REINHOLD ENVIRONMENTAL ®

2022 Reinhold/PCUG Round Table Presentation

Hosted by Duke Energy in the Charlotte Sheraton/Le Meridien Hotel, Charlotte, NC on June 27-28, 2022

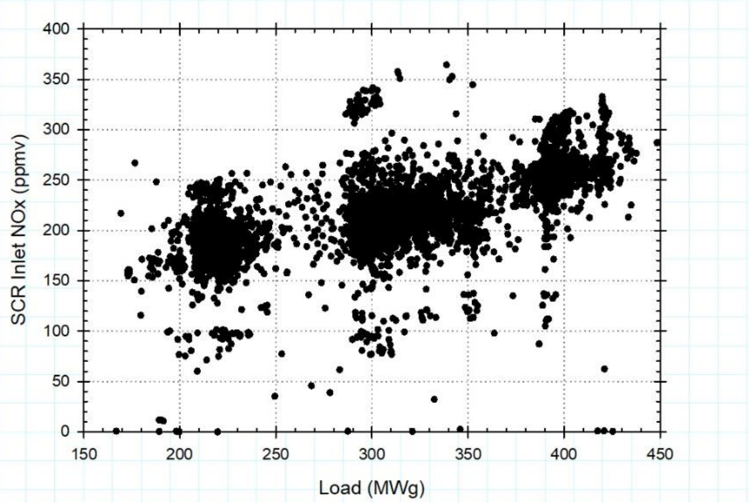
Unit Specific Assessment of Coal-Fired Unit Minimum Load

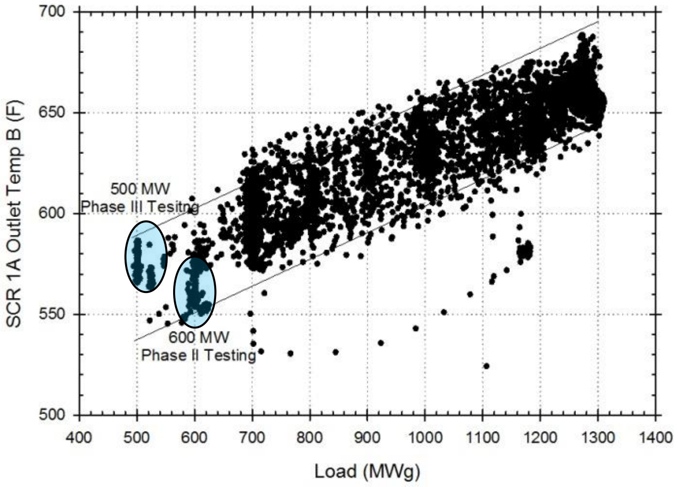
In Context of SCR ABS Formation and Duct H_2SO_4 Concentration

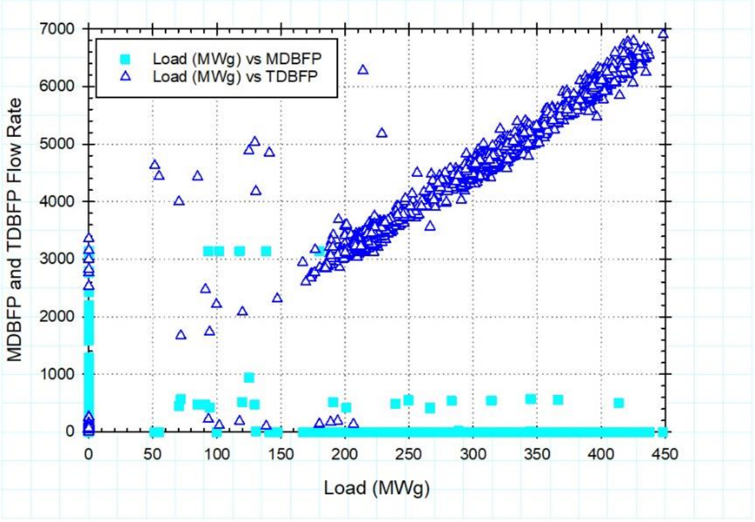
Reinhold Round Table
June 27, 2022
Charlotte, NC

Agenda

- Background
- Scope of unit assessment
- Operating factors influencing minimum load
- Plant management factors
- SO_3 measurements
- Case study examples

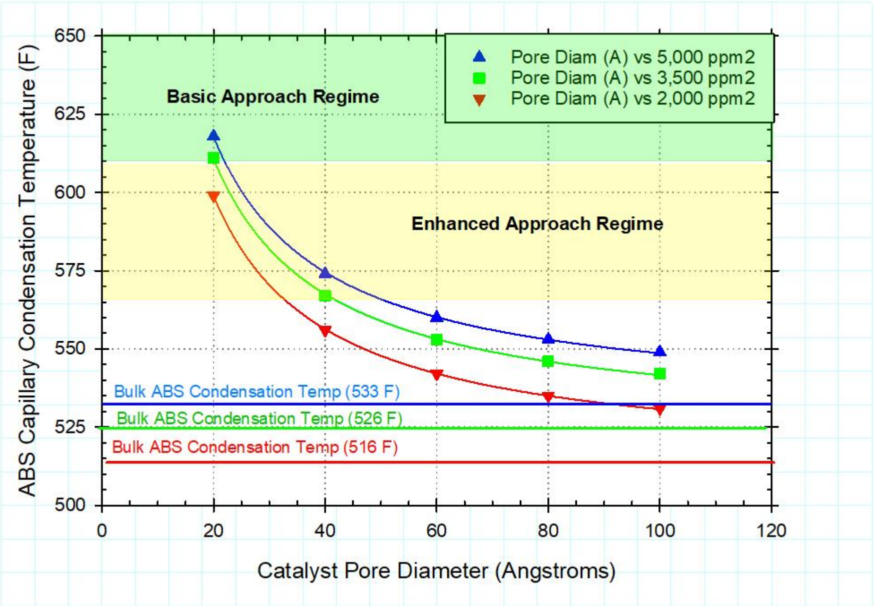


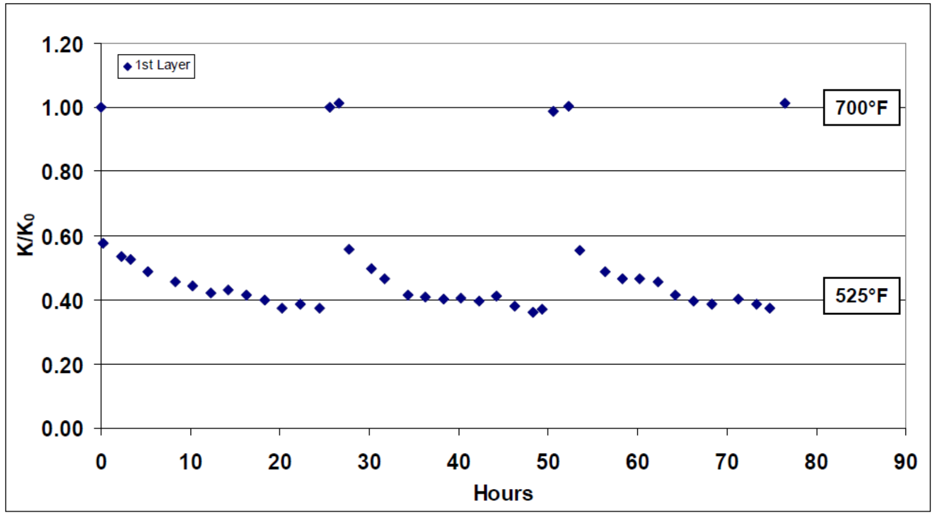




Initial Vendor SCR Minimum Operating Temperature Guidance

- Initial belief that ammonium bisulfate formation (ABS) was irreversible
  - Prompted initial vendor guidance to operate SCR at temperatures above 600°F
- Modified SCR MOT approach adopted in 2005 – 2010 timeframe
  - Scale back SCR NOx reduction at reduced load
  - Operate temporarily in ABS capillary condensation regime
- EPRI demonstrated that ABS formation was reversible
- EPRI lab tests also demonstrated that Matsuda ABS correlation biased high
  - EPRI developed independent correlation based on two sets of lab data





Minimum Load Assessment Requires a Holistic Approach

Controllable Parameter	CO	NOx	SO_2	SO_3	Corrosion	FEGT	LOI / Particulate	Mercury	Multi-Media	Heat Rate
Improve Mill PSD	+				+		+			+
Improve Fuel/Air Balance	+	+		+		+	+			+
Increased Staging	−	+			−	−	−			−
Increased Excess Air	+	−		−	+	+	+			−
Mercury Sorbents (Halogens/PAC)							−	+	−	
Increase in SCR Reagent		+		+				−	−	
Increase in Alkali Sorbent			+	+	+		−	+	−	

+ Potential positive impact

− Potential negative impact

References

Combustion and Fuel Quality

- *Combustion and Fuel Quality Impacts on Post Combustion Environmental Controls – 2019 Update*. EPRI. Palo Alto, CA: 2019. 3002015869
- *Fuel Quality and Combustion Impacts on Emissions*. EPRI. Palo Alto, CA, 2018 3002013044
- *Status Report on Approach for Sustainable Dynamic Combustion Optimization*. EPRI. Palo Alto, CA. 2017. 3002010259

Selective Catalytic Reduction

- *Selective Catalytic Reduction System Guidelines for Flexible Operation – Assessment of Minimum Operating Temperature and Potential Impacts of Ammonium Bisulfate*. EPRI. Palo Alto, CA. 2019. 3002015879
- *Laboratory Assessment of Cyclic Ammonium Bisulfate Deposition Impacts on Catalyst – Long-Term ABS Exposure on Plate SCR Catalyst*. EPRI. Palo Alto, CA. 2019. 3002015878
- *Assessment of SCR Catalyst Impacts with Hydrated Lime Injection – In-Situ Mini-SCR Catalyst Field Evaluation*. EPRI. Palo Alto, CA, 2019. 3002013390
- Muzio, L., Bogseth, S., Himes, R, Chien, Y., Dunn-Rankin, D., "*Ammonium Bisulfate Formation and Reduced Load SCR Operation*", Fuel, 206, 180-189, (2017).
- *Update on SCR Operation During Reduced Load*, Reinhold Round Table Training Class 1, 2017, Cleveland, OH
- *Low Load SCR Operation,* Reinhold Round Table, Workshop 24, 2016, Orlando, FL

Dry Sorbent Injection

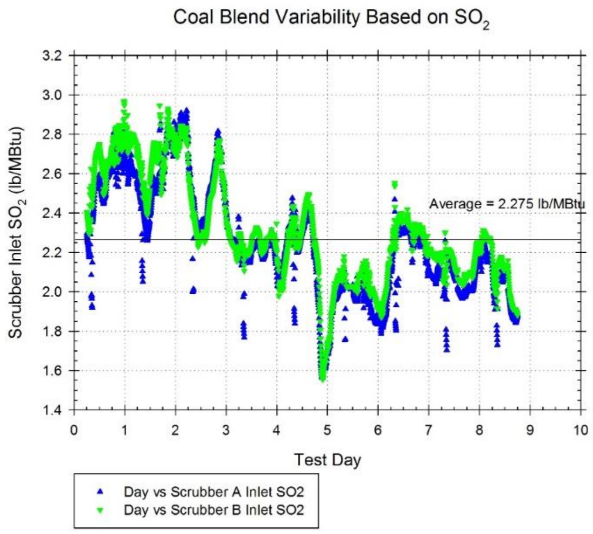
- *Computational Fluid Dynamic Model Characterization of Dry Sorbent Injection Mixing*. EPRI. Palo Alto, CA. 2019. 3002015866
- *Implementation of Mercury and Air Toxics Standard Control Technologies and Best Practices*. EPRI. Palo Alto, CA. 2018. 3002008327

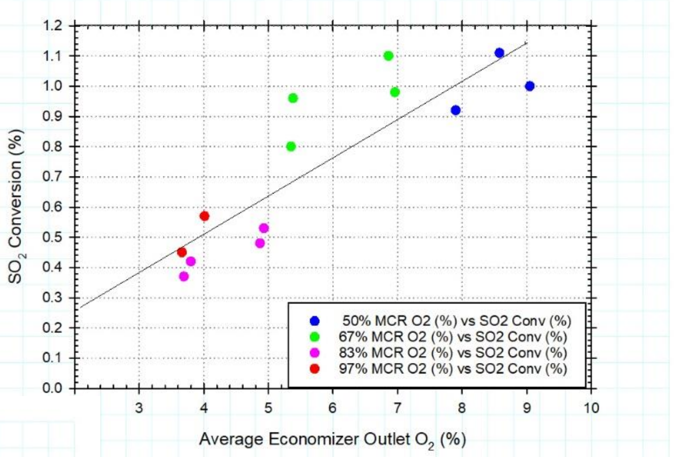
Unit Data Typically Reviewed in Analysis

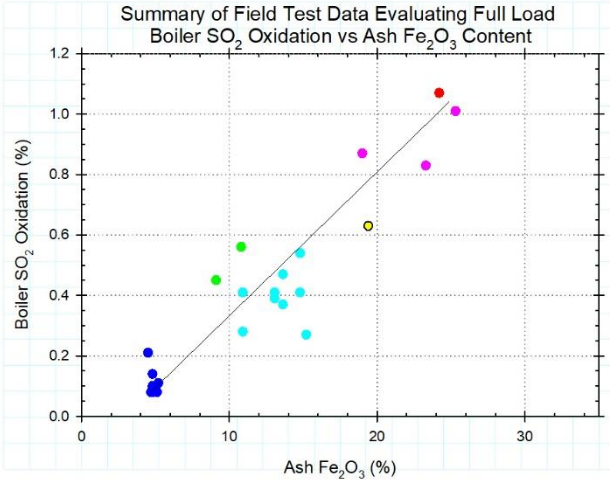
- Hourly average DCS data over one year time period
- Operating data includes
  - Load (MWg)
  - Boiler feed pump flow rates
  - Furnace/WB pressure differential
  - Mill coal flow rates
  - Mill PA flow rates
  - Mill outlet temperature
  - Individual economizer O_2 probes
  - SCR NH_3 flow rate for each reactor
  - SCR inlet temperature for each reactor
  - SCR inlet NOx for each reactor
  - SCR outlet NOx for each reactor
  - SCR outlet temperature for each reactor
- Operating data (con't)
  - DSI flow rate by location
  - AH gas inlet temperatures
  - AH gas outlet temperatures
  - AH air inlet temperatures
  - AH air outlet temperatures
  - PAC flow rate (if applicable)
  - Flue gas temperature at baghouse inlet (if applicable)
  - Scrubber inlet SO_2
  - Stack NOx
  - Stack SO_2
  - Stack CO_2
  - Stack temperature
  - Stack flow rate
- Coal proximate/ultimate analyses
- Unit permit conditions

Factors Impacting SCR Minimum Operating Temperature

- ABS capillary formation temperature a function of SCR inlet [NH_3] and [SO_3]
- SCR inlet [SO_3] varies with:
  - Coal / coal blend sulfur content
  - Boiler SO_2 oxidation tends to be a function of boiler excess O_2 and ash Fe_2O_3 content
  - Fly ash accumulation in convective pass
- While operational control over SO_2 oxidation to SO_3 in the boiler may be limited, coal additives may be of benefit
- Some sites injecting $Ca(OH)_2$ upstream of the SCR

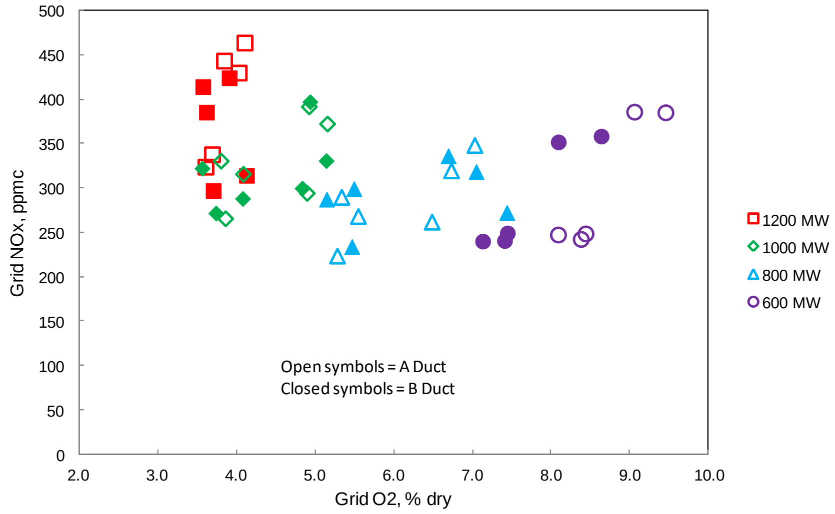


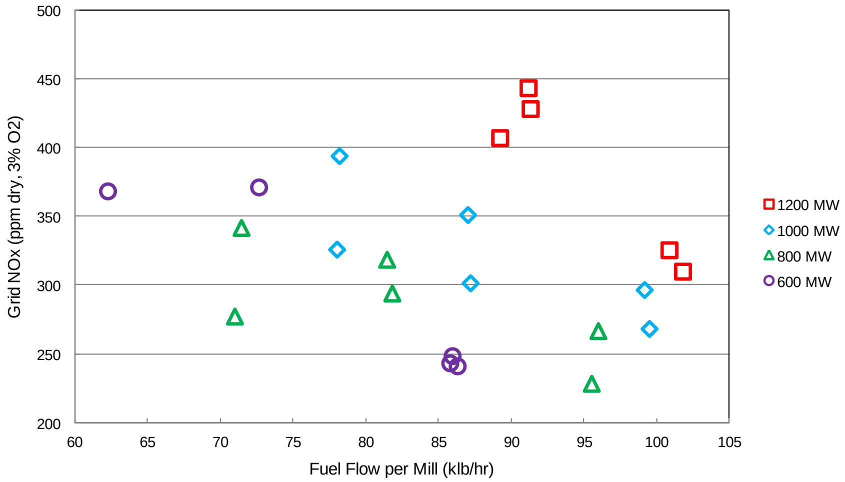




Factors Impacting SCR Minimum Operating Temperature

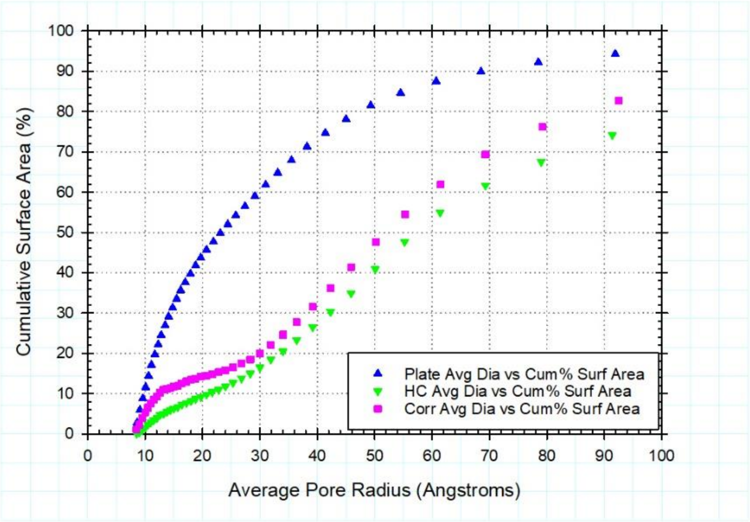
- SCR inlet [NH_3] varies with SCR inlet NOx to maintain SCR outlet NOx level
  - With deployment of SCR systems, trend of relaxing staged combustion levels to alleviate lower furnace corrosion and/or slagging
  - NOx can be impacted by mill particle size distribution and mill firing configuration
  - Primary air to coal ratio can also impact NOx at reduced loads
  - Boiler excess O_2 levels typically set to maintain ash LOI levels for resale and limit CO emissions

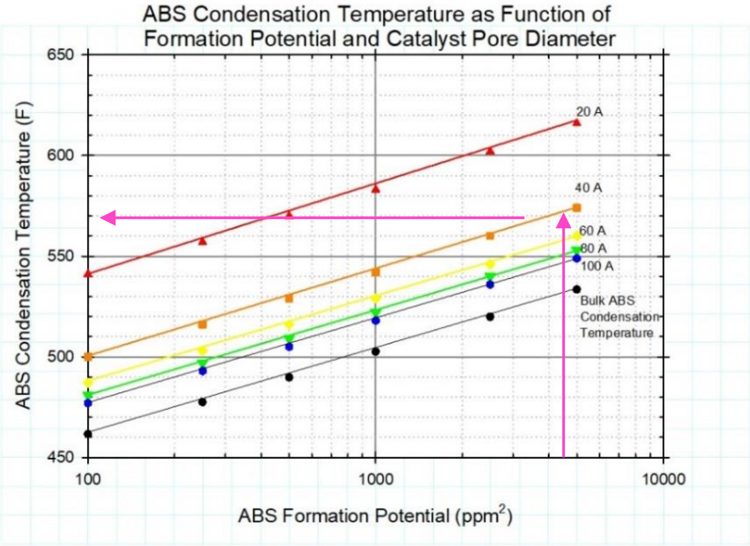




Potential Impact of SCR Inlet NOx and SO_3 on MOT

- ABS formation temperature model based on lab data enables calculation of changes in SCR MOT with reductions in $[NH_3]$ and $[SO_3]$
- Baseline case with as-found SCR inlet case
  - SCR Inlet NOx = 170 ppmw
    - SCR NOx reduction of 90%
    - SCR inlet NH_3 = ~ 150 ppmw at actual O_2
  - SCR Inlet SO_3 = 30 ppmw at actual O_2
  - ABS Potential = 4,500 ppm^2
  - SCR MOT = ~570°F




ABS Condensation Temperature as Function of Formation Potential and Catalyst Pore Diameter

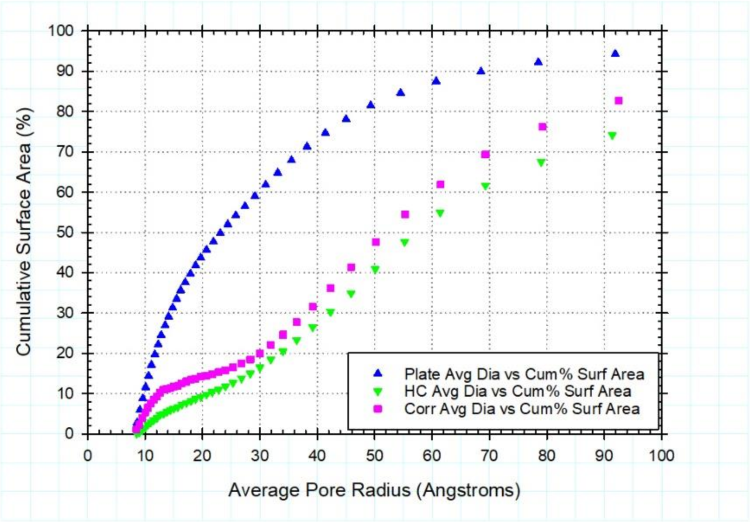
Potential Impact of Changes in SCR Inlet SO_3 on MOT

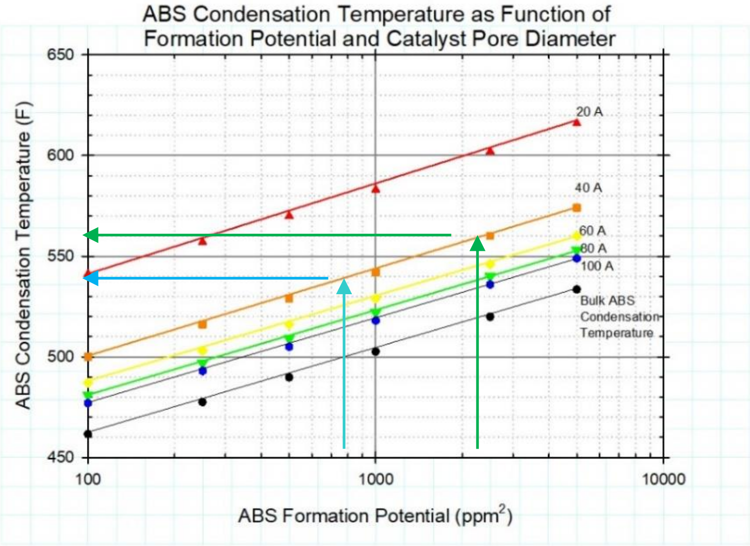
Scenario 1

- Coal additive to reduce SCR inlet SO_3 by 50%
  - SCR Inlet NOx = 170 ppmw
    - SCR NOx reduction of 90%
    - SCR inlet NH_3 = ~ 150 ppmw at actual O_2
  - SCR Inlet SO_3 = 15 ppmw at actual O_2
  - ABS Potential = 2,250 ppm^2
  - SCR MOT = ~560°F

Scenario 2

- $Ca(OH)_2$ injection upstream of SCR inlet to reduce SCR inlet SO_3 to 5 ppm
  - SCR Inlet NOx = 170 ppmw
    - SCR NOx reduction of 90%
    - SCR inlet NH_3 = ~ 150 ppmw at actual O_2
  - ABS Potential = 750 ppm^2
  - SCR MOT = ~540°F

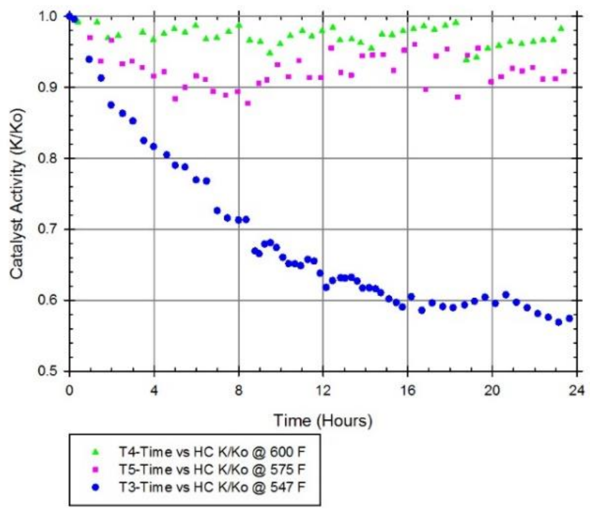




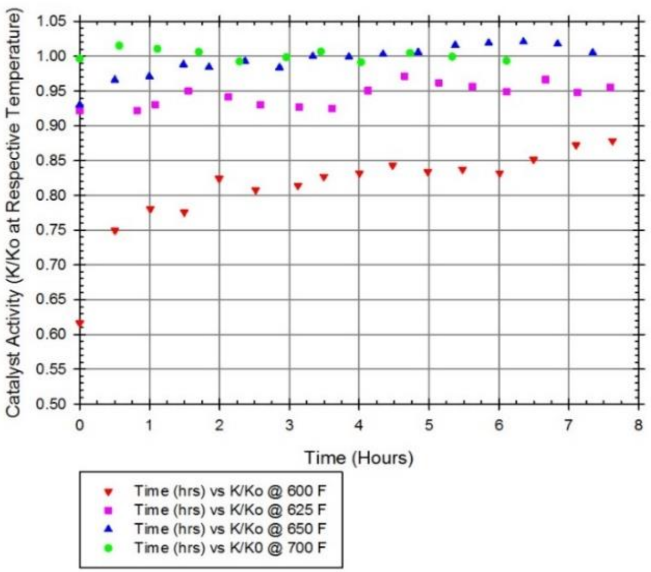
SCR Catalyst Impacts

- Catalyst deactivation level a function of catalyst depth
  - As NH_3 reacts with NOx in initial catalyst layer, ABS potential decreases with depth
- Catalyst deactivation reaches an equilibrium state
- Catalyst activity recovery found to be very rapid
  - ABS starts to decompose around 600°F, with temporary spike in SO_3
  - At 600 °F, activity recovers to 0.90 of baseline within 8 hours

Regenerated Honeycomb Catalyst Activity vs Time and Temperature
ABS Potential of 5,000 ppm^2

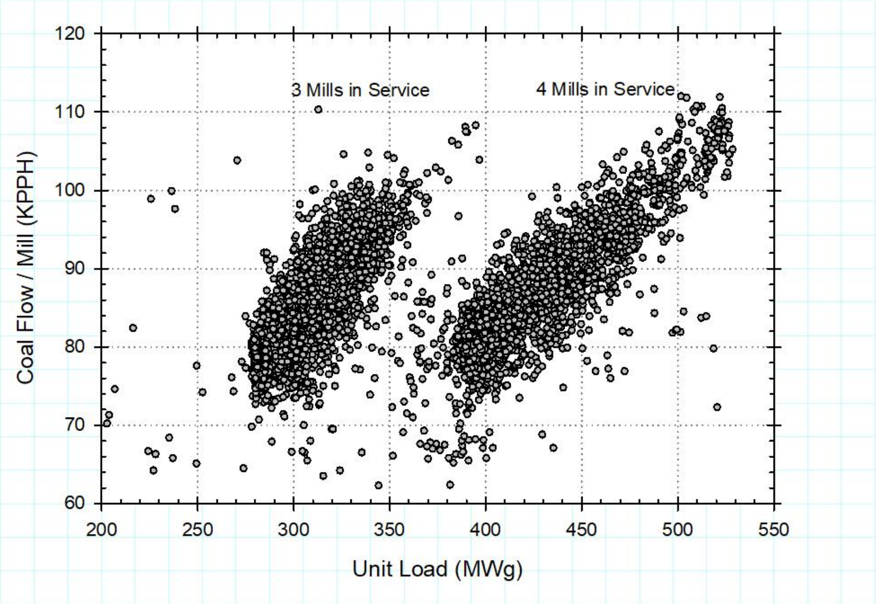


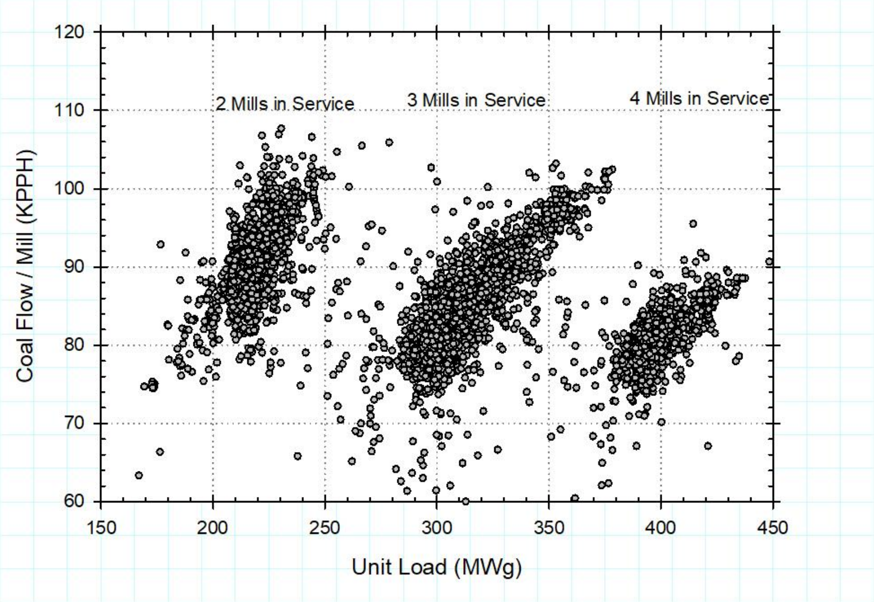
Catalyst Activity Recovery vs Temp



Combustion Considerations

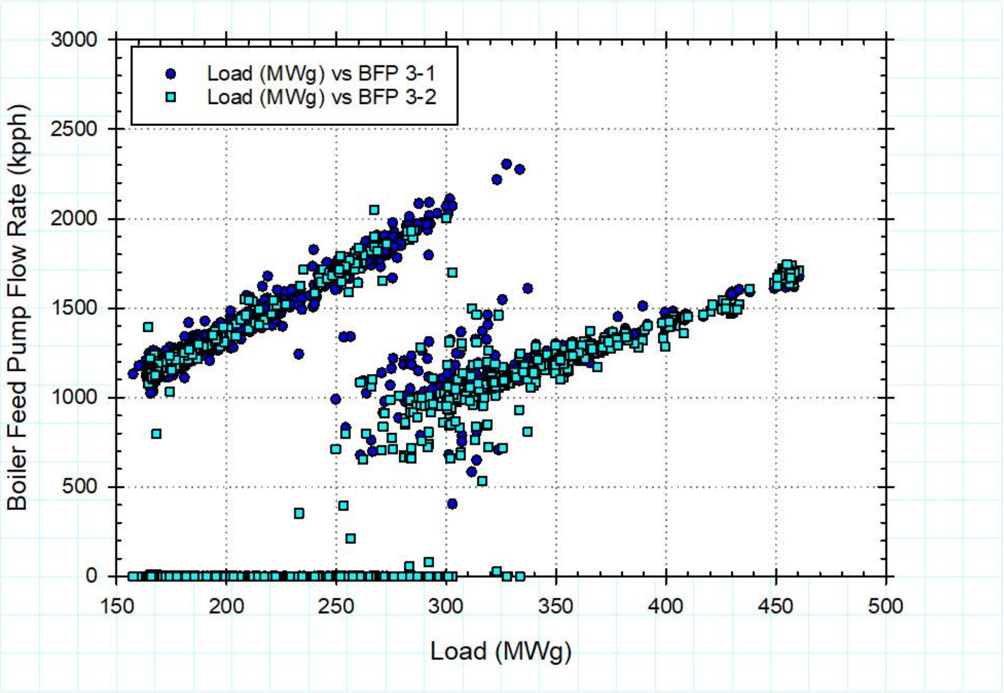
- As load is reduced, coal flow per mill decreases and mills are removed from service
  - Many sites prefer operation with no fewer than 3 mills in service
    - Enables rapid increase in coal flow/mill with single mill trips
  - Lower reduced load economic benefits have prompted some sites to operate with 2 mills in service
    - Unit trip likwly with loss of any mill operation
- Review of coal flow/mill at reduced load often identifies opportunity to reduce NOx
  - Increased coal flow per mill with fewer mills in service reduces PA/coal ratio





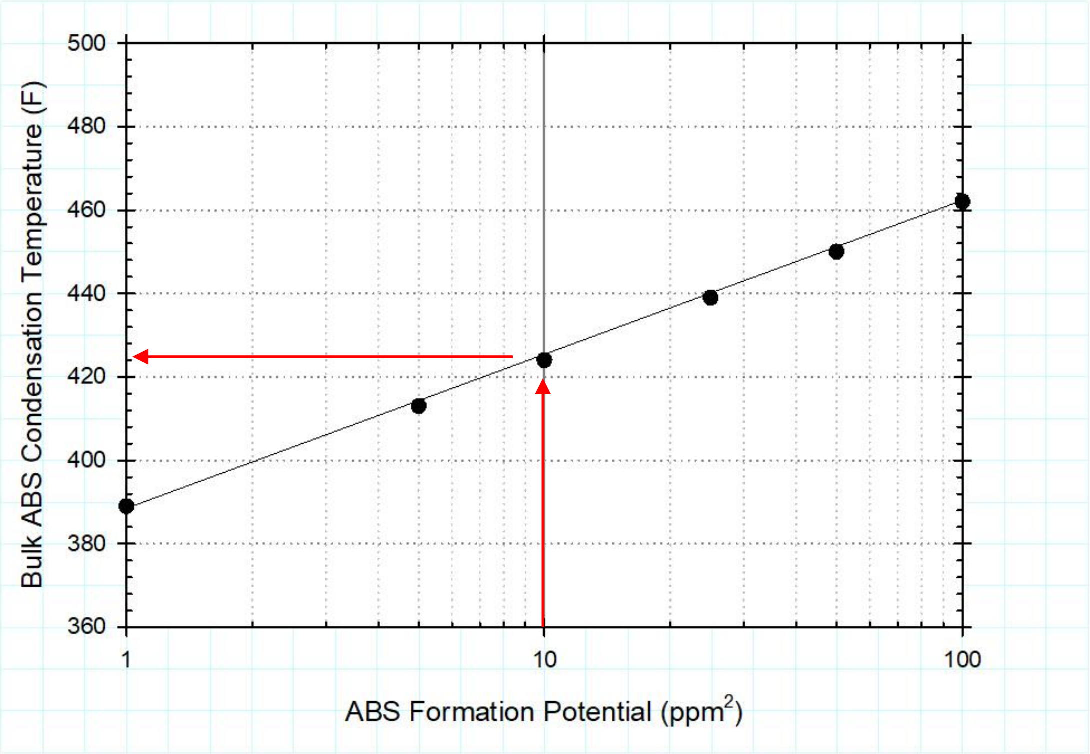
Boiler Feed Pump Considerations

- As load is reduced, minimum load for two BFP operation reached
  - Many sites prefer operation with both BFPs in operation
    - Enables rapid increase in flow with BFP trip
  - Lower reduced load economic benefits have prompted some sites to operate with single BFP
    - Unit trip with loss of BFP operation
- Review BFP flow rate over load range
  - Increased BFP flow at load where one BFP removed from service
  - Single BFP operation enables lower minimum load operation



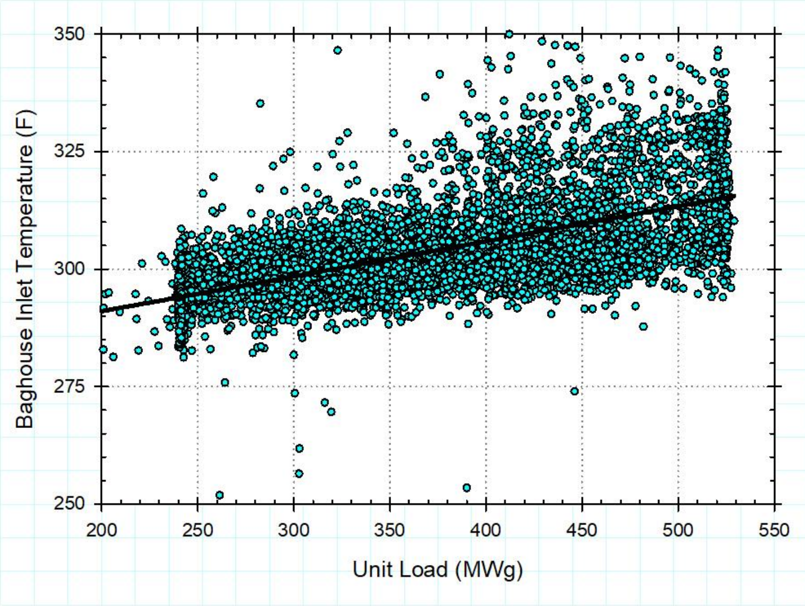
Air Heater Considerations

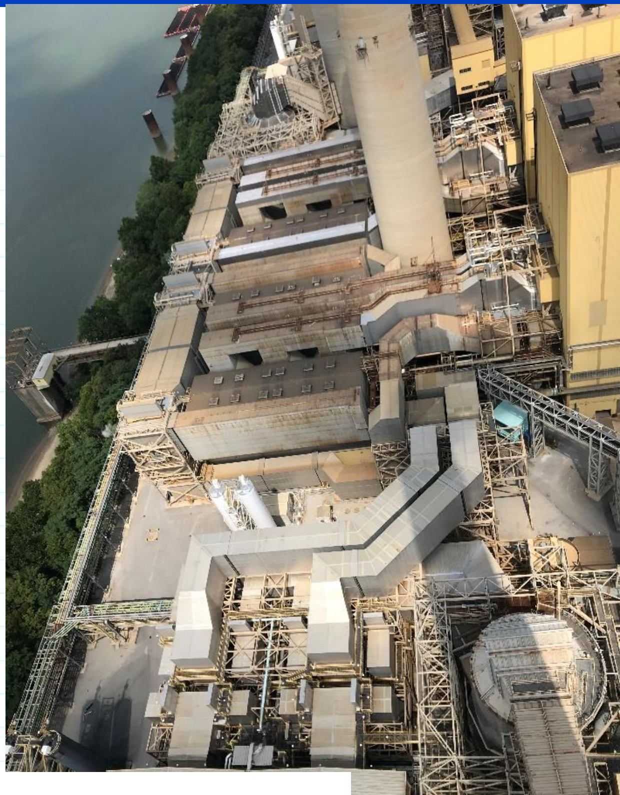
- Primary consideration with air heater (AH) is to minimize ABS formation and restrict any ABS formation to cold-end baskets
- Most bituminous coal-fired sites inject $Ca(OH)_2$ between SCR outlet and AH
  - Typically maintain SCR NH_3 slip to < 2 ppm
  - Control SO_3 to < 5 ppm with DSI
  - ABS formation potential = 10 ppm^2
  - ABS bulk condensation T = **424°F**
- AH gas outlet temperatures at reduced load typically 300°F ± 20°F
  - ABS will still form but typically in cold end baskets
  - Cleanable with cold-end sootblowers
  - Minimal formation also typically cleanable with fly ash ‘scouring’ of AH basket surface

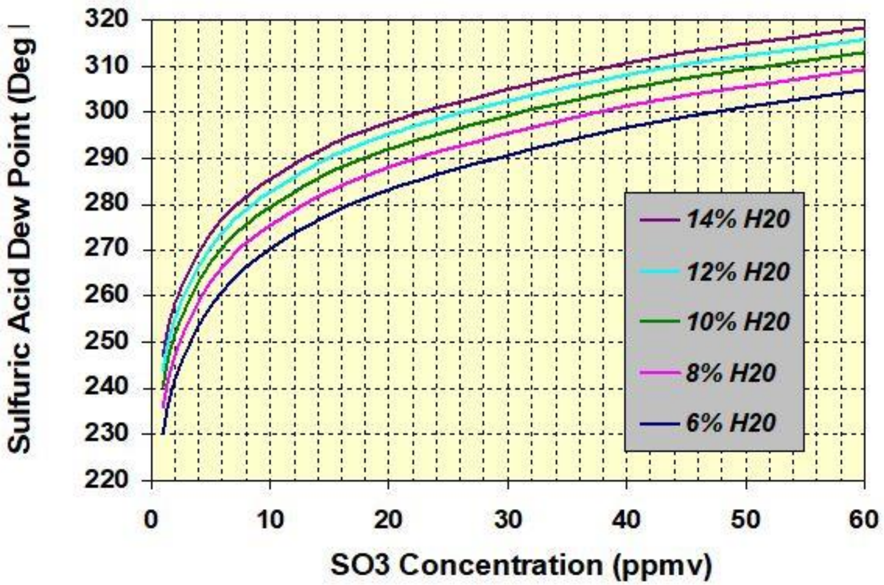


Duct Corrosion Considerations

- Duct corrosion typically addressed through DSI
  - Unit analysis evaluates DSI/SO_3 molar ratio, as well as injector design and configuration
    - Measure or estimate [SO_3]
  - Compare reduced load flue gas temperature to H_2SO_4 dew point
    - Trend plot of flue gas temperature vs load represents annual data
  - Assess duct temperature gradients and/or ambient air in-leakage
- Control of flue gas SO_3 to < 5 ppm maintains H_2SO_4 dew point to ~ 265°F







Plant Management Factors

- Utility plant operating incentives can disincentivize higher risk operating scenarios
  - Plant bonuses can be tied to:
    - Number of unit outages and/or trips
      - Can impact minimum number of mills in service allowed
      - Can restrict unit to two BFP operation
    - Unit availability
- Important that utility corporate and plant management objectives are aligned
  - Adjust plant operating incentives to allow consideration of acceptable risk/reward operating scenarios

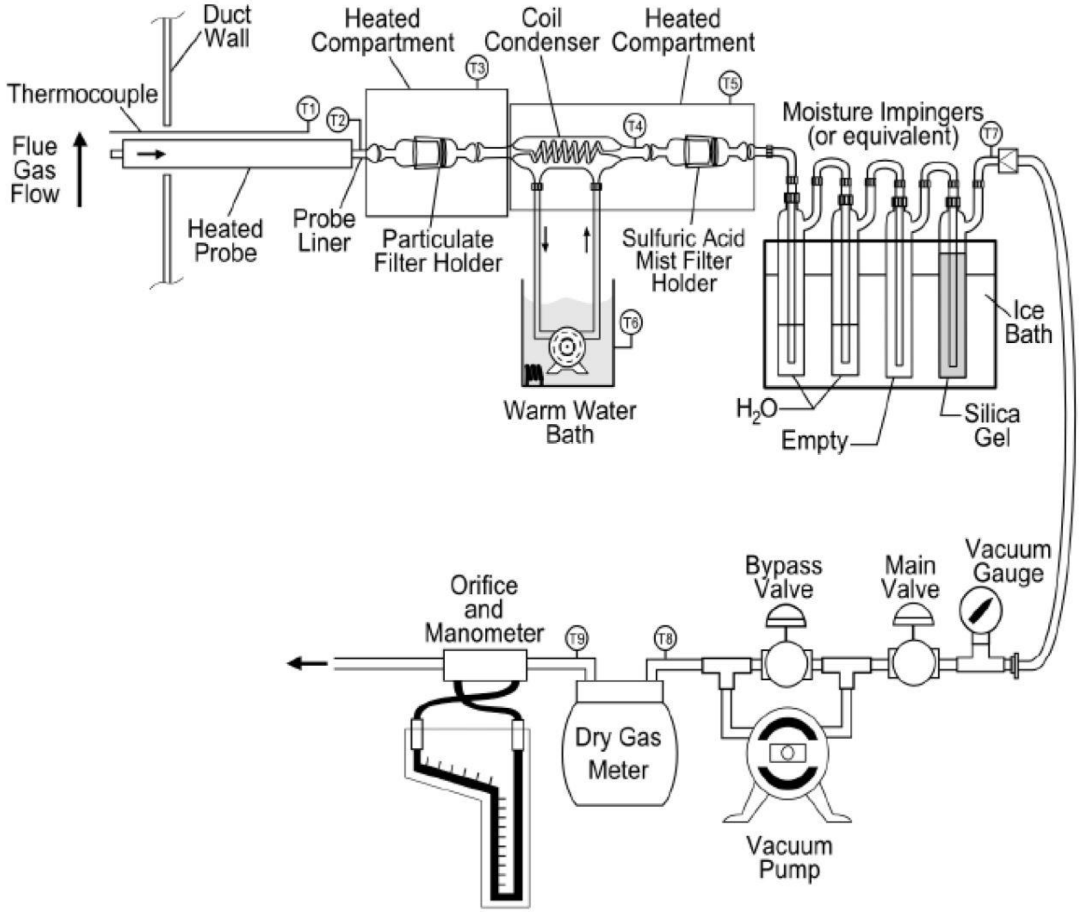
Cost Benefit Example

- Minimal unit loads most beneficial during negative power pricing time periods
  - Time periods when bid power price is less than generation cost
  - Insufficient duration to offset start-up costs by taking unit off-line
- Assume additional 100 MW reduced load feasibility
    - Typically represents 10 – 30°F change in SCR inlet temperature
    - Assume $10/MW-hr negative cost differential
    - 100 MW lower load provides $1,000/hr reduced loss
      - 88 weekly hours of deeper reduced load operation potential during slack load periods of Mon – Thu (10 pm – 6 am) and Fri 10 pm to Mon 6 am
      - Weekly loss reduction of $88,000

SO_3 Measurements

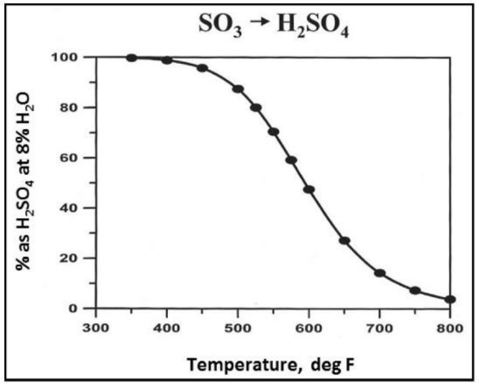
Industry Need and Issues Encountered

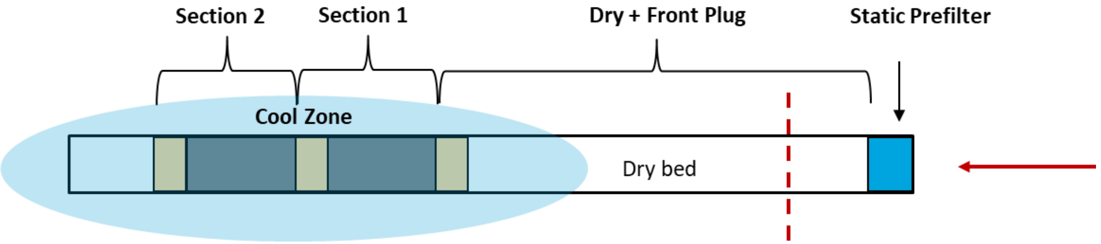
- Implementation of SCR systems on coal-fired boilers for NOx control typically resulted in increased SO_3 flue gas levels
- Utility industry experienced a range of issues associated with increased SO_3
- Dry sorbent injection implemented where needed to control SO_3 levels
  - Industry need to accurately measure SO_3
  - No continuous monitor available
- Varied industry experience with controlled condensate measurement
- Sorbent trap methodology represents simpler approach

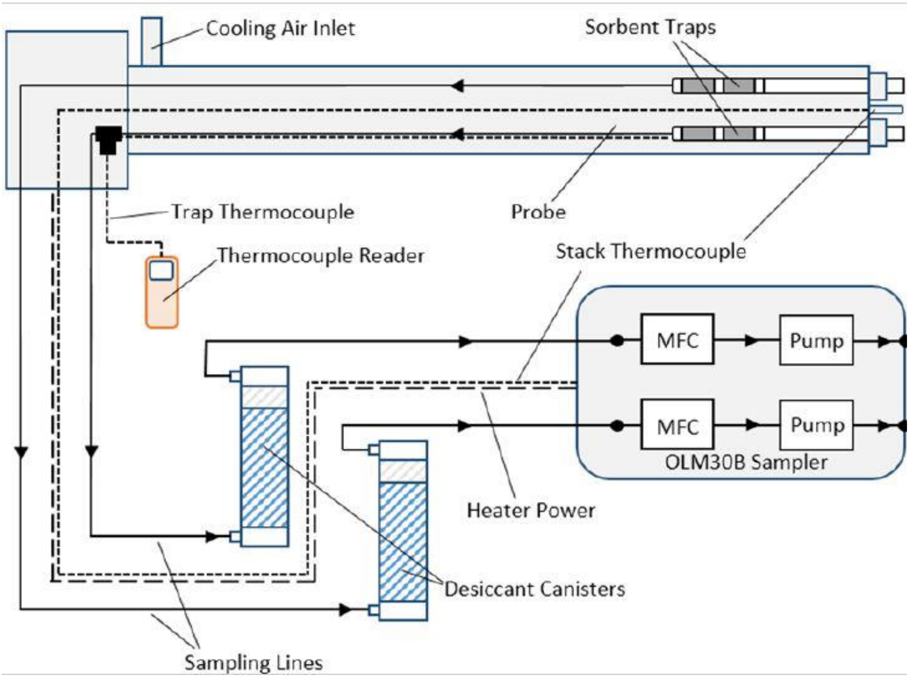


SO_3 Sorbent Trap Operation

- Typical Sampling Parameters
  - Standard M30B probe and sampling console
  - Cooling air used to maintain target trap temperature (~80 psig compressed air)
    - 390 to 445°F trap temperature for SO_3
  - 0.25 to 1 LPM sample flow rate
  - Typically implement 20 – 30 minute sample runs, depending on estimated SO_3 concentration
- Analysis Approach
  - Sorbent sections diluted in DI water and analyzed using anion chromatography
  - LOQ of 0.3 mg/dscm, (~0.1 ppmvd)
  - Analyzed sections: front plug (if desired), glass rinse, section 1, and section 2
- QA/QC similar to M30B







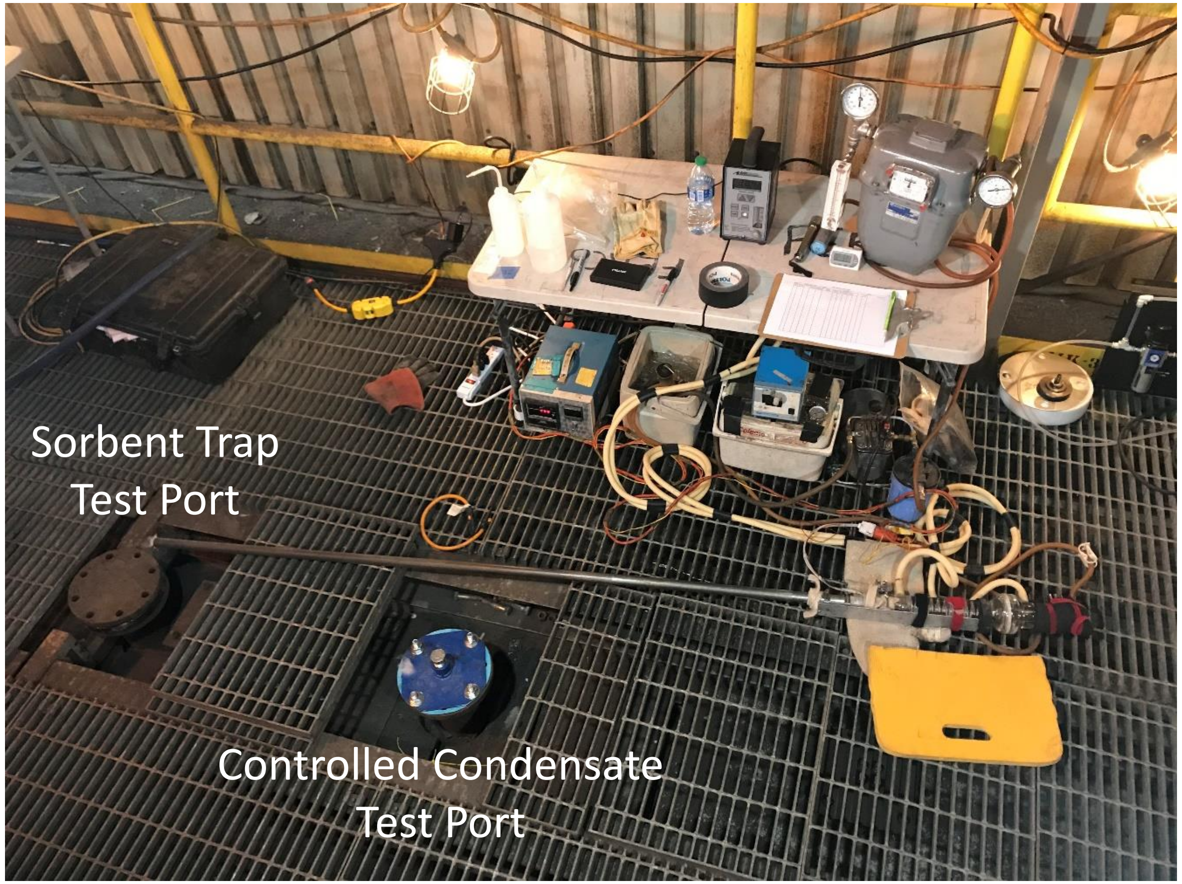
Field Test Comparison of Condensate and Trap Methods

- Field test conducted at SCR outlet on unit firing a nominal 4% sulfur coal
  - No alkali sorbent present at measurement location
- Tests conducted at three different unit operating conditions
  - Triplicate condensate and trap measurements obtained at each operating condition
  - Sorbent trap sampling system operated in close proximity to controlled condensate

					Duct A			
Date	Start	Stop	Load		O2	Calc H2O	Calc SO2	SCR Outlet
	Time	Time	MWg	MWn	(%, wet)	(%)	(ppmw)	(F)
3/16/2021	7:00	17:00	697.0	648.0	3.02	6.93	2,988	660
3/17/2021	7:00	17:00	648.0	601.0	3.70	6.56	2,954	646
3/18/2021	7:00	12:30	543.0	499.0	5.12	6.21	2,691	619

Relative Sampling Locations and Associated Systems

Controlled Condensate Sampling System



Sorbent Trap Sampling System

Comparison of Condensate and Trap Measurements

O2	Sorbent Trap 1			Sorbent Trap 2			Trap Avg	CTM-013	Abs Diff	(Trap-CTM)
(%, dry)	ppmvd	ppmvdc	Trap %Diff	ppmvd	ppmvdc	Trap %Diff	ppmvdc	ppmvdc	ppmvdc	Average
5.3	33.0	37.9	4.3%	30.3	34.8	-4.3%	36.3	42.2	5.9	15.0%
5.3	30.2	34.7	-3.0%	32.1	36.8	3.0%	35.7	45.0	9.3	22.9%
5.3	28.3	32.5	0.5%	28.0	32.1	-0.5%	32.3	37.6	5.3	15.2%
5.1	39.3	44.5	0.8%	38.7	43.8	-0.8%	44.2	45.7	1.5	3.4%
5.0	38.1	42.9	2.4%	36.3	40.9	-2.4%	41.9	45.1	3.2	7.4%
5.1	36.7	41.6	0.3%	36.5	41.4	-0.3%	41.5	42.3	0.8	2.0%
7.2	41.5	54.2	3.1%	39.0	51.0	-3.1%	52.6	59.5	6.9	12.3%
7.0	39.8	51.3	14.4%	29.8	38.4	-14.4%	44.8	52.6	N.A.	N.A.
6.9	36.3	46.4	-1.5%	37.4	47.8	1.5%	47.1	54.4	7.3	14.4%
								VS	B	
							Average	46.48	5.03	11.6%

Relative Bias (B_R) = abs(B/VS)*100 = 10.9%

- Condensate measurements consistently higher but sorbent trap measurements typically within 2% - 15%
  - Std dev of controlled condensate triplicate measurements ranged from 4% - 9%
  - Fly ash observed in condensation coil on some tests (shaded grey)

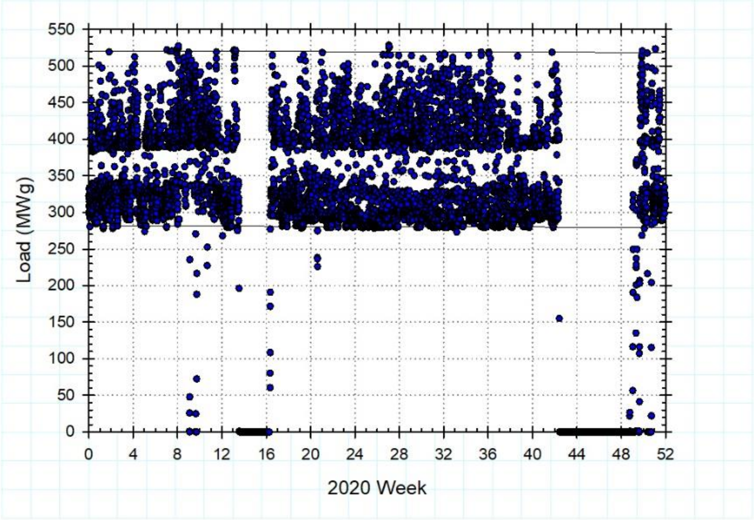
Good comparison between condensate and trap measurements

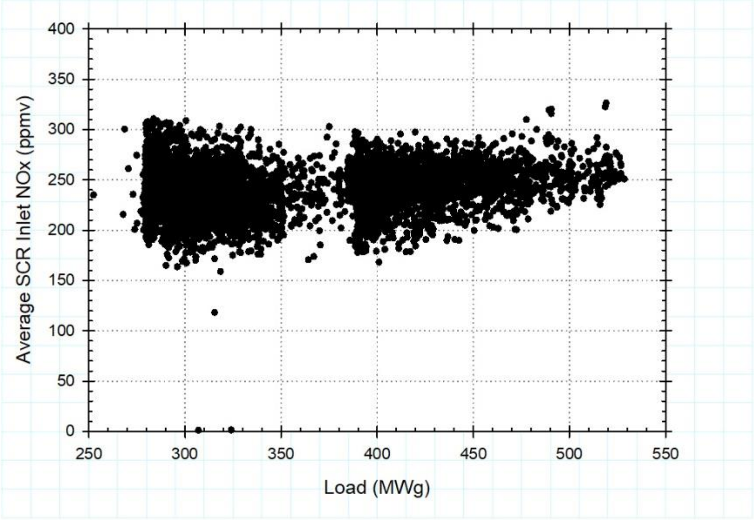
SO_3 Measurement Summary

- Controlled condensate SO_3 measurement results require close attention to operating parameters and sample recovery
  - Probe temperature (typically 560°F)
  - Sample filtration to remove fly ash
  - Condensate coil temperature (typically 160°F)
- Sorbent trap system provides entire sample collection within sorbent trap sample tube
  - Static pre-filter typically separated, glass sample tube rinse combined with first sorbent section analysis, second sorbent section analysis provides breakthrough QA/QC
- Field tests demonstrate good correspondence between both measurement methods
  - Calculated relative bias of 10.9% based on limited data set from one field test site

Case Study

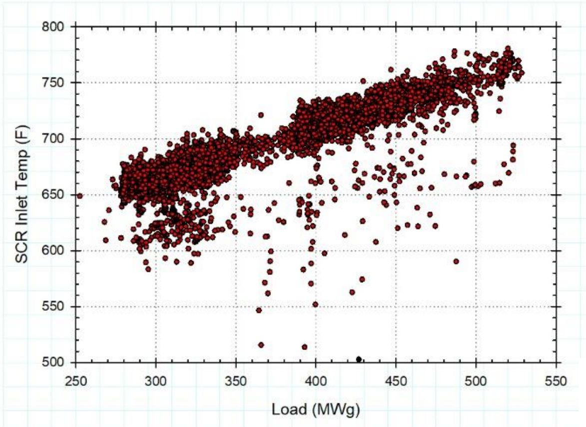
Case Study Unit - Load Profile and SCR Temp vs Load

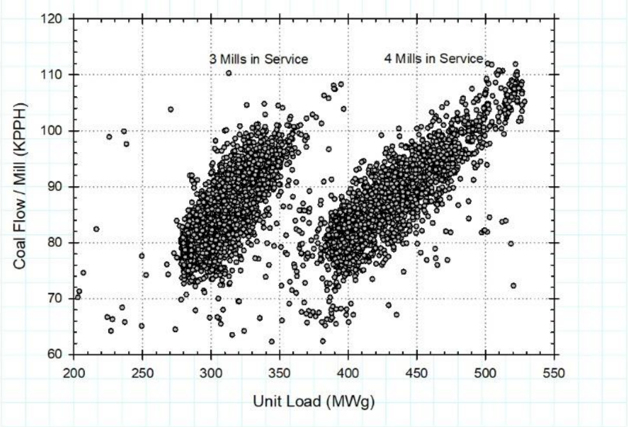


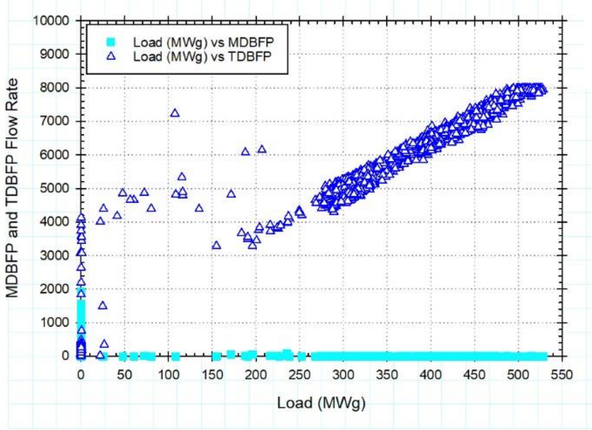


- 530 MWg opposed wall design boiler
  - Current load range of ~ 280 – 520 MWg
  - LNBs limit full load SCR inlet NOx to ~ 250 ± 50 ppm over current load range
  - 5 mills with 115 kpph coal capacity
  - Two elevations of 3 excess O_2 probes/duct
- 2003 SCR retrofit with NOx pre-mixers and Delta Wings designed for 90% ΔNOx
  - Economizer bypass incorporated in design
- DSI implemented at two locations
  - SCR outlet upstream of the air heater
  - ESP outlet upstream of the baghouse/scrubber
- PAC available for incremental Hg control on an ‘as-needed’ basis

Case Study Unit - Load Profile and SCR Temp vs Load







- Current SCR inlet temperatures > 650°F at 280 MW indicate SCR not constraining further load reduction
  - SCR MOT of ~ 580°F
- Current minimum load with 3 mills-in-service suggest opportunity for further load reduction with 2 mill operation
- Motor driven BFP for start-up with single turbine driven BFP used over load range

SO_3 Measurements Across SCR

Reduced Load - 275 MWg		A-1	A-2	A-3	Average		B-1	B-2	B-3	Average
SCR Inlet										
Temperature	(F)	670.3	682.7	677.6	677		668.9	666.0	665.0	667
O2	(%, dry)	6.0	6.0	6.0	6.0		6.7	6.4	6.5	6.5
SO2	(ppmvd, @3% O2)	2,957	3,031	2,870	2,953		3,027	2,755	2,747	2,843
Condensable SO3	(ppmvd, @3% O2)	33.6	35.5	32.00	33.7		34.9	39.1	31.3	35.1
SCR Outlet										
Temperature	(F)	655.2	657.2	658.2	657		675.0	674.5	674.2	675
Condensable SO3	(ppmvd, @3% O2)	40.0	43.5	54.0	45.8		63.5	62.5	71.6	65.9
% SO2 Conversion		0.22%	0.26%	0.77%	0.41%		0.94%	0.85%	1.47%	1.08%

- Current ABS formation potential at 275 MWg of 7,250 ppm^2
  - SCR MOT of ~ 585°F relative to ~650°F SCR inlet temperature
  - Potential opportunity to reduce minimum load closer to 200 MW
- DSI injection adequately controls downstream SO_3 levels
  - Verified with controlled condensate SO_3 measurements
- Opportunities to reduce SCR SO_2 oxidation if needed
  - Review fly ash build-up on catalyst layers and improved methods for cleaning
  - Review need for economizer bypass use
  - Consider tailoring NH_3 slip to 1 – 2 ppm to mitigate SO_2 oxidation across the SCR catalyst
    - Multi-channel NH_3 TDL for NH_3 reagent control

Summary

- Increasing renewable and/or natural gas GTCC generation will likely continue to require increased coal-fired unit load flexibility
  - Lower reduced loads important to minimize losses during ‘out-of-the-money’ operating time periods without having to take units off-line
- Current unit operating restrictions and plant bonus incentives should be reviewed to ensure proper alignment with most cost-efficient operating objectives
- Opportunities frequently exist to reduce minimum loads
  - Assessments should be conducted on a holistic basis
  - Actual SO_3 measurements better than estimates

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