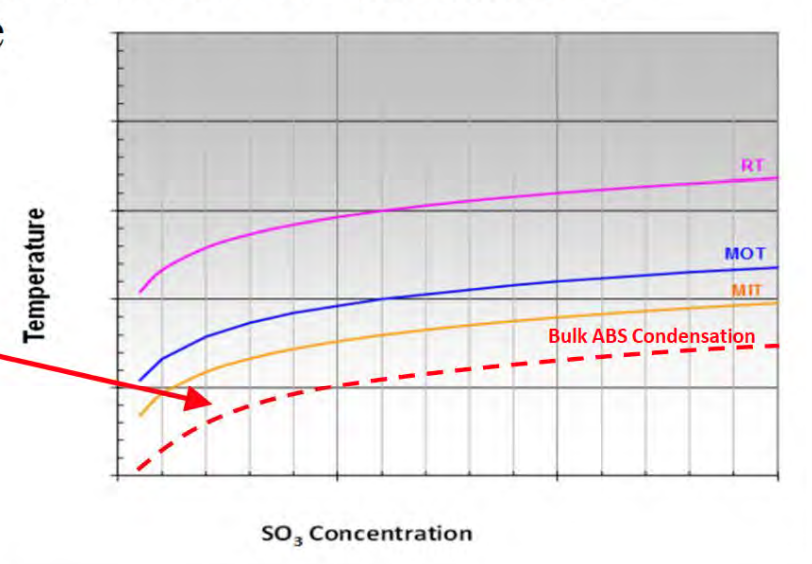
Some Thoughts From Ceram



MIT, MOT, and RT

- ABS Deposition in Pore Structure can be Reversed Given Operation above a Certain Temperature (MIT)
  - MIT is Less than MOT but Above Bulk ABS Condensation Temp in the Flue Gas
  - As ABS Builds up in the Pore Structure, some Activity is Lost
- SCR can Operate Between MIT/MOT for a Limited Amount of Time Before Full Recovery of Activity Becomes Problematic
- Recovery Requires Operation above MOT to Facilitate ABS Decomposition (RT) and Time

Temperature of ABS Condensation in Cell Openings, Duct, Etc.



Defining Operation with MIT/MOT/RT

- Key considerations
  - Is the Reduced Activity Between MIT/MOT Acceptable?
  - What is the Ammonia Distribution?
  - What is the Actual SO_3?
    - At low load?
  - What are Risks of Process Upsets?
    - Spikes in Ammonia, SO_3
    - Unit Trips
  - What Control Philosophy Changes are Needed?
  - MOT is Function of Physics, and is Catalyst Independent
- Because of Risks, Good Testing (and reasonable) Conservatism at Implementation are Recommended!

CERAM

Summary of Catalyst Vendor Thoughts

- Minimum Operating Temperatures vary from specification based on many factors including:
  - Inlet SO3
  - Ammonia Distribution
  - Inlet Temperature
- Operating Below MOT is practical with consideration for Recovery Temperature / Duration
- MOT can be lowered by:
  - Allowing Higher NH3 Slip
  - Reducing NOx reduction target
  - Changing Inlet SO3 via Hydrate Injection

So How do We Get There?

A Masters Course in DSI

The Current State of the Industry

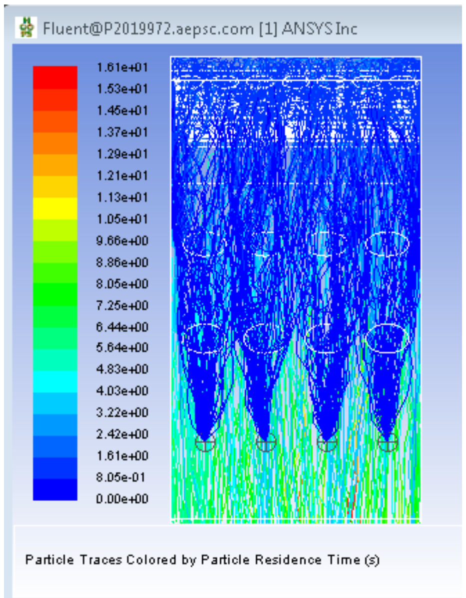
The Right Sorbent for the Application

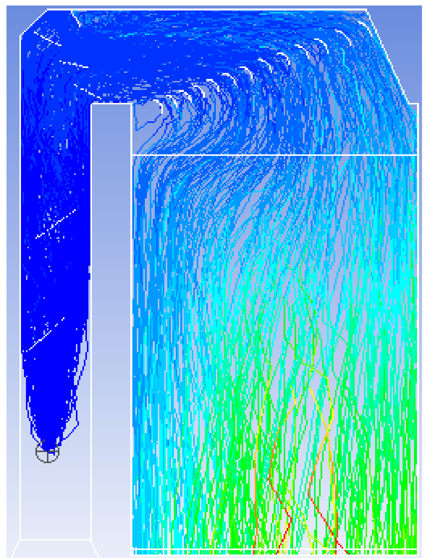
Injected at the right location based on CFD Modeling

Controlled by real-time Monitoring and Feedback

With controlled distribution, dispersion and mixing

CFD Modeling of Flue Gas Patterns

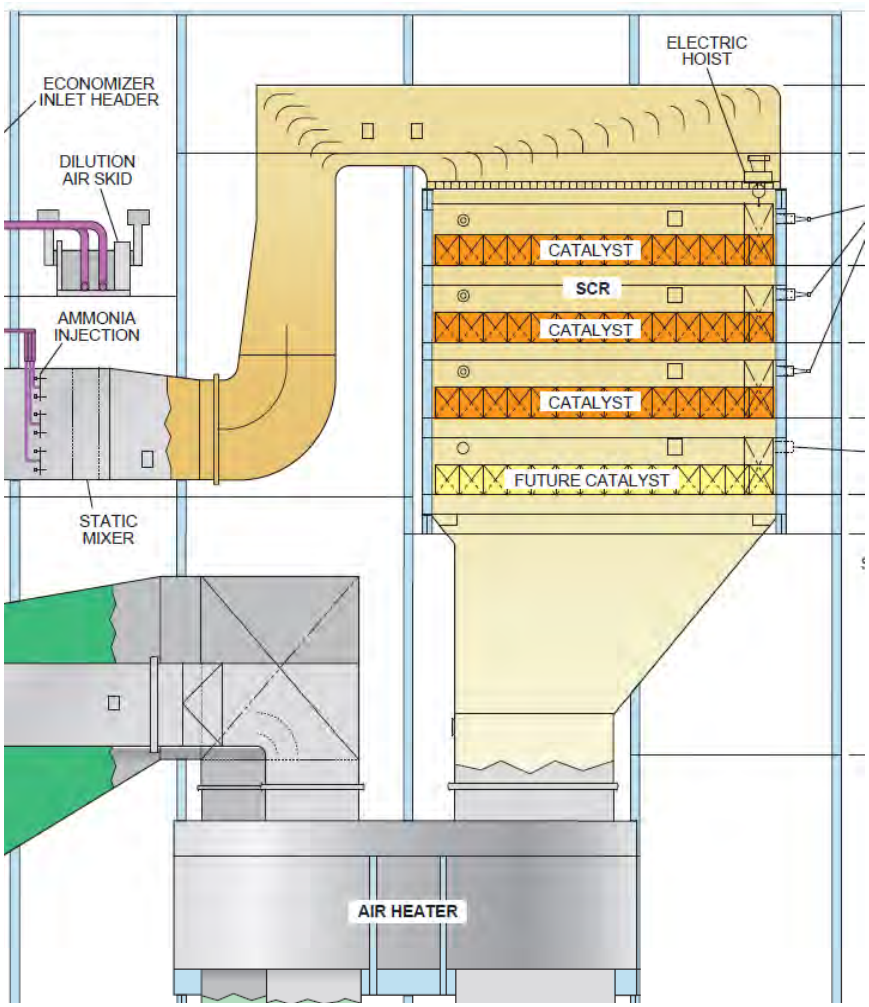




Due to the *very short physical distance* from the SCR Outlet to the Air Heater Inlet, *pre-SCR Injection*, and an understanding of normal and plugged SCR gas flows is Important

- CFD Modeling of Gas Flow Patterns is critical to understanding the exact injection location
- This is especially true as conditions in the SCR change with pluggage and the flue gas lanes move
- A CFD Model covering the Economizer Outlet to the ESP Inlet will be generated

Pre-SCR Injection is non-trivial

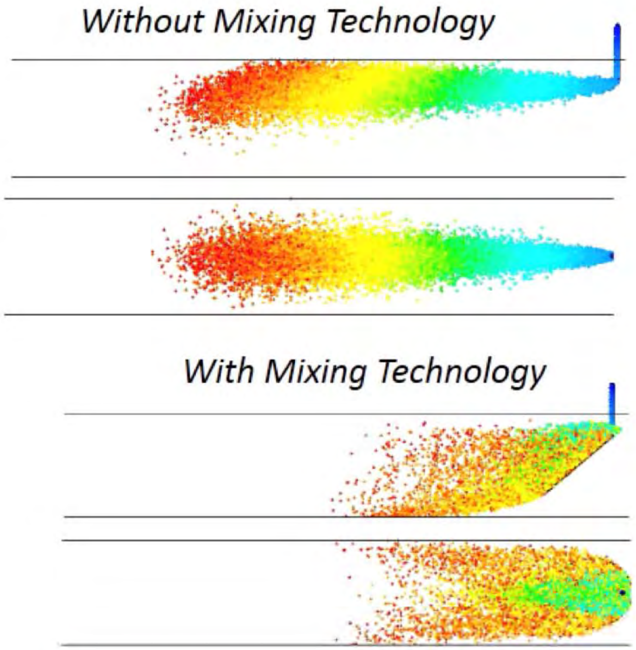


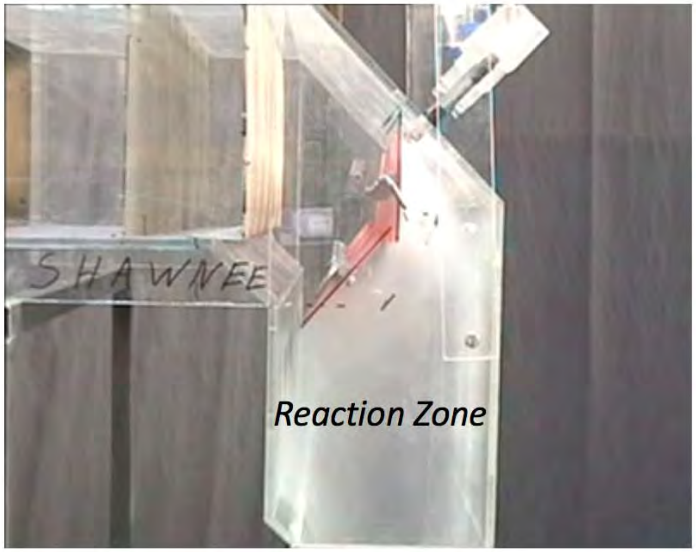
High Dispersion Mixing

Mixing Technology - DSI

Mixing and distribution at the injection point

- Full mixing in short section of ductwork
- Improve removal and/or reduce sorbent consumption





Babcock Power ENVIRONMENTAL

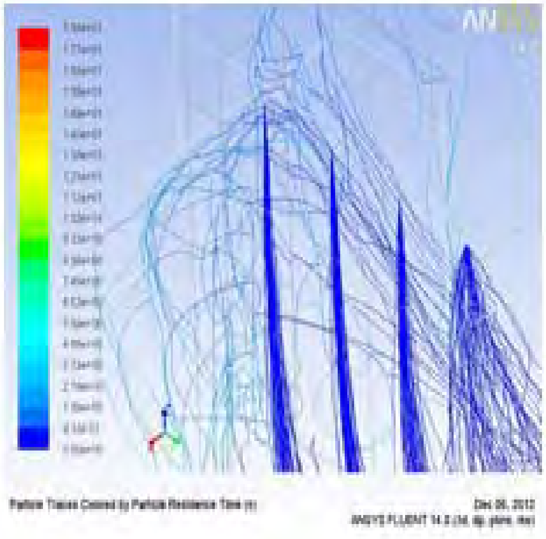
Delta Wings

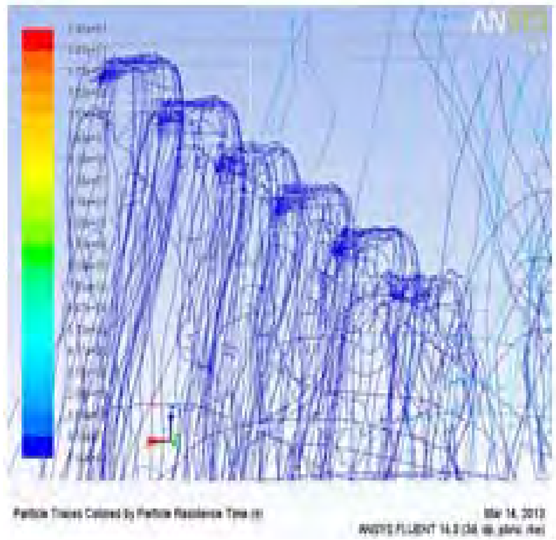
Injection Coupled with Mixers

- Reduction in number of valves
- Larger diameter injection ports
- Reduced startup time
- Simpler operation
- Reduced maintenance

Babcock Power ENVIRONMENTAL

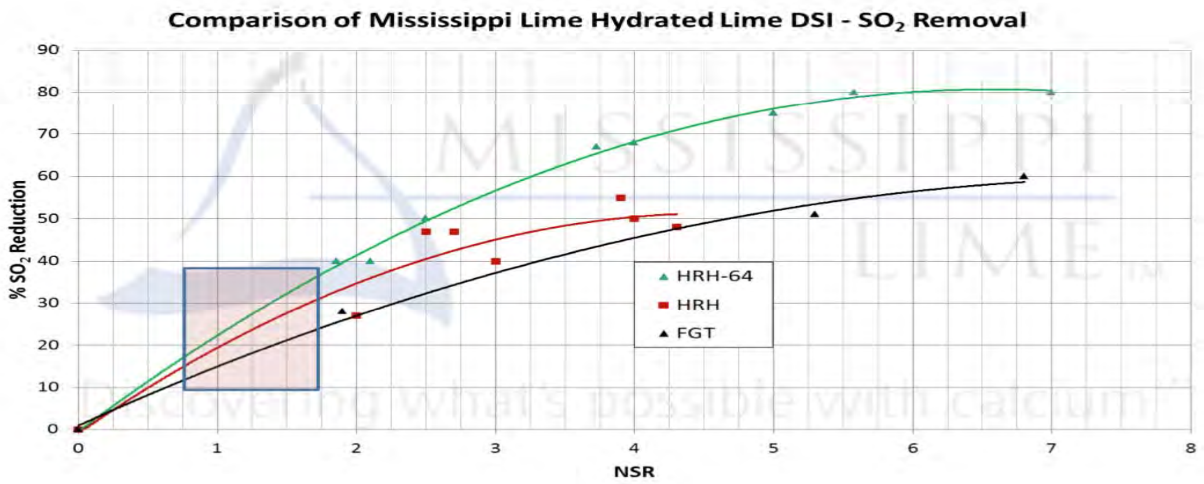
Advanced Dispersion Injectors





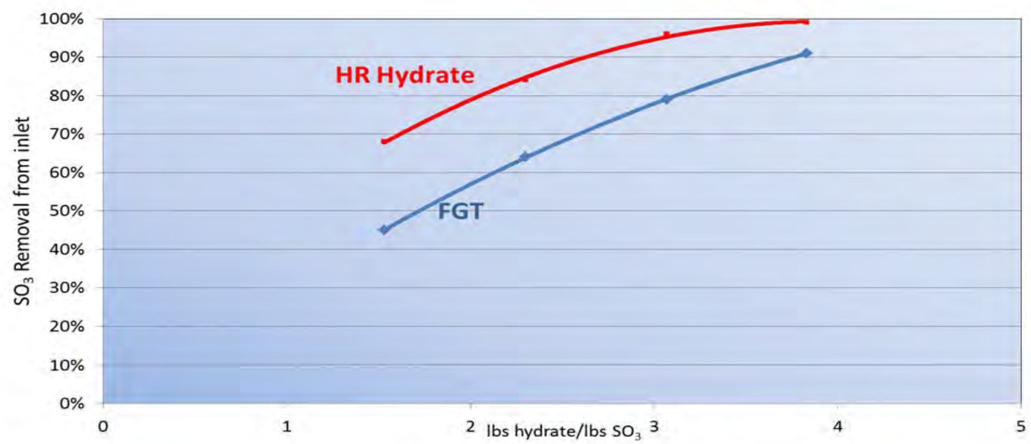
The Key to Advanced Dispersion Injectors is to create localized turbulence to break injection streams into highly dispersed "clouds". Better Distribution yields better mixing and chemical interaction

Hydrates Targeted for Performance



HRH-64 is designed and manufactured for optimum SO2 and HCl Capture

HRH is designed and manufactured for optimum SO3 in Flight Capture



How to Control the Process?

And

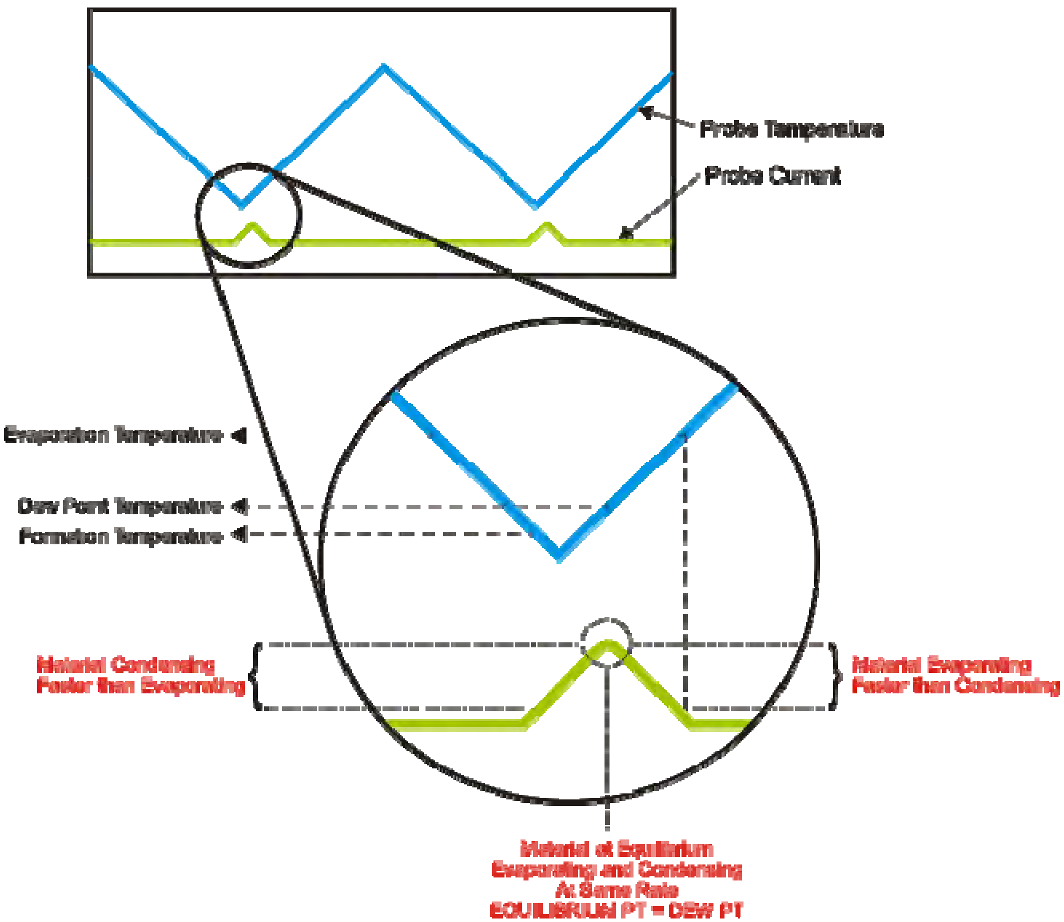
How Do you Know Your Actual MOT

IN-DUCT VAPOROUS COMPOUNDS

- The concentrations of any vaporous compound within the plant ducts or equipment is the net value of two components:
  - Steady state real-time formation of the vaporous compound from combustion or other plant processes and,
  - release or storage of the compound vapors from surface areas due to increasing or decreasing temperature transients, respectively.
- Understanding this one can utilize a measurement of such to establish the true Minimum Operating Temperature (MOT) of an SCR system
  - Allow greater flexibility in unit operation by allowing lower minimum loads while maintaining the SCR in service.
  - Lower minimum loads can realize savings both at the plant and utility level.

MONITORING IN-DUCT VAPOROUS COMPOUNDS

- Breen Condensable Measurement



Condensable States

PROBE CONDENSABLE SPECIES GUIDELINES							
IF		AND		AND		THEN	
FmT		EvT		AVG(FmT,EvT)			State
Min	Max	Min	Max	Min	Max		
=13	=13	=13	=13				No Cond
	< 200		< 200				H2O/HCL
	< 200	>= 200	<= 310				H2O + SO3
>= 200	< 300		<= 310				SO3
	< 300	>= 310	<= 550				SO3 + AbS
> 300		>= 310	<= 550		375		Low AbS
> 300		>= 310	<= 550	375	425		Med AbS
> 300		>= 310	<= 550	425			High AbS
	< 300	> 550					SO3 + NabS/AS/Other
> 300		> 550					NabS/AS/Other

1: Evaporation Temperature is used to determine the dominant species of the condensable,

2: Formation Temperature is used to determine the relative concentration of the dominant species,

3: “Sulfuric Acid Dewpoint” is used to calculate “SO_3” ppm

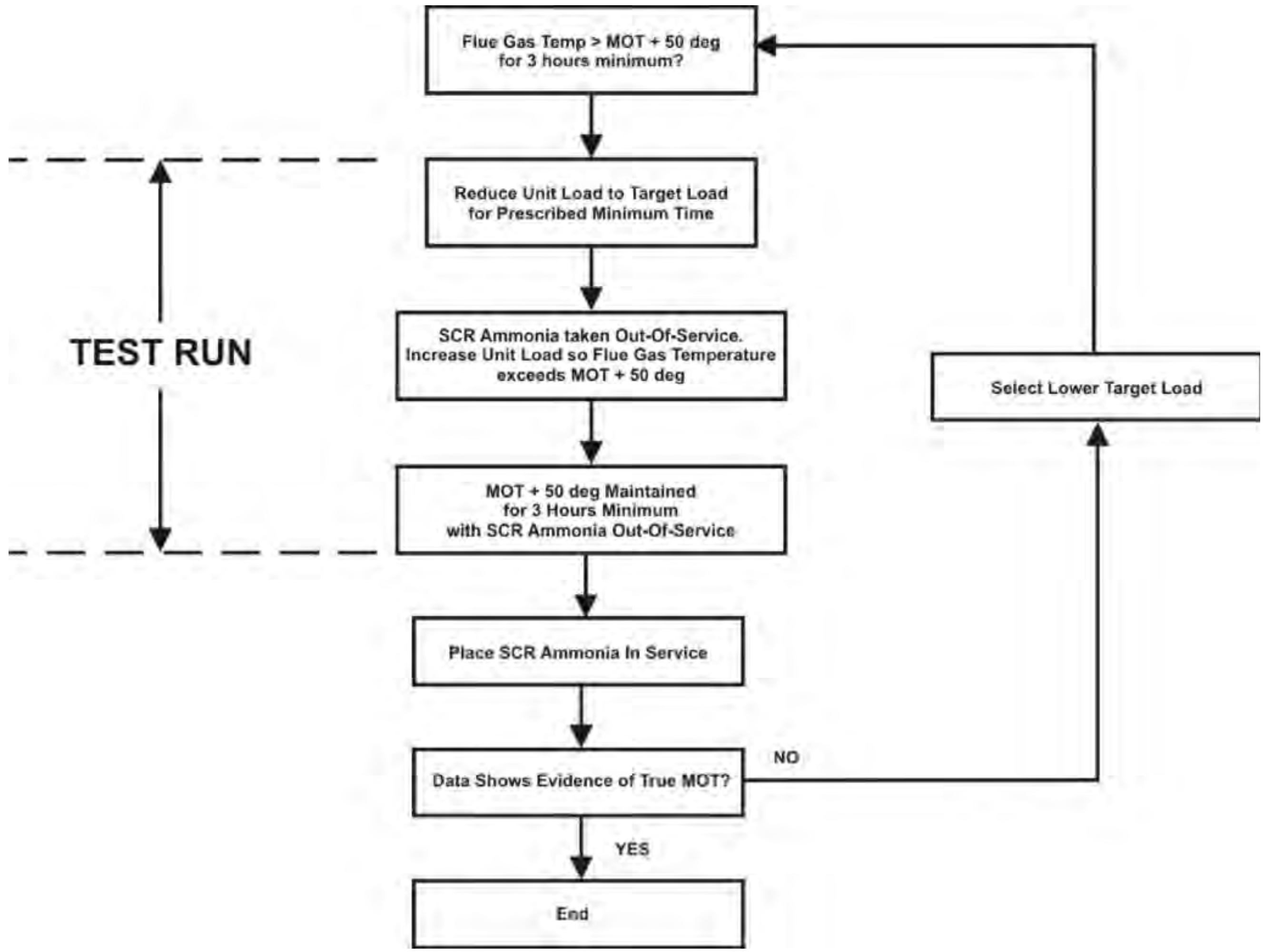
Protocol for Establishing True MOT

- Measure the release of sulfur condensable compounds after a period of reduced Operating temperature

- Installation of two probe systems
  - SCR Inlet
  - SCR Outlet

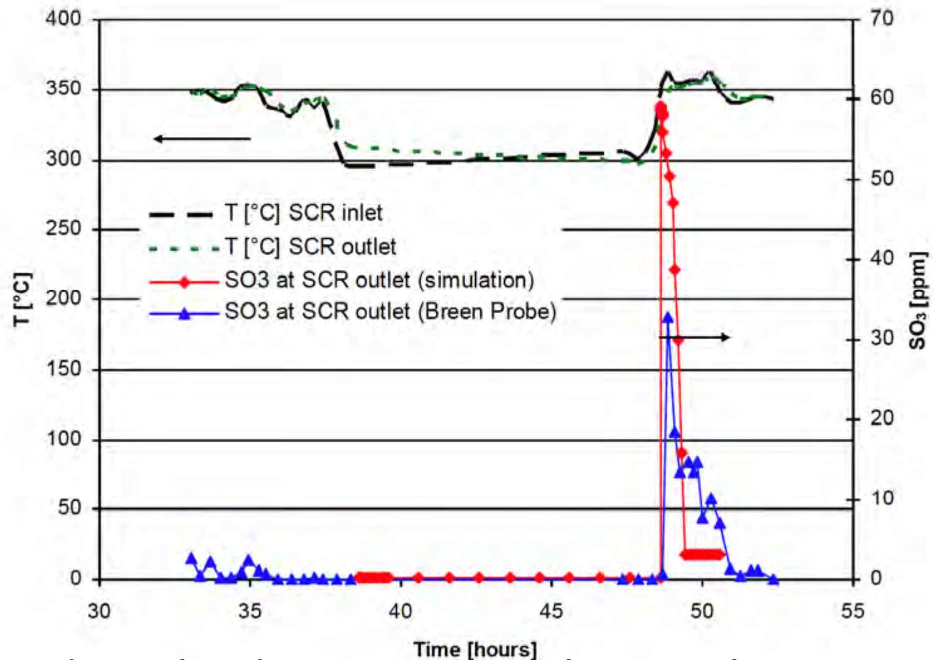
- Maintain
  - Unit load during low temperature operation
  - Duration of operation of low load operation
  - Mill Configuration during low load operation
  - Fuel sulfur content during low load operation
  - Unit ramp rate from low load to high load operation

Protocol for establishing True MOT



Operating Below MOT

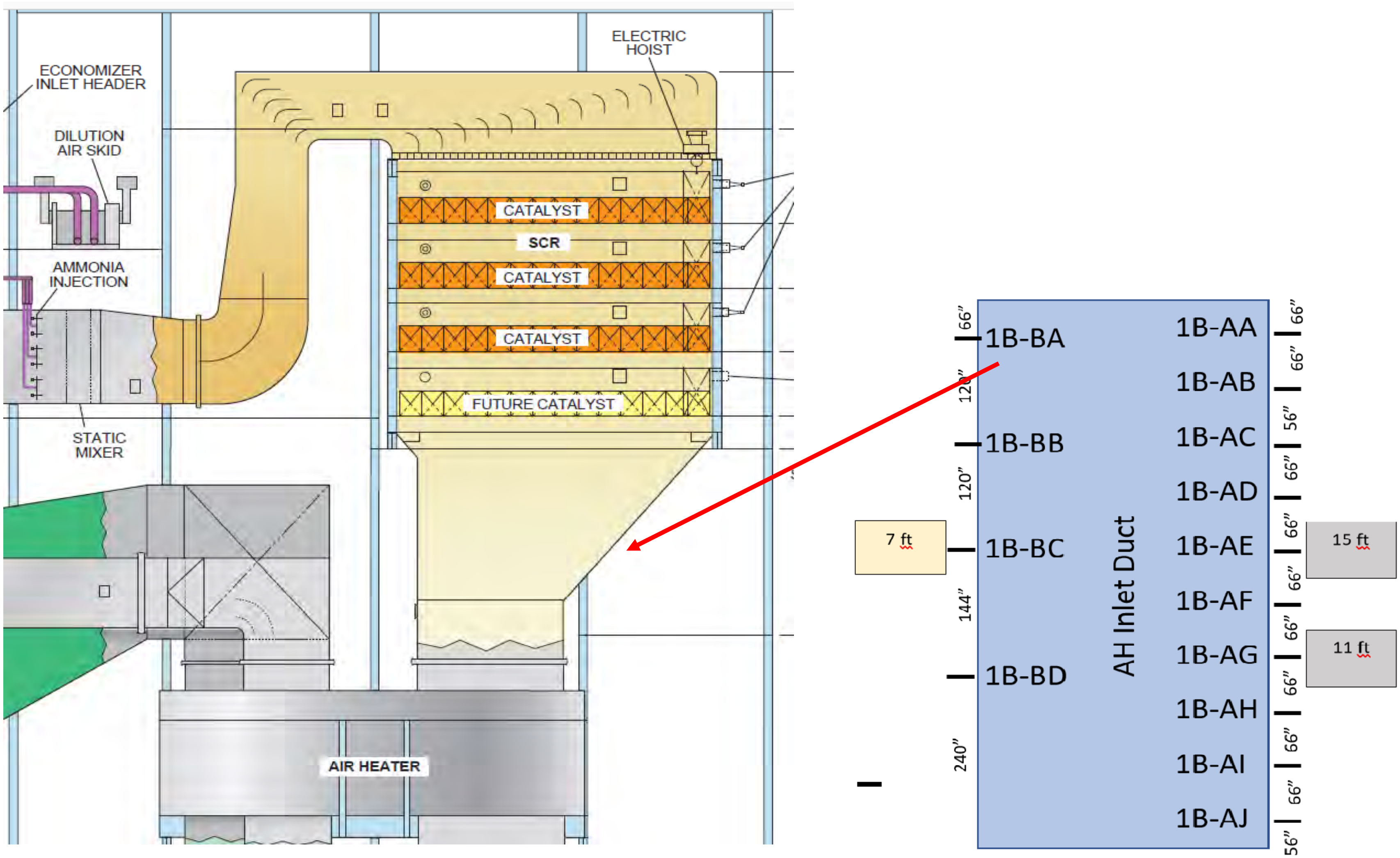
- In this case study the plant uses a MOT setting of 320C for normal operation of the SCR.
  – This graph shows the load duration at temperatures below MOT and shows the theoretical (red trace) and Breen probe (blue trace) acid release on load ramp.



- If the SCR had been operated at a load consistent with SCR inlet temperatures above 320C, the blue trace would have been much smaller in magnitude

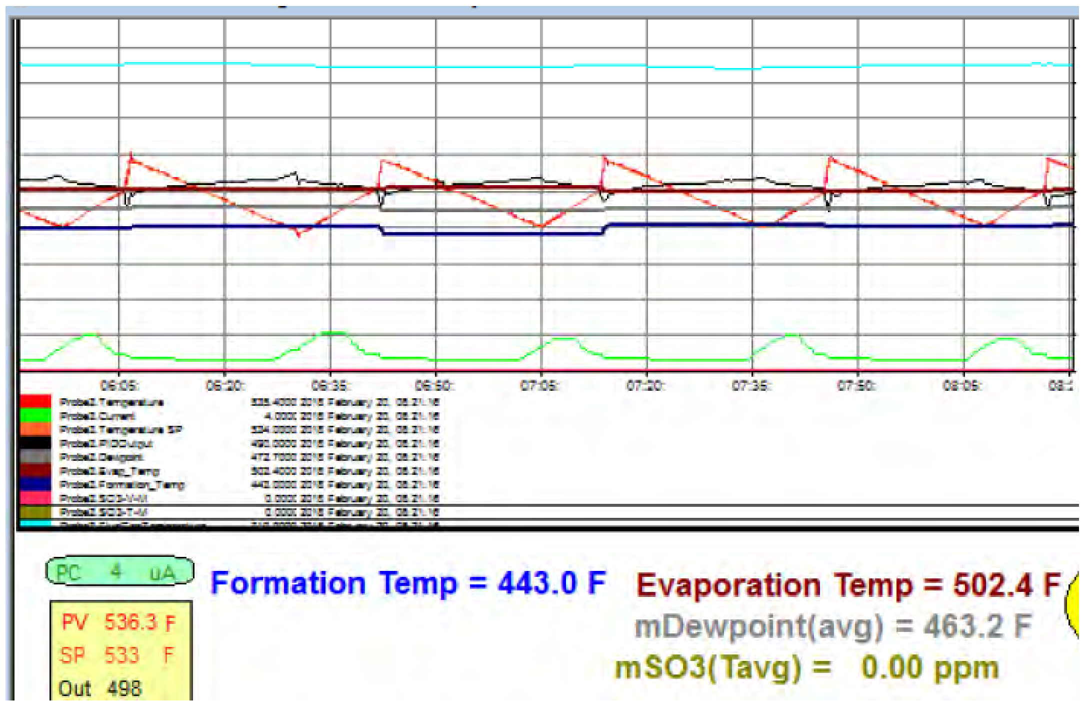
HALDOR TOPSOE

Probe Location



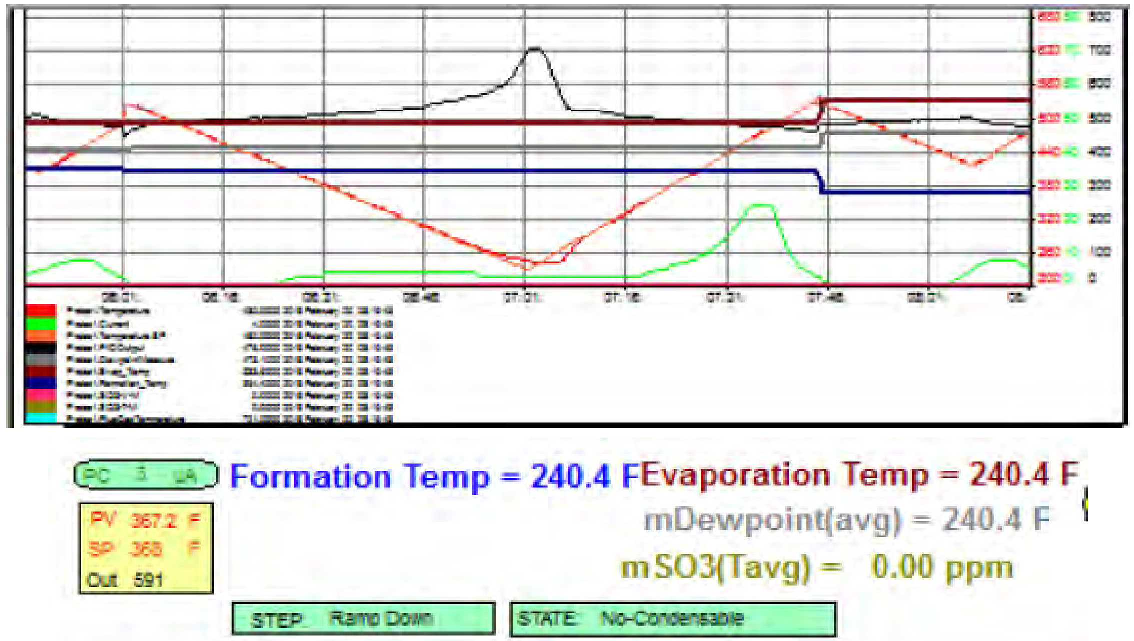
Probe Location

- 7 ft depth

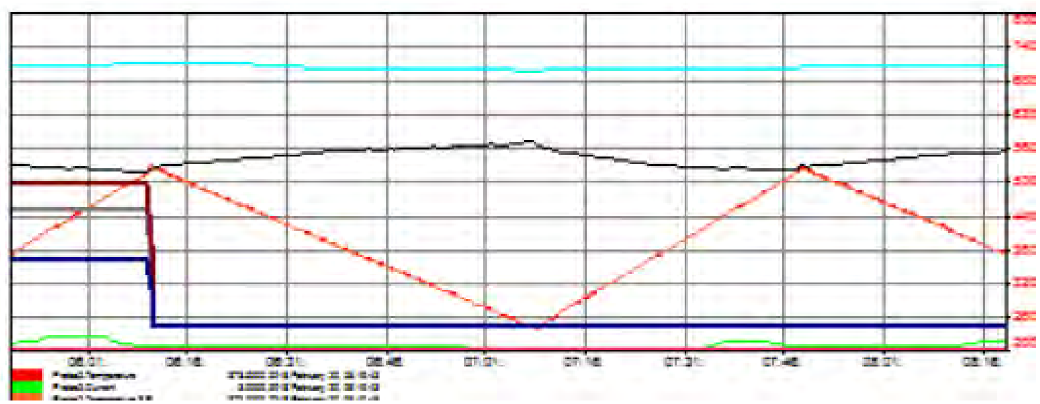


Probe Location

- 10 Ft Depth



- 15 ft depth



Air Heater Fouling

- **Feedback from the Breen probe**
  - State of the condensable material in the flue gas during baseline plant operating conditions.
  - Optimally the formation and evaporation temperature of the detected condensable species should reside in the orange band associated with sulfuric acid.

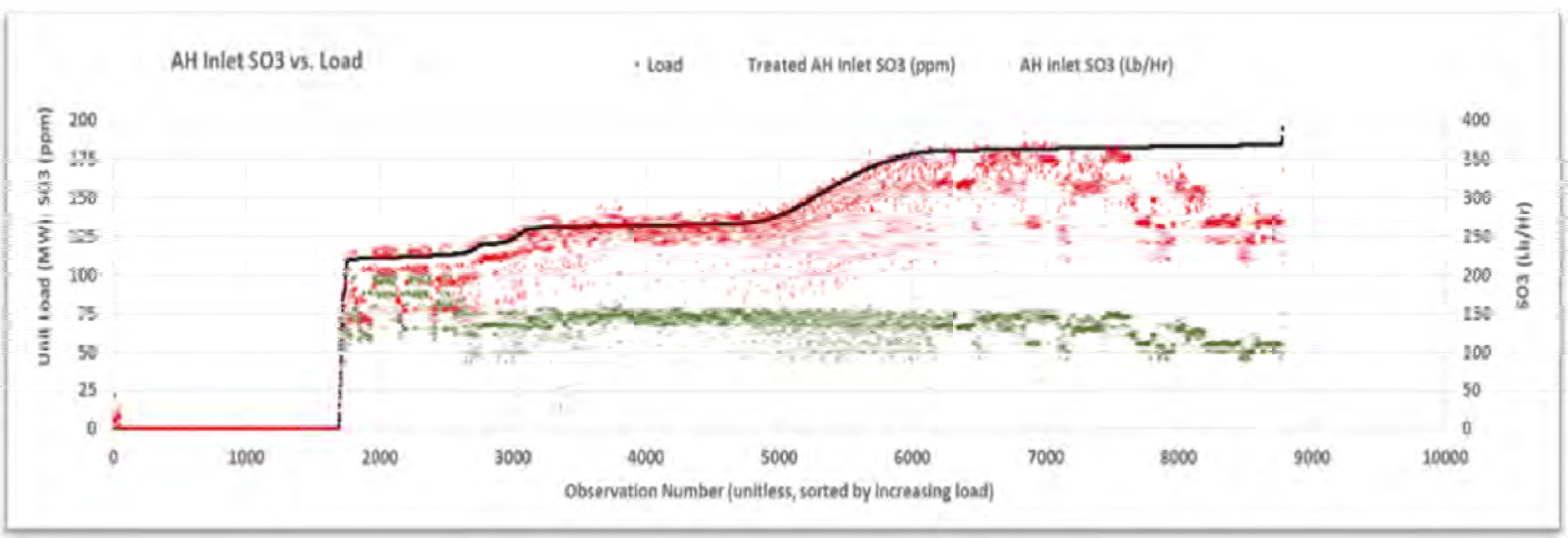
Original Feed Rates

- Low load the flue gas exhibits no detectable condensable material
- High load the material is firmly in the Ammonium Bisulfate range (nominally 330F to approximately 500F)
- The plant's hydrated lime process, targeted at 500 Lb/Hr., seems to have been over-treating at low loads and undertreating at high loads.
- In an effort to minimize sorbent usage at low loads and to reduce the severity of deposits at high loads, the plant moved to a practice of 750 Lb/Hr. at high load and 300 Lb/Hr. at low load.

Sorbent Use Prediction

- Presented below is a theoretical plot of the SO3 concentration at the AH Inlet as a function of increasing load. The calculations assume that the SCR ammonia injection if OFF. As can be seen, the projected values move between 50 and 75 ppm (250 – 350 Lb/Hr.) of SO3.

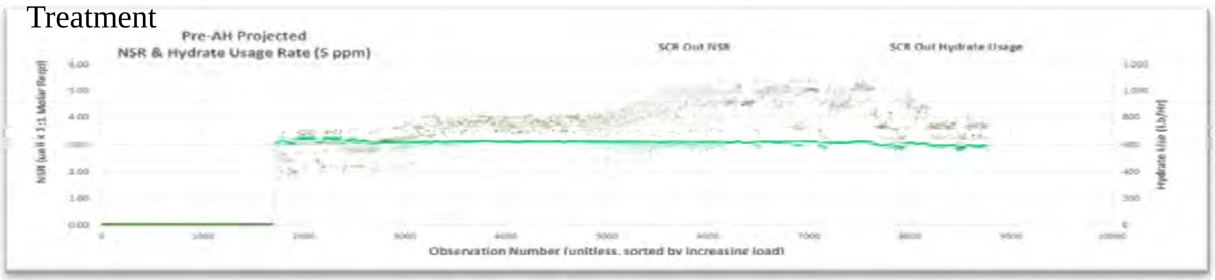
Figure 2 - Projected SO_3 vs. Load

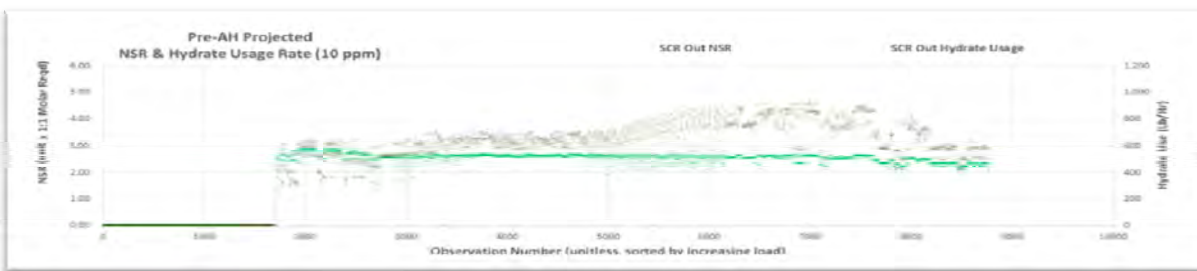


Sorbent Use Prediction

- Plotted below that are two graphs (Figure 3) showing the theoretical hydrated lime usage to reduce SO3 concentration to levels of 10 ppm and 5 ppm respectively

Figure 3 - Projected Hydrate Metrics for Target Treatment

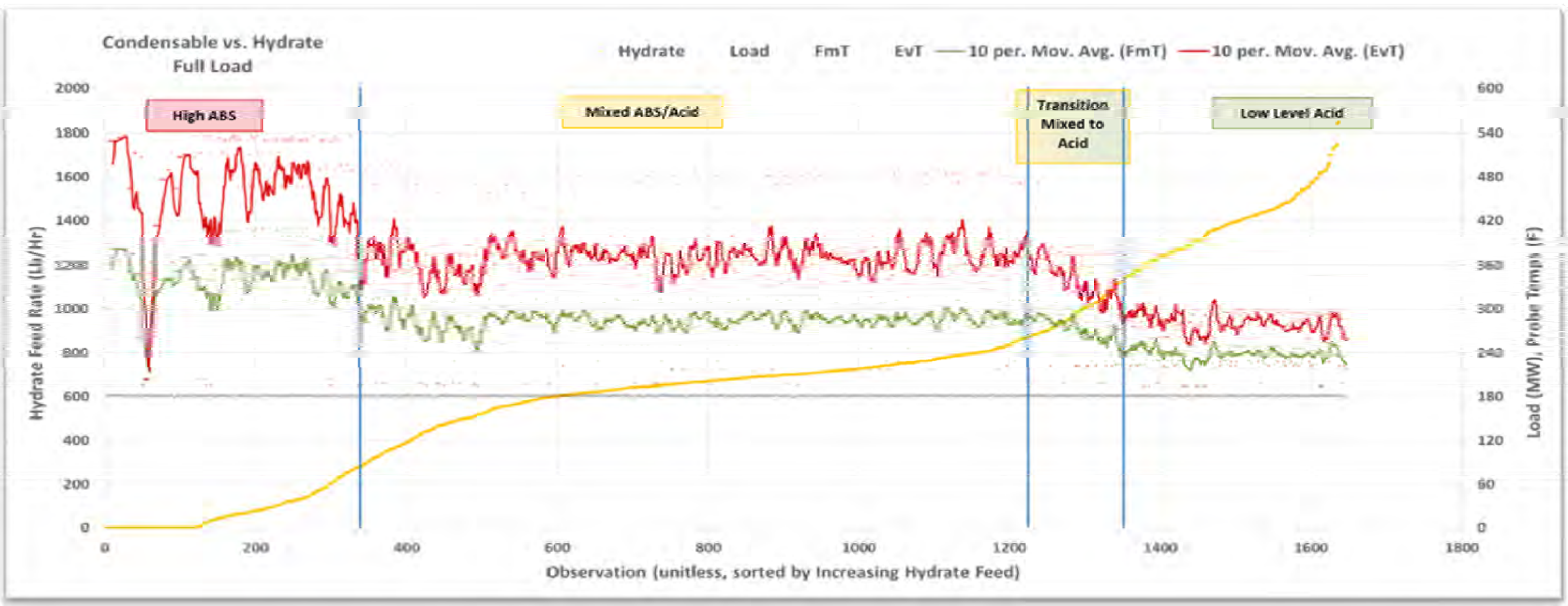




- In summary, the calculations predict a nominal level of 1,100 Lb/Hr. to achieve 5 ppm and 900 Lb/Hr. to achieve 10 ppm.

Condensables Species Transition

- Full Load
  - Varying Hydrate Feed Rates
    - High Level ABS below 300 Lb/Hr.
    - Mixed Acid and ABS between 300 Lb/Hr. and 900 Lb/Hr.
    - Low Level Acid above 1,100 Lb/Hr



Measurement Summary

- **By Using the measurement for feedback**

- **Increased hydrated lime to reduce the AH Inlet SO3**
  - Increasing the full load hydrate injection rate by 350 Lb/Hr. to a level of 1,100 Lb/Hr.,
  - Reducing the low load hydrate injection rate by 200 Lb/Hr. to a level of 100 Lb/Hr.
  - Eliminated the use of steam coils
- **Results in an immediate cash flow improvement 2-3 times the cost of the increased sorbent usage.**
- **Co-benefits**
  - Reduced steam coil maintenance
  - Reduced AH Outlet gas temperature
  - Reduced back end corrosion

Presentation Summary

DSI Is a Powerful Tool

- Significant Operational Benefits can be derived by Advanced Application of pre-SCR Hydrate Injection
  - Heat Rate at AH Outlet
  - Eliminate Auxiliary Inlet Air Heat
  - Reduce ID Fan Loading
  - Reduce Back End Duct Corrosion
- Unit Turndown can be dramatically improved
  - MOT Impact on Min Load can be removed
- Total Acid Gas Loading Can be Projected and NSRs reduced through Intelligent Distribution and Feedback.

Thank You – Questions?

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