REINHOLD ENVIRONMENTAL Ltd.

2017 NOx-Combustion-CCR Round Table Presentation

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Update on SCR Operation During Reduced Load

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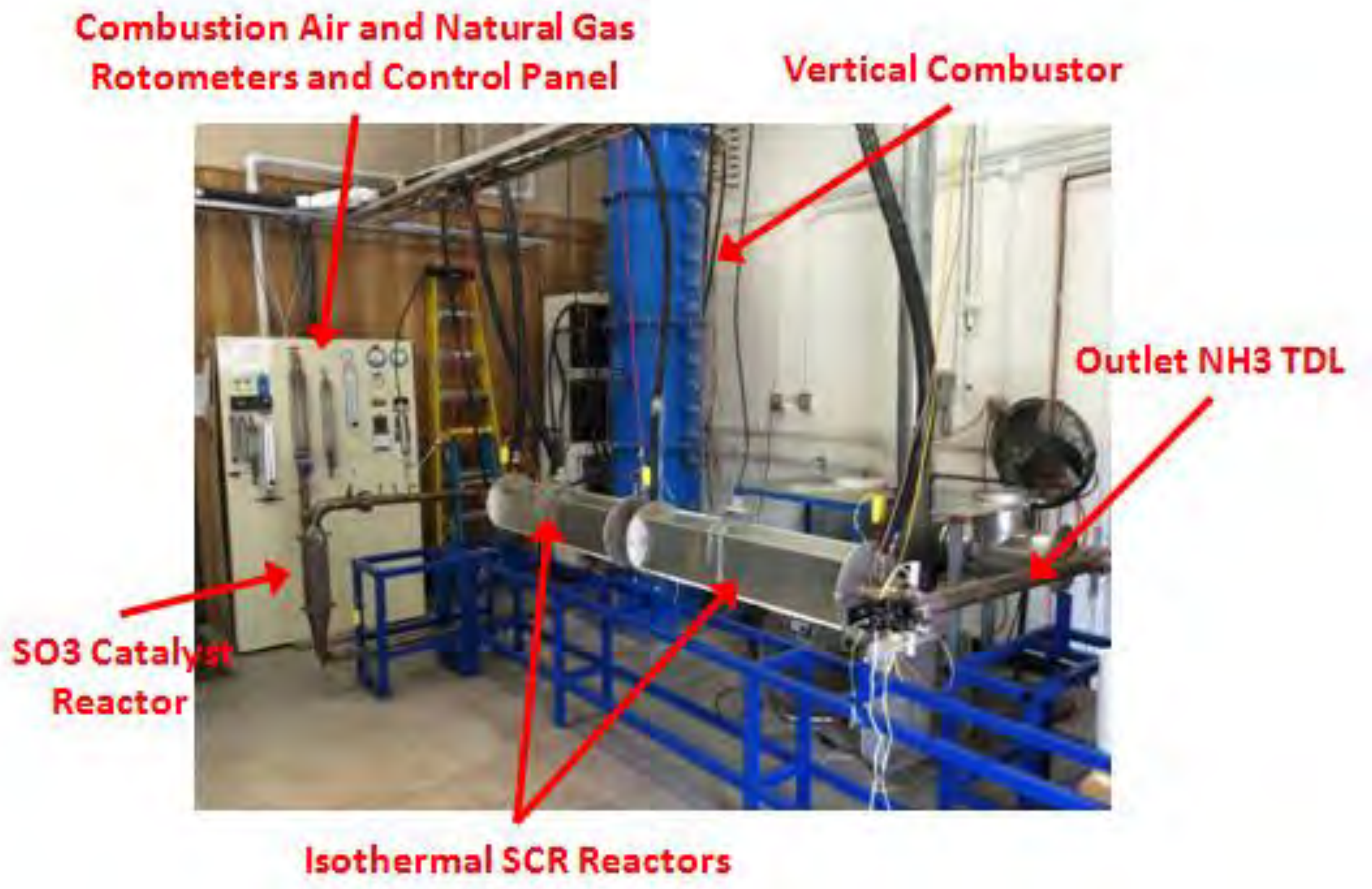


Agenda

- EPRI
- Changing mission profile for coal generation
- R&D Objective
- Current understanding of ABS formation temperatures
- Lab experiment verification of more recent UCI data
- Full scale demonstrations

Three Key Aspects of EPRI

Independent

Objective, scientifically based results address reliability, efficiency, affordability, health, safety, and the environment

Nonprofit

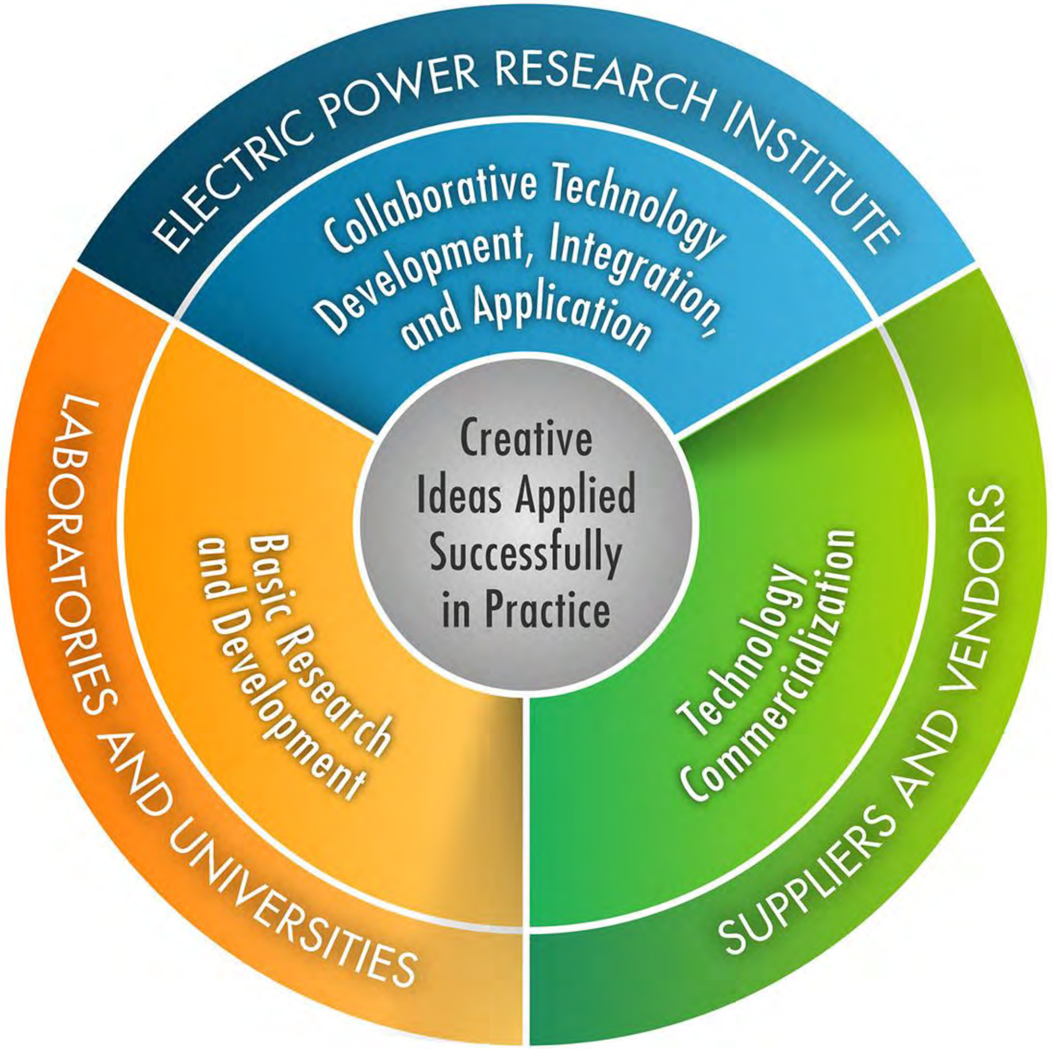
Chartered to serve the public benefit

Collaborative

Bring together scientists, engineers, academic researchers, and industry experts

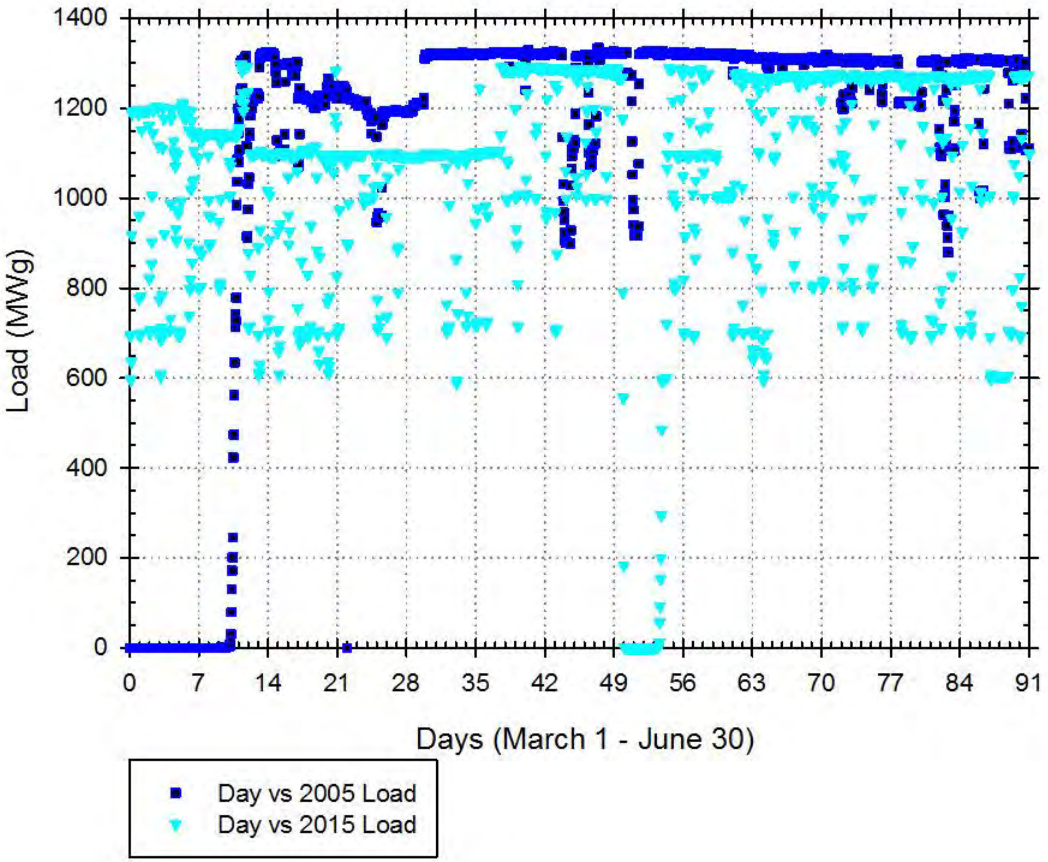
EPRI's Role

Stimulate innovation; help accelerate technology development



Changing Mission Profile for Coal-Fired Generation

- Increased natural gas and renewable generation
  - Formerly base load coal-fired units experiencing greater cycling
- Geographic locations where coal generation periodically uneconomic
  - Unit start up costs and increased maintenance associated with increased unit starts
    - Time required to bring units back on-line limit ability to respond to daily load peaks
  - Need for deeper load reduction capability to keep units on-line
- SCR system for NOx control often represents minimum load constraint
  - Minimum operating temperatures prescribed by catalyst vendors due to ABS concerns



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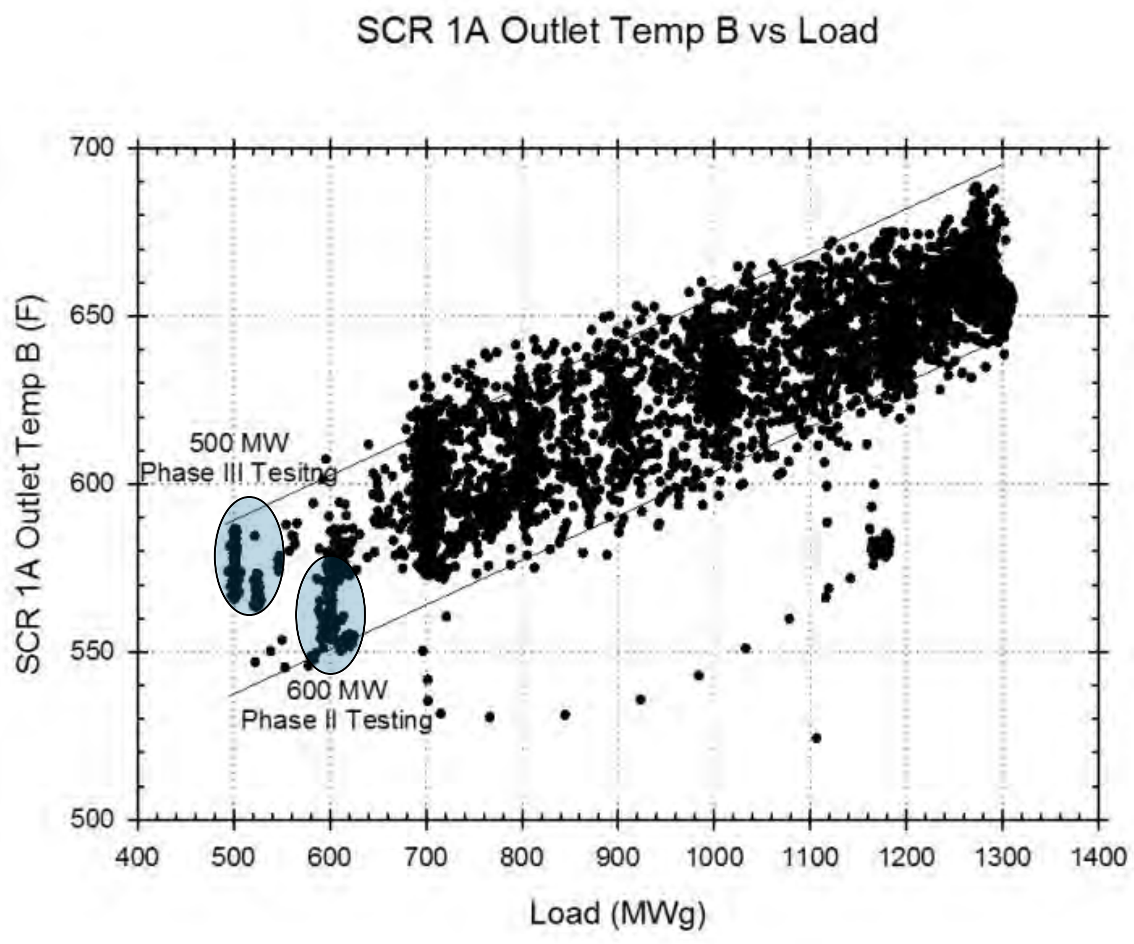
R&D Objective

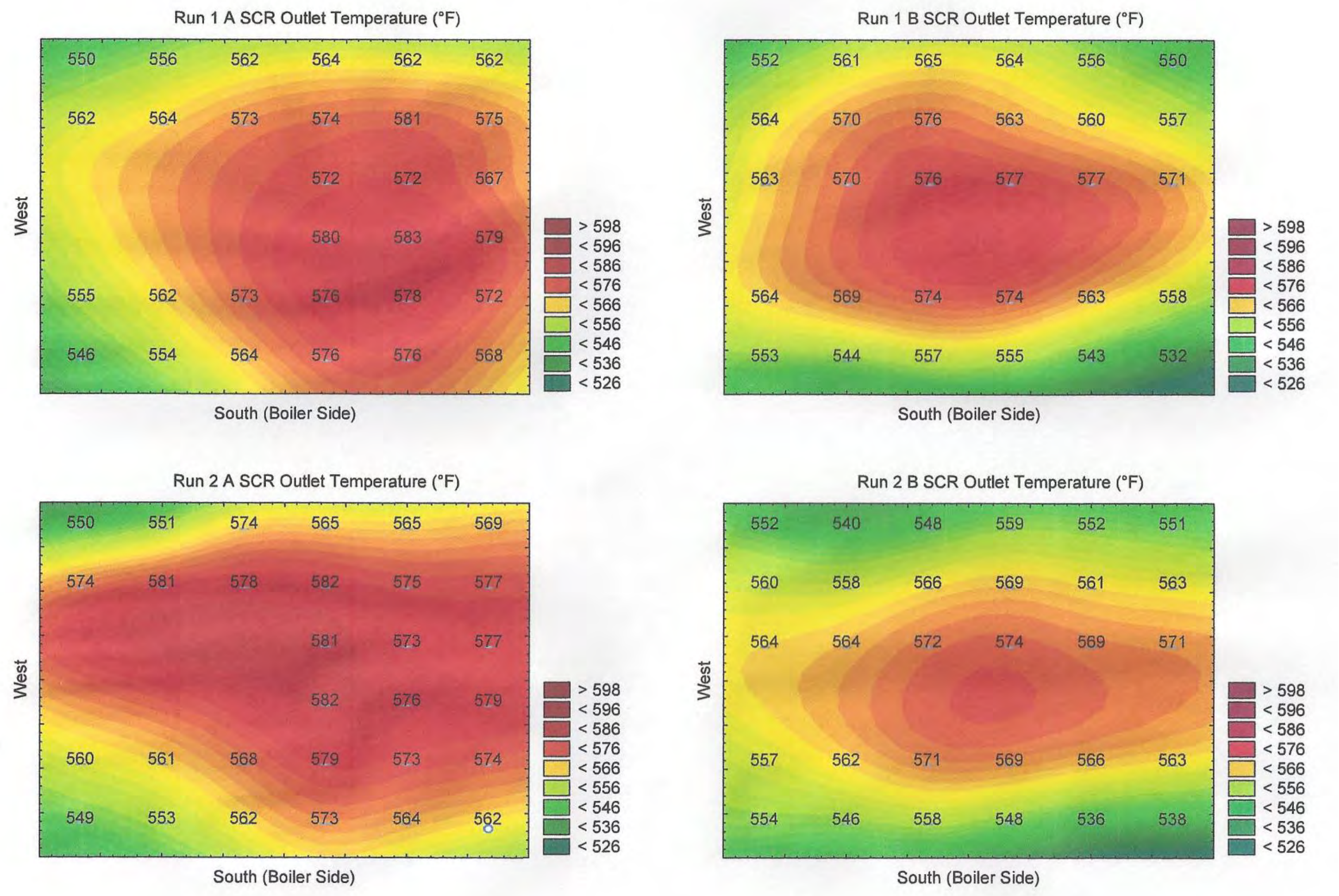
- Enhance understanding of ABS formation temperature
  - Validate through both laboratory and field demonstrations
- Develop dynamic methodology to calculate SCR minimum operating temperature (MOT)
  - On-line response to changes in:
    - Coal supply / blend ratio
    - Unit operating conditions
    - NOx reduction requirements

Temporal Variation



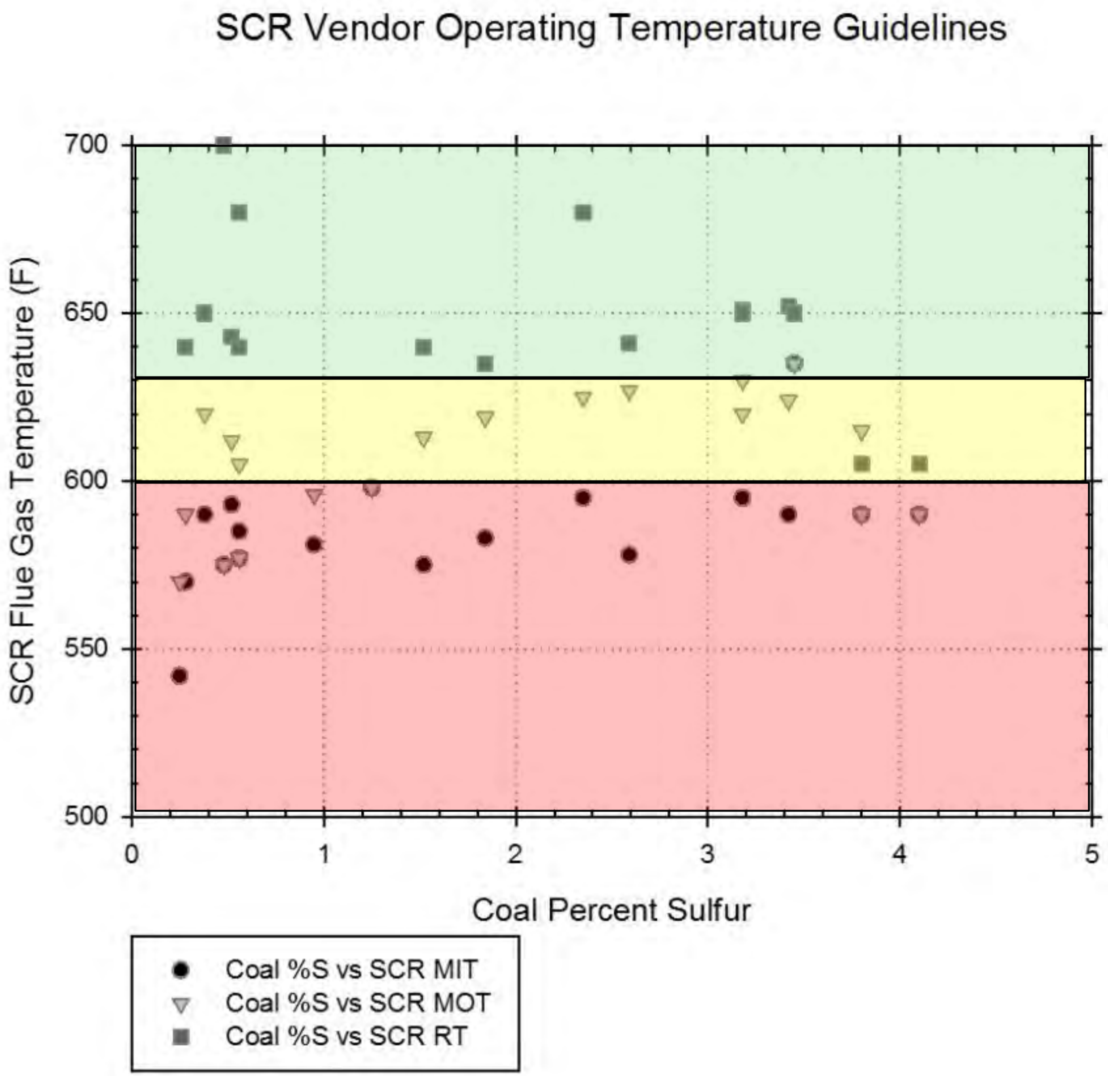
Range of operating conditions at same load that affect ABS formation temperature

Plan View of Spatial Variation of SCR Outlet Flue Gas Temperature



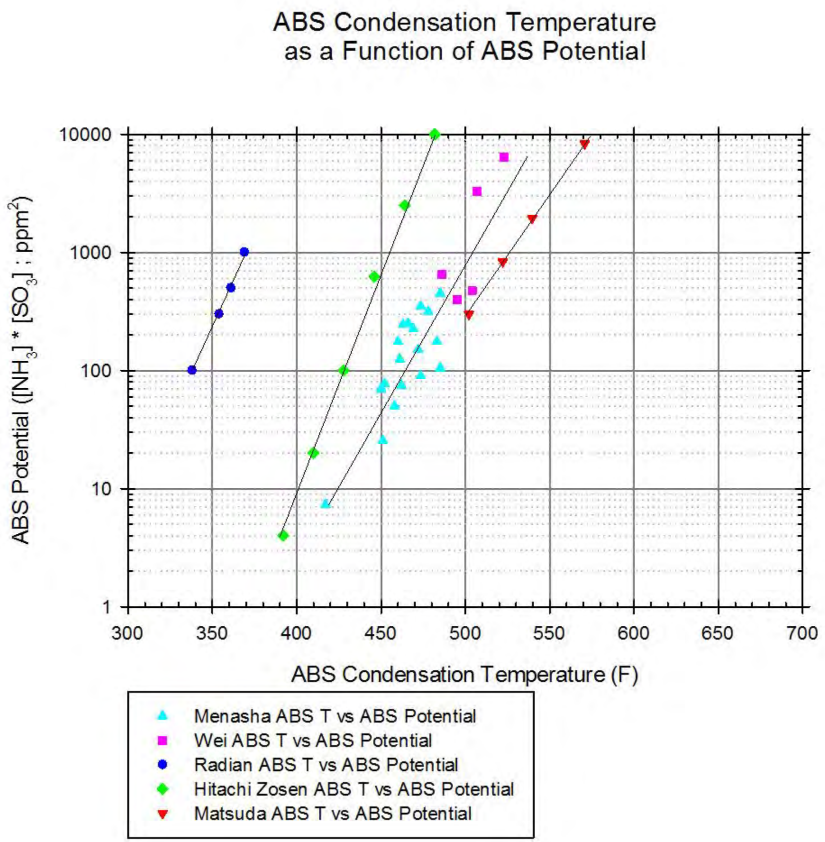
Range of SCR MOT Guidance Provided to SCR Operators

- 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



Range of ABS Formation Temperature Correlations

Comparison of ABS Studies



Summary

- Detailed review of experiments presented by EPRI at 2016 Reinhold NOx Conference
- Catalyst vendors often reference Matsuda correlation
  - Broad ABS formation temperature uncertainty
  - Limited set of 5 data points
  - Correlation developed based on several assumptions
- EPRI funded two different experiments at UCI
  - UCI experiments provided 22 data points
    - Experiments more precise
    - Data used to replicate Matsuda calculations
    - Demonstrated nominal 28°F lower ABS condensation temperature

More accurate data set suggests 28°F lower ABS formation temperature

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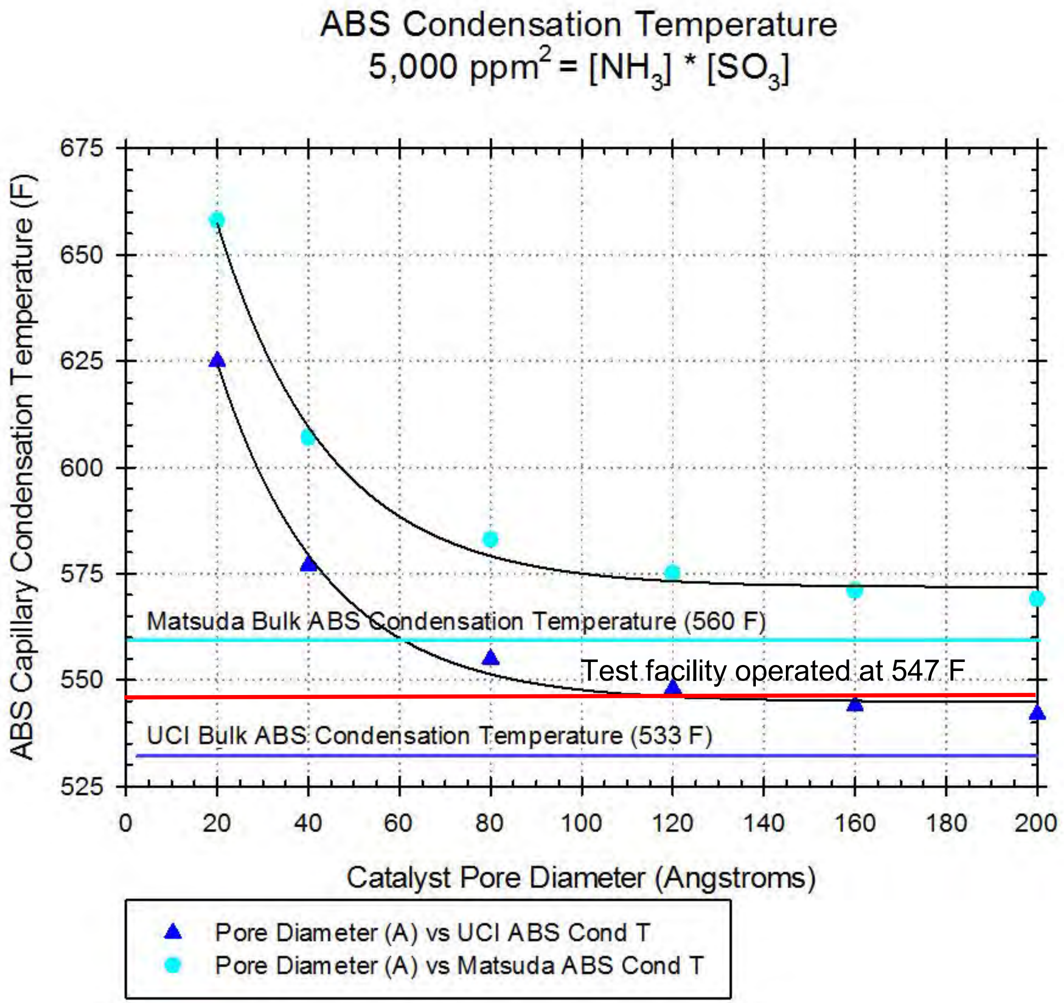
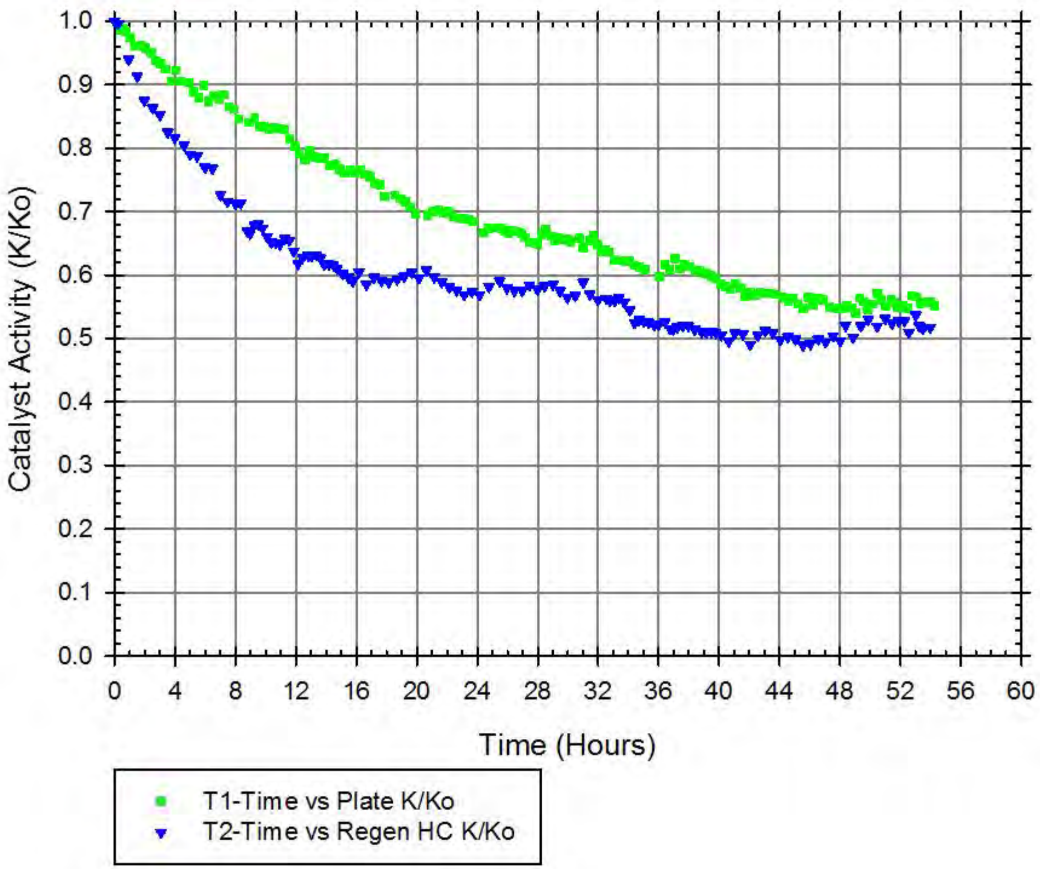
Lab Experiment Assessing UCI and Matsuda ABS Calculations





Experiment supports UCI data calculation of ABS formation temperature

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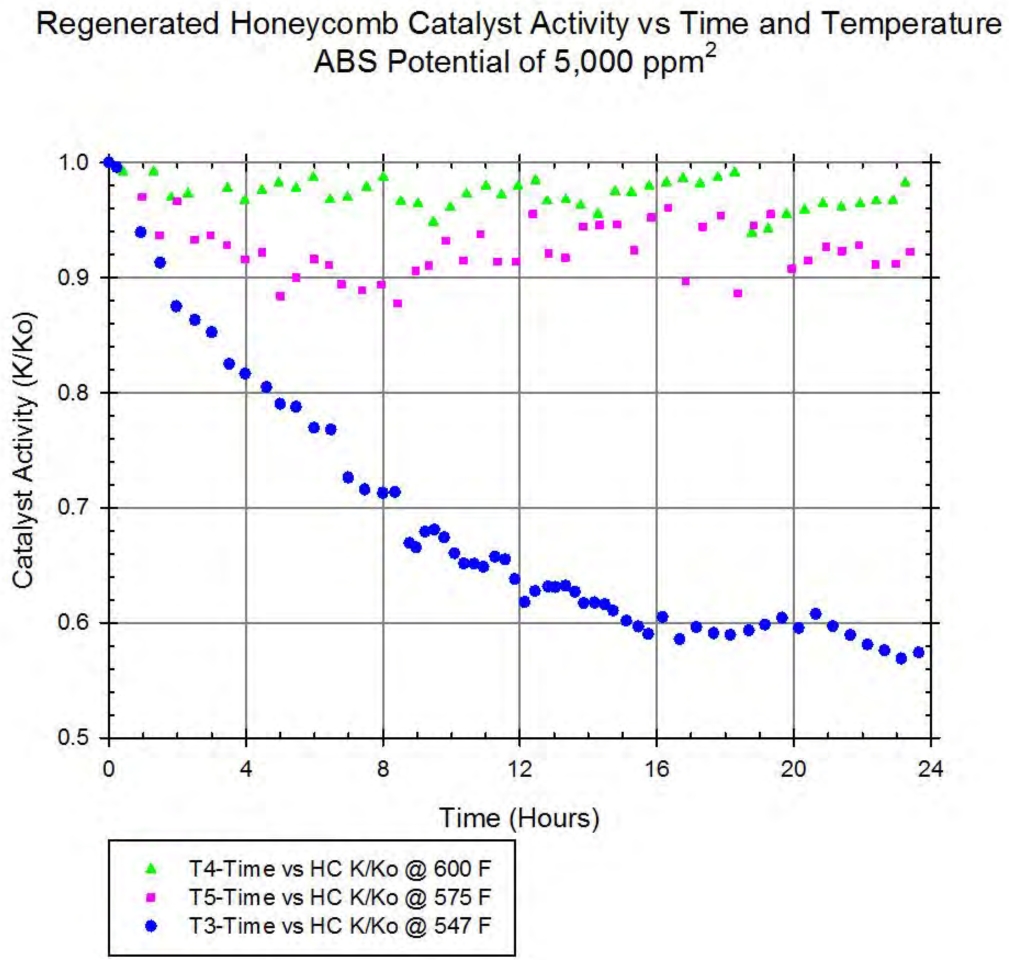
Rate of Catalyst Deactivation vs Temperature

- Test with regenerated honeycomb catalyst
  - Operated for 24 hours at 3 temperatures with 25 ppm SO_3 and 200 ppm NH_3
  - Catalyst recovered for 24 hours at 700°F prior to each test
- Limited catalyst deactivation observed at 600°F and 575°F after 24 hours
- Catalyst deactivates at 550°F but reaches equilibrium
- Lab test results again supportive of UCI ABS formation correlation



Limited catalyst activity deactivation at 575°F with ABS potential of 5,000 ppm^2

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ABS Formation Temperature Correlation (UCI Data)

- ABS bulk formation temperature correlation

P_{NH3} (atm) * P_{SO3} (atm) = 2.97 * 10^{13} * exp (-54,950/RT)

R = 1.987 cal/K-mol

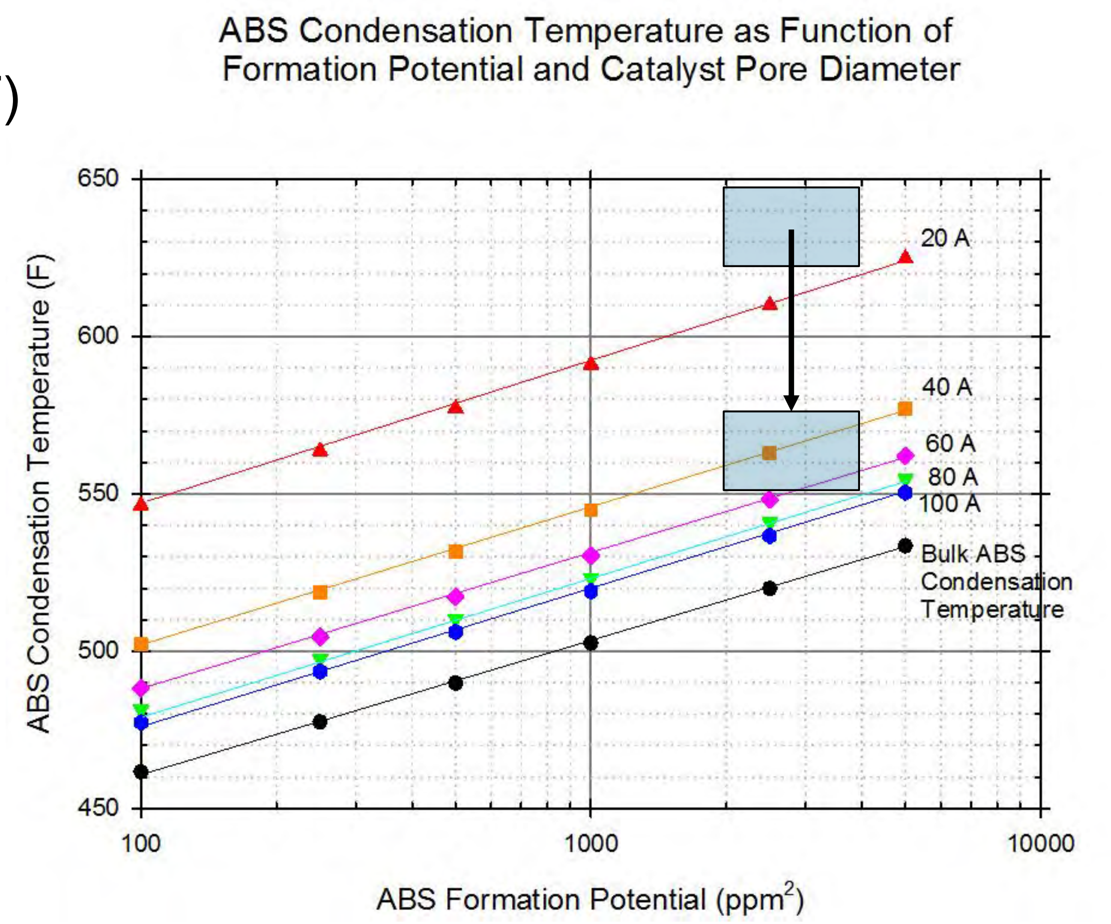
T = flue gas temperature in degrees Kelvin

- Thomson's theory of capillary condensation used to calculate ABS formation in micro pores

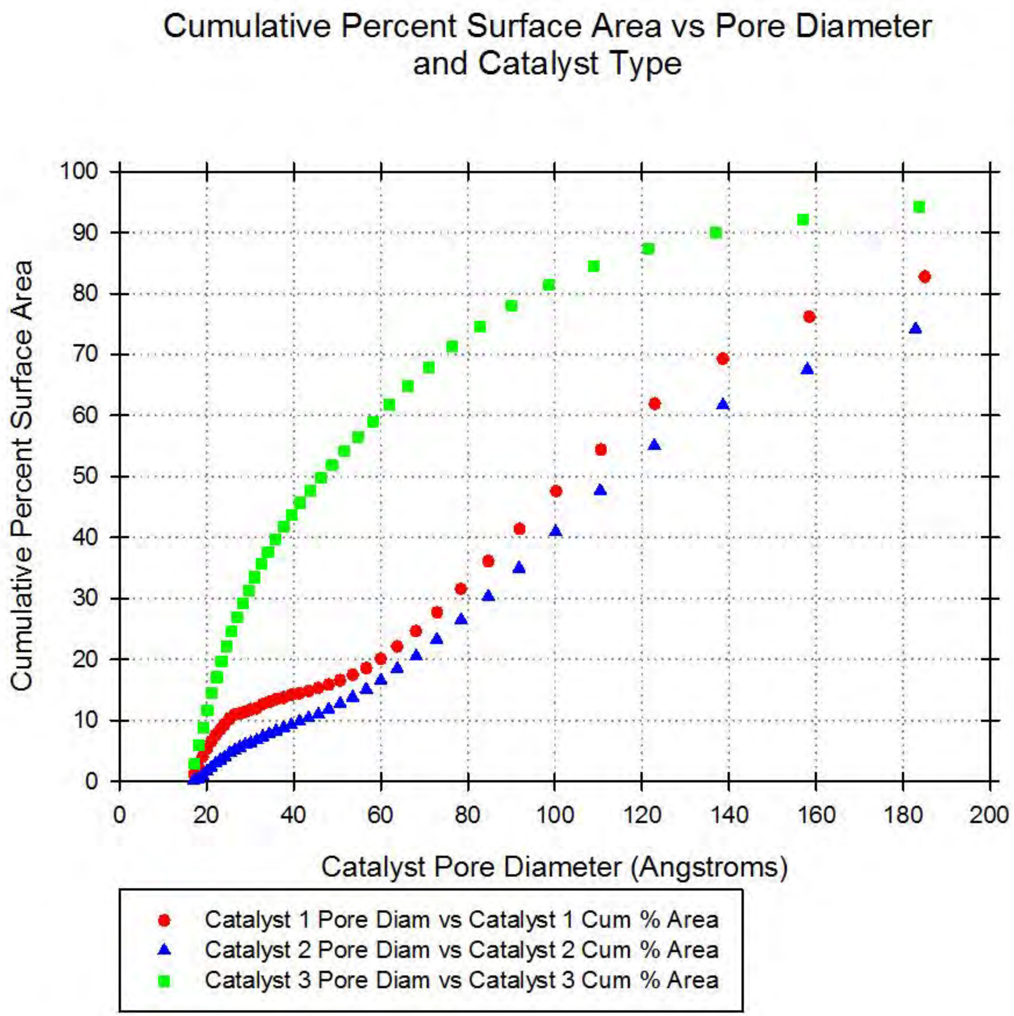
$$\ln (P/P_{eq}) = 2\,\sigma\, M / \rho\, \gamma\, R\, T$$

  – Surface tension (σ) = 150 dyn/cm^2
  – Density (ρ) = 1.78 g/cm^3 for ABS
  – Pore size (γ) = cm

$$\ln (P/P_{eq}) = 2.33 * 10^{-4} (cm^{-1}\, K^{-1}) / \gamma\, T$$

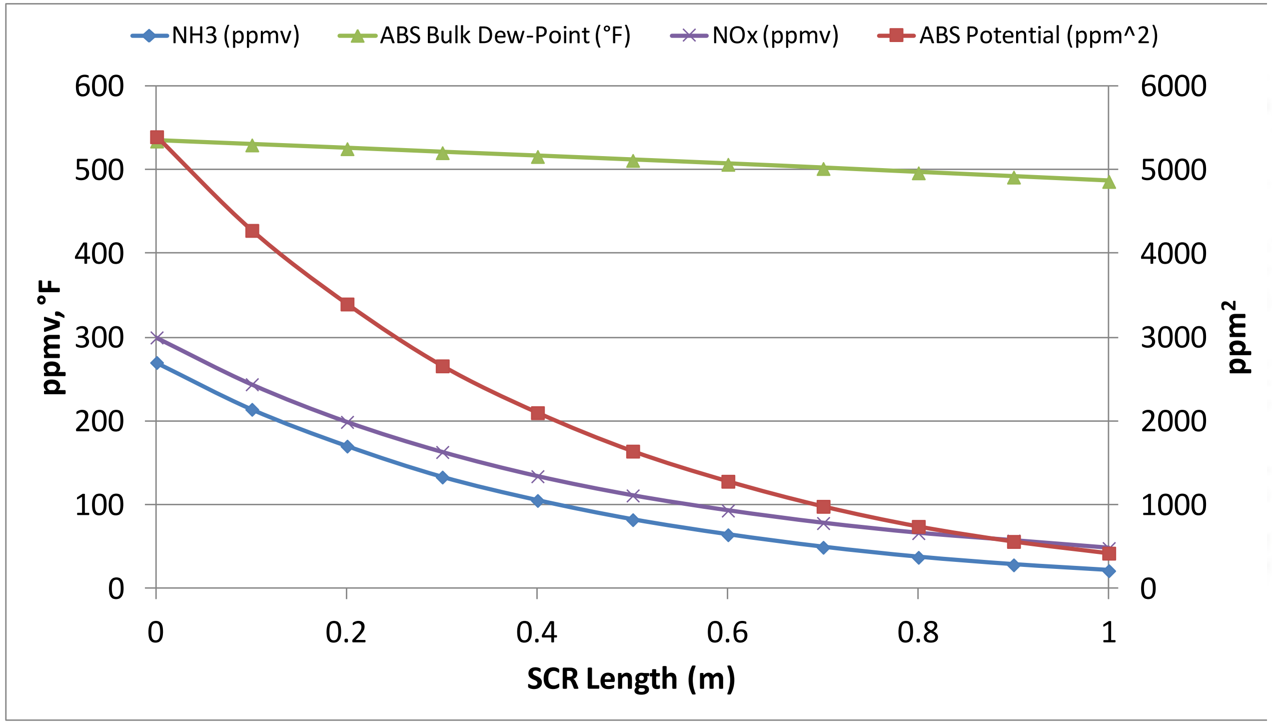


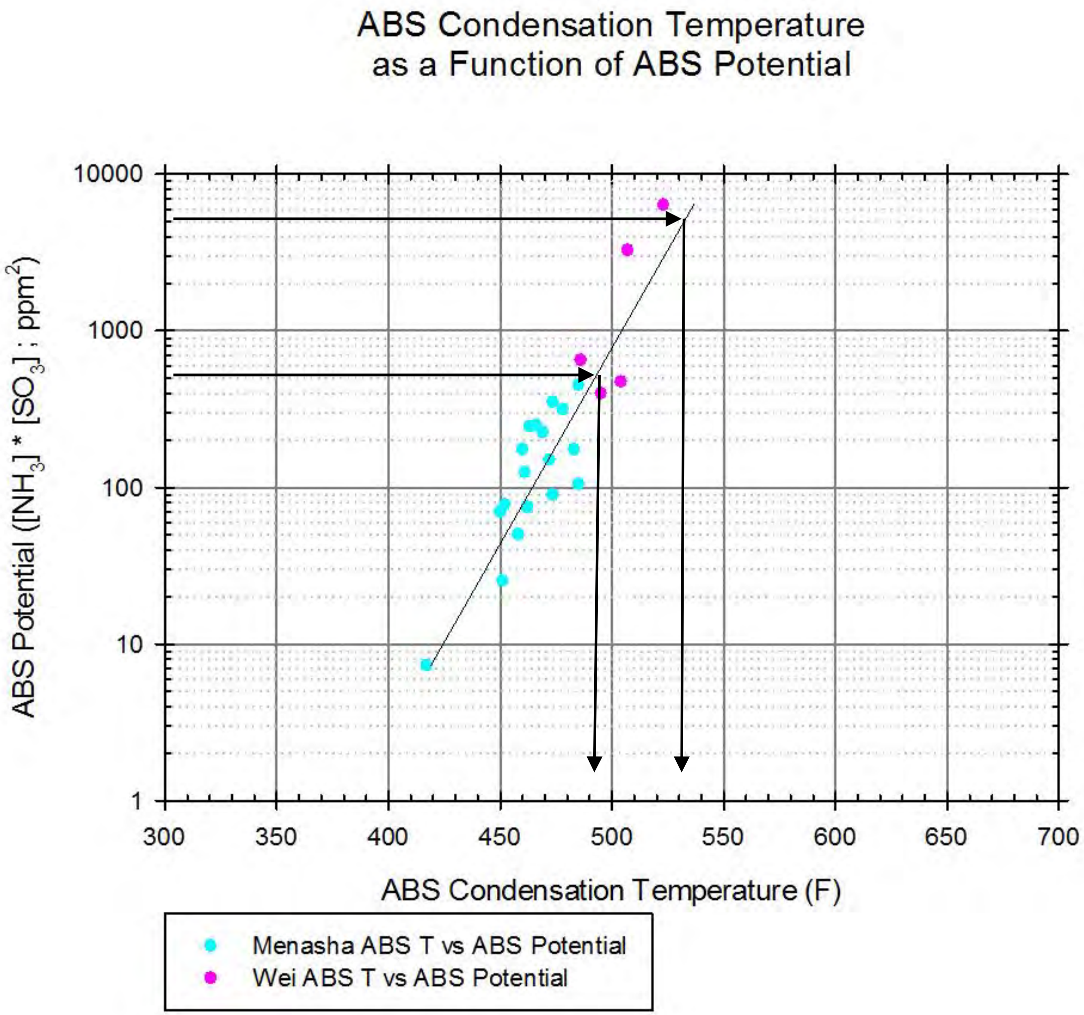
Examples of SCR Catalyst Pore Size Distribution



Pore size distribution can be catalyst specific – limited affect at 40 – 100 angstroms

Change in ABS Potential vs Catalyst Depth





Catalytic reaction of NOx with NH_3 reduces ABS potential and formation temp

Case Study 1

1300 MW Opposed Wall Fired Unit

2.1% coal sulfur

3 + 1 SCR Design with 3 Layers of Catalyst Installed

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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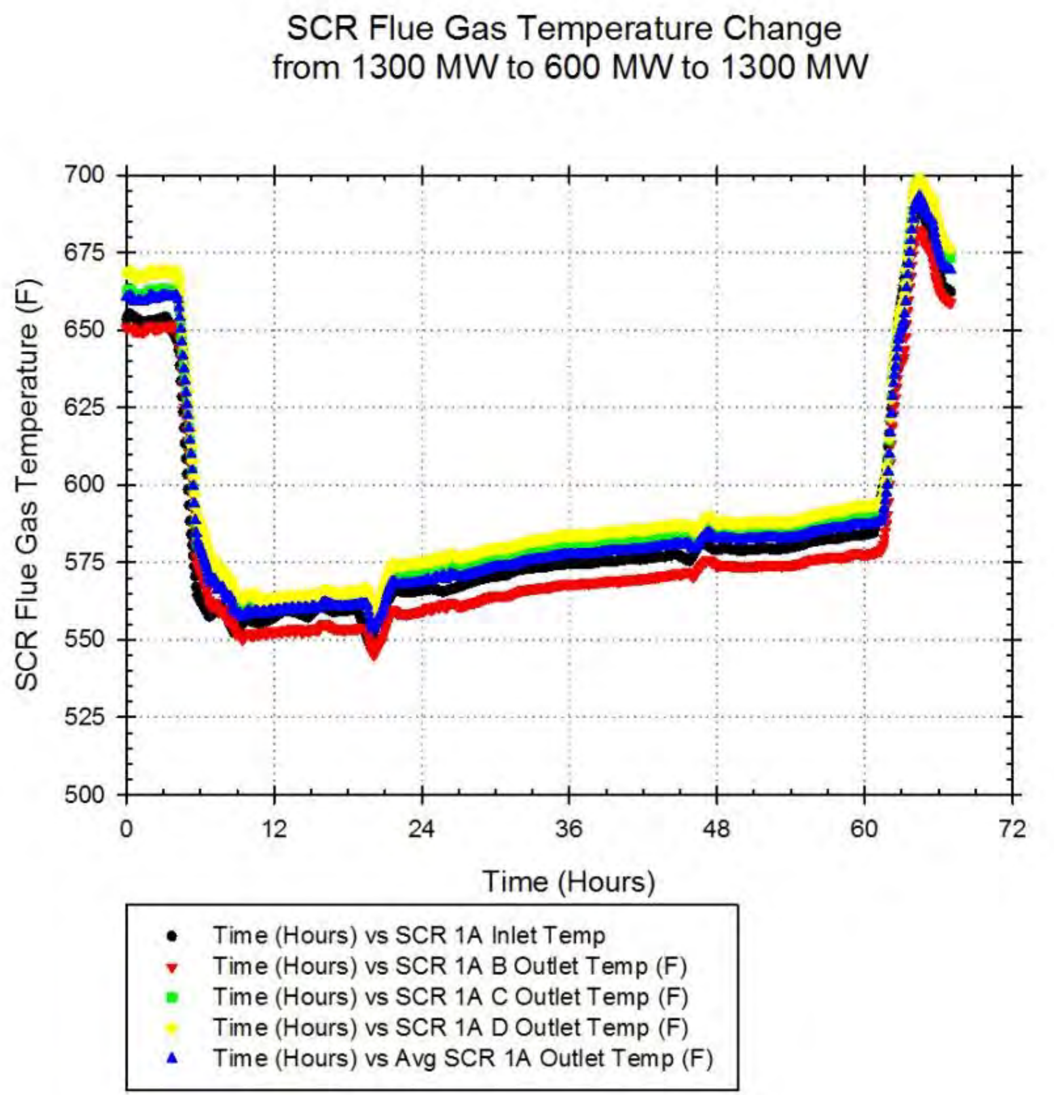
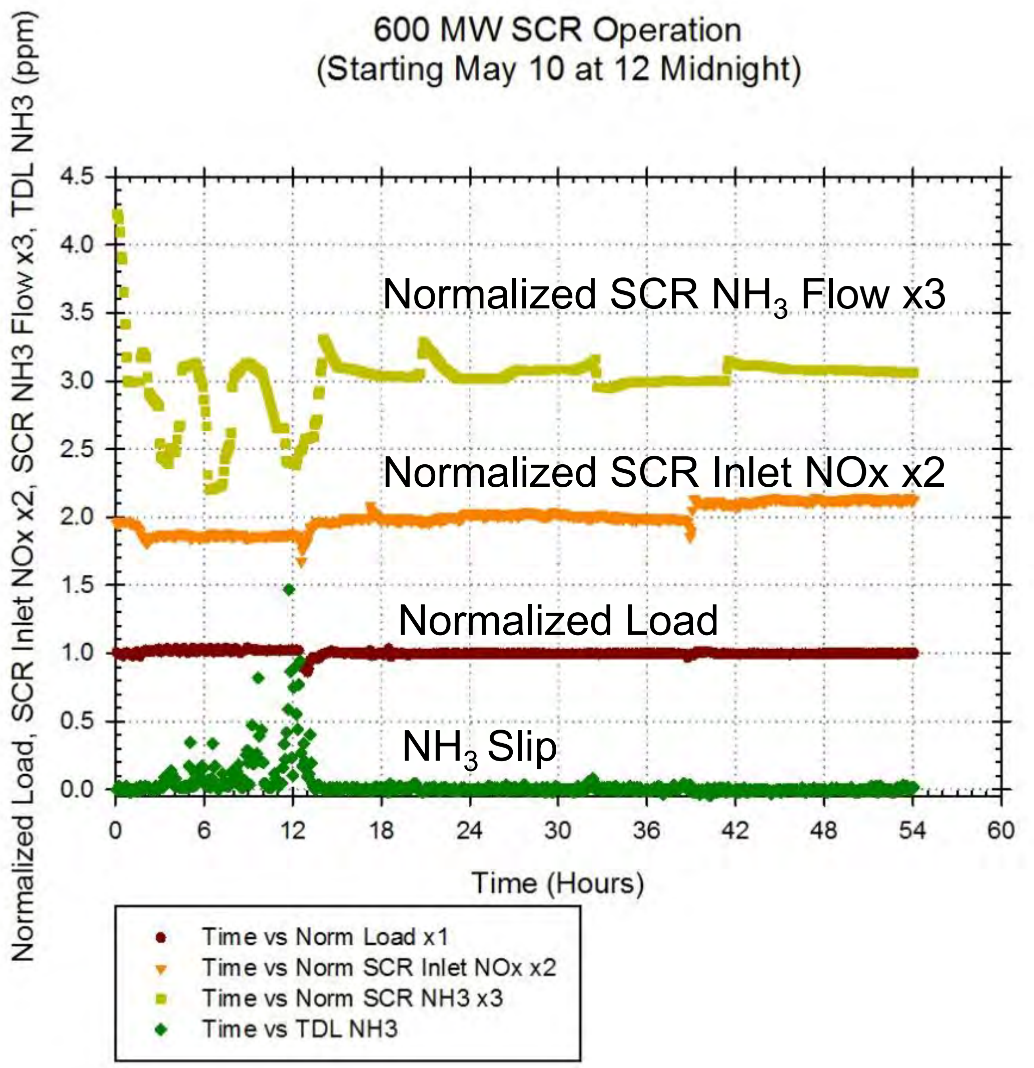
SCR Inlet Temperature

- 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



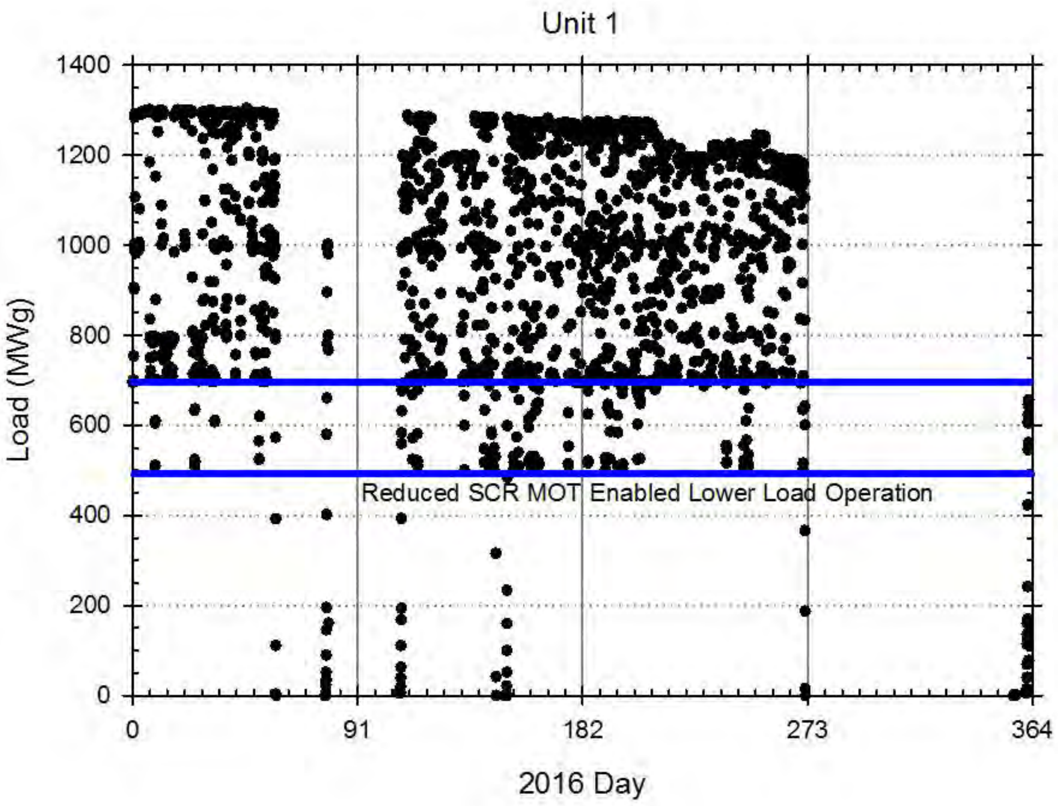
SCR 600 MW Operation



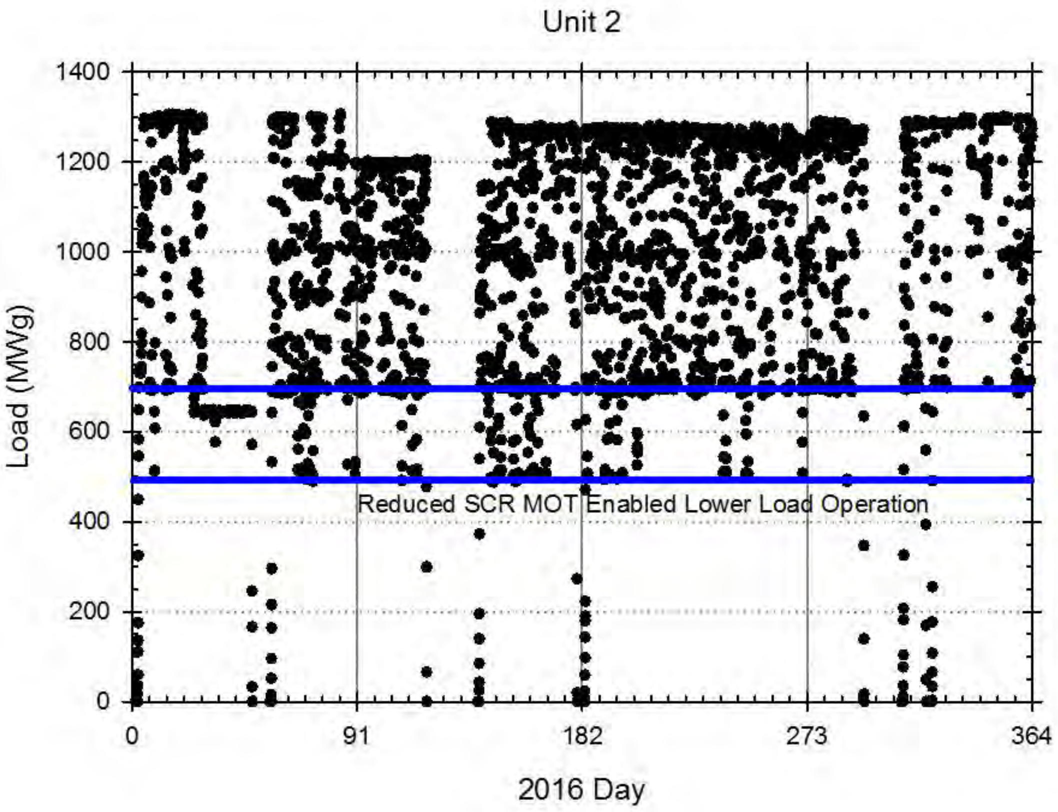
Case Study 1 Summary

- SCR operation maintained 90% ΔNOx at 600 MW and 500 MW
  - Unit fired nominal 2.1% sulfur coal (nominal 14 – 16 ppm SO_3 at SCR inlet)
  - Flue gas temperatures ranged from 550 – 590 F over a 54 hour time period
  - No changes in ΔNOx noted across first catalyst layer
- Full load SCR performance after reduced load test identical to performance at outset of tests
- TDL ammonia slip measurements exhibited levels less than detection limit throughout test
- Measured data supports current assessments of ABS bulk and capillary condensation temperatures associated with SCR inlet reduced load conditions
- At 500 MW other boiler operations limit further load reductions

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

Case Study 2

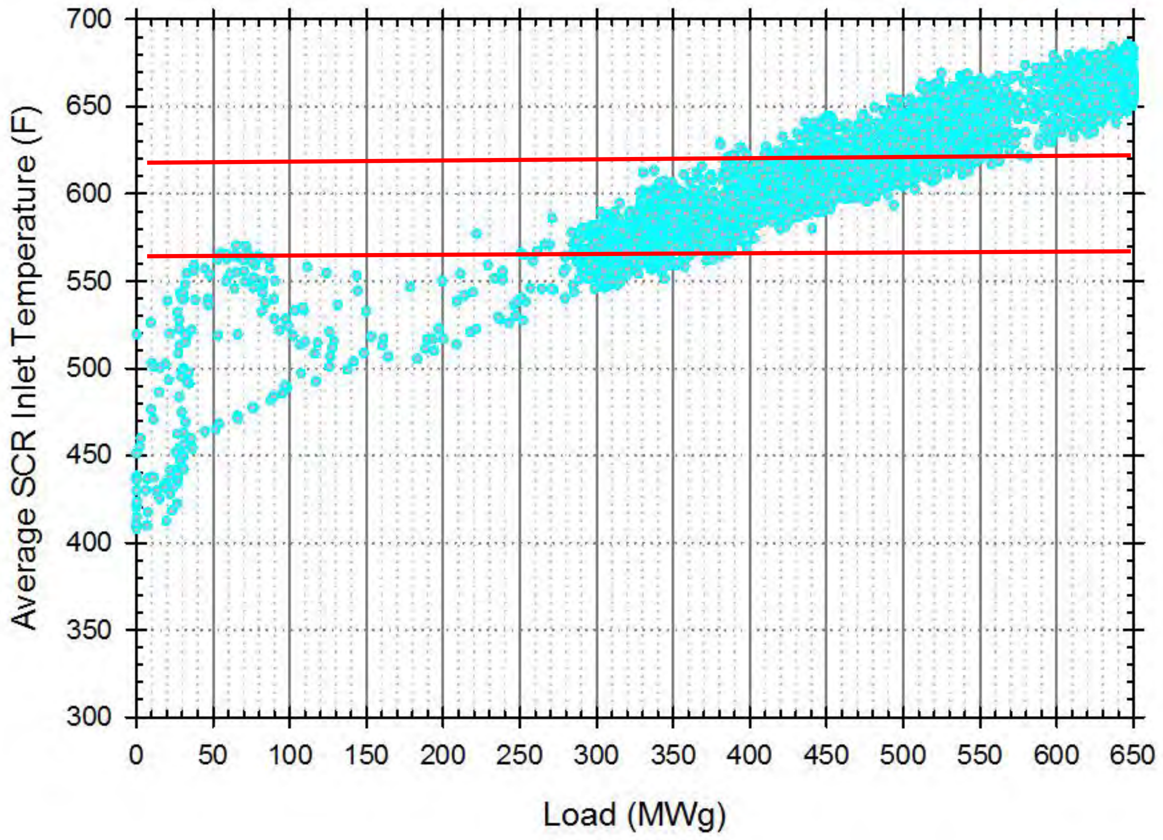
650 MW Opposed Wall Fired Unit

2.7% coal sulfur

3 + 1 SCR Design with 3 Layers of Catalyst Installed

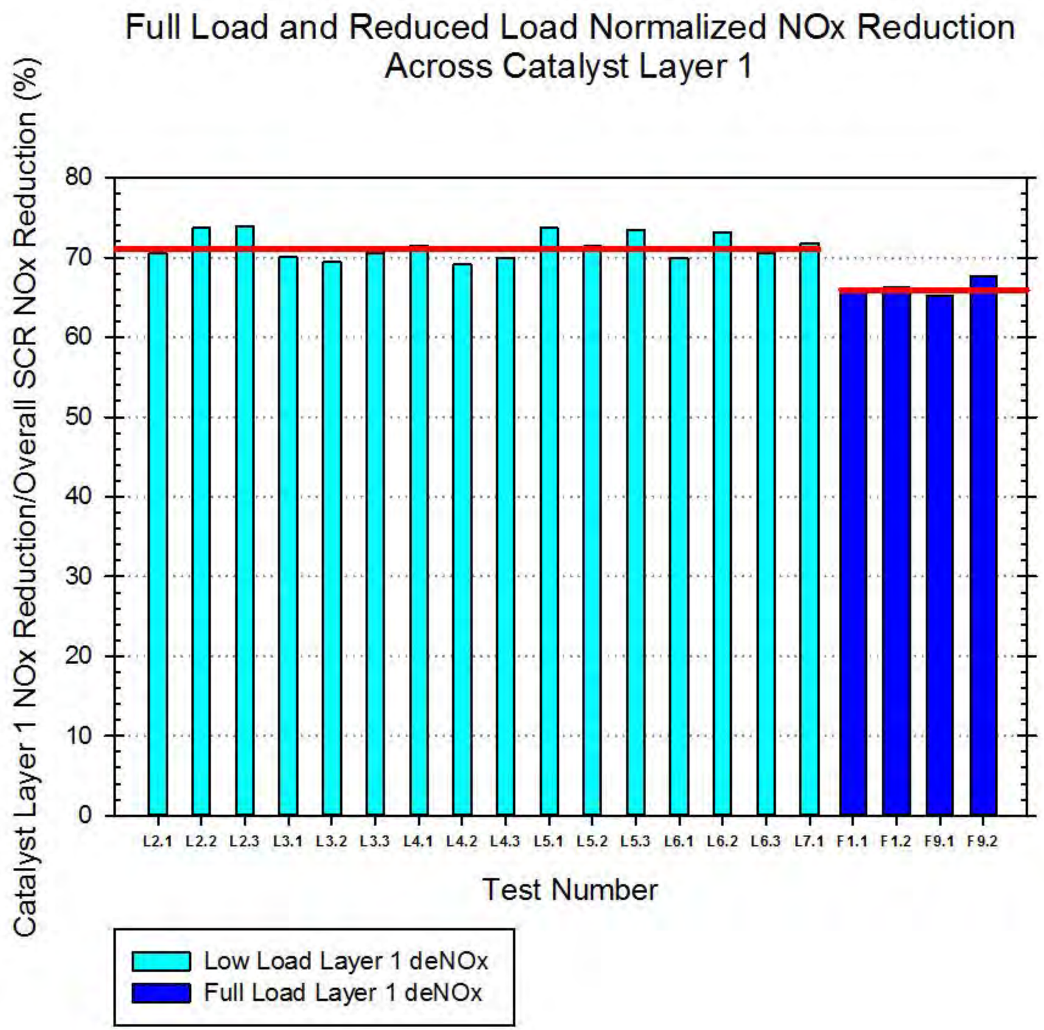
Case Study 2 Summary

- 650 MWg unit firing 2.74% sulfur coal
  - Retrofit with 3 + 1 SCR design in 2010
  - Original catalyst during test in 2015
  - SCR operational restrictions begin at temperatures < 625°F
  - SCR operated at 346 MWg and 573°F
- Unit operated 54 hours at 52% MCR (2 BFP minimum load)
  - ABS potential of ~3,120 ppm^2
    - 21 ppm SO_3 at SCR inlet
    - 201 ppm NOx at SCR inlet
    - 74% SCR ΔNOx
    - 52 ppm NOx at SCR outlet (0.072 lb/Mbtu)
  - Maintained same SCR outlet NOx as full load



Case Study 2 Full Scale Test Results

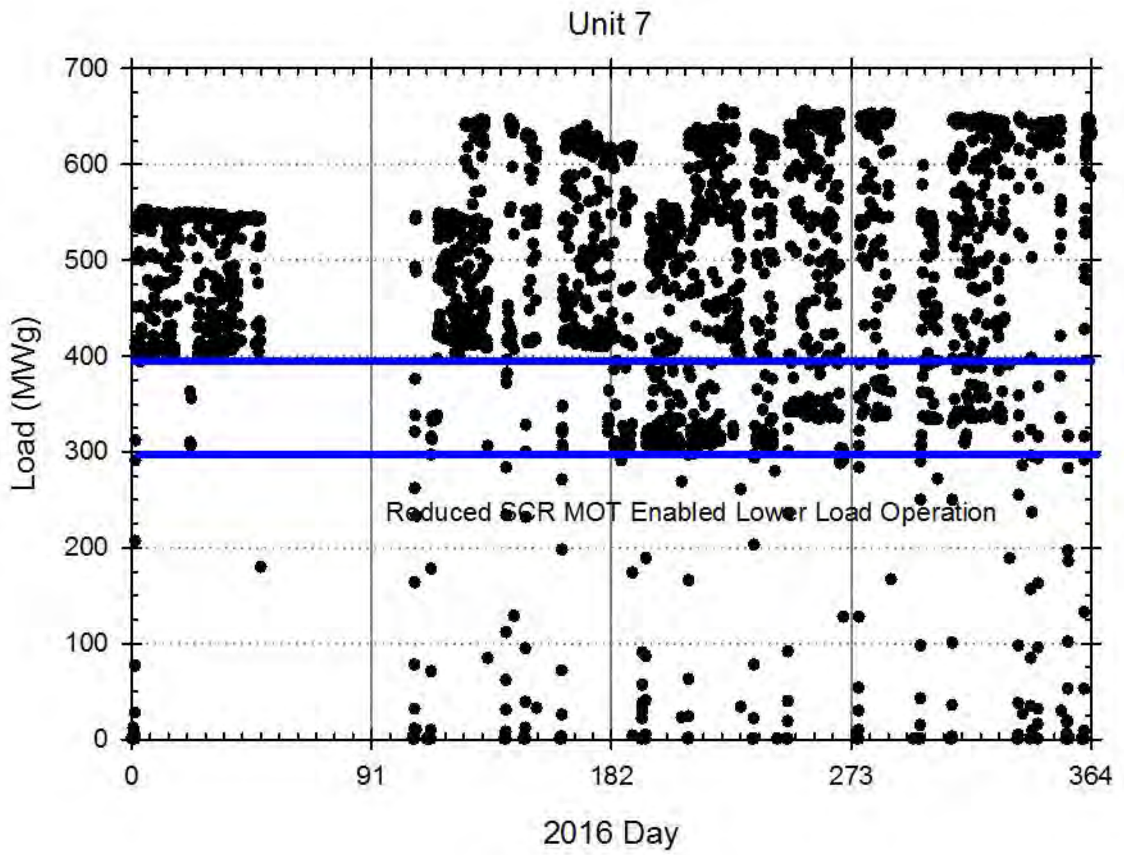
- No catalyst performance impact observed over test duration at reduced load
  - Average 52.6% ΔNOx across layer 1 (71% of total ΔNOx)
  - 74.1% average overall SCR ΔNOx
- Normal ramp to full load evidenced a brief increase in SO_3 levels at SCR outlet
- Full SCR recovery after 2 - 4 hours of operation at full load based on SCR outlet SO_3 measurements
- Plant has extended reduced load SCR operation beyond 54 hours at conditions tested



Confirmation of lab test results with full scale demonstration tests

Extended Operating History Post Demonstration

2016 Operation



SCR outlet NOx ~ 0.09 lb/MBtu

773 hours at loads at reduced SCR MOT between 300 – 400 MW

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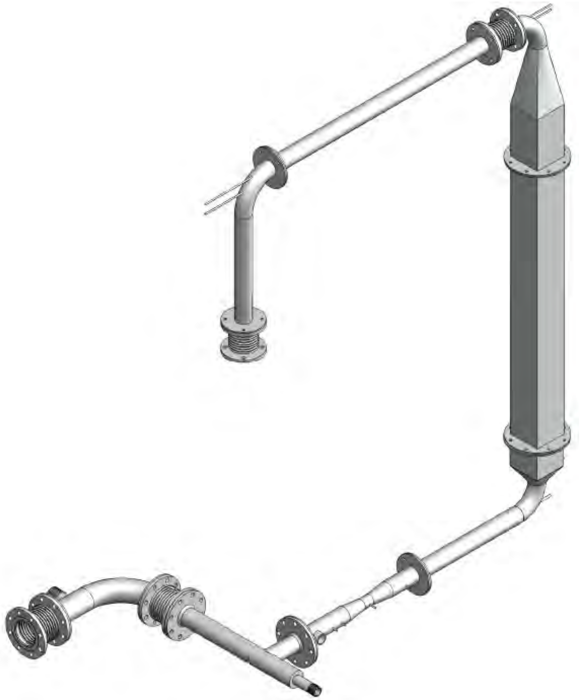
Summary

- UCI experiments provide more accurate/precise assessment of ABS formation temperatures
  - ~28°F lower than Matsuda calculation at typical SCR inlet conditions
- Revised ABS formation calculations, lab experiments, and full scale demonstrations suggest SCR operation feasible down to 560°F with ABS potentials <5,000 ppm^2
  - ABS potential decreases along catalyst depth
  - Limited catalyst surface area impact, so long as above bulk ABS formation temperature
- ABS formation observed to be reversible and not permanent
  - Supported by growing length of full scale operating experience
- ABS decomposition and increased SO_3 release from SCR during load ramp can be controlled by rate of temperature increase

EPRI Provides Range of SCR MOT Assessment Approaches

- Site specific measurements to establish SCR inlet NOx, SO_3, and temperature
  - Calculate SCR MOT based on catalyst properties
- Portable catalyst test facility (PCTF)
  - One or two catalyst samples / weekend reduced load test
  - Minimize 'risk' with *ex situ* catalyst specific results
- Full-scale weekend reduced load test
  - Document SCR performance and flue gas conditions
- For even lower loads, evaluating sorbent injection upstream of SCR
  - Reduce SO_3 and ABS formation potential
  - *In situ* catalyst mini-reactor tests



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