REINHOLD ENVIRONMENTAL Ltd.

2015 NOx-Combustion Round Table & Expo Presentations

February 23 & 24, 2015, in Richmond, VA / Hosted by Dominion

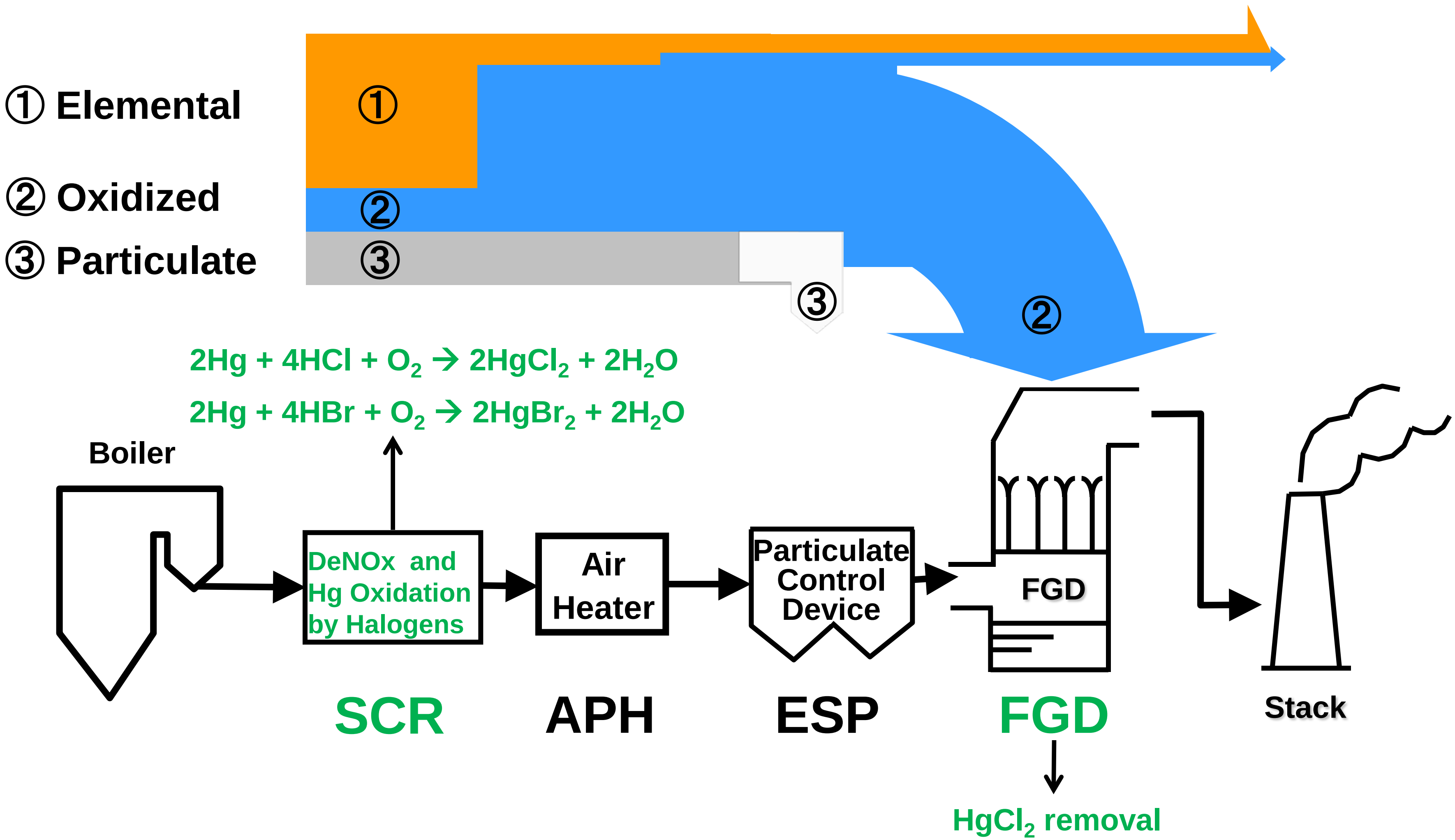
Managing the Utility Fleet for Hg & NOx Reliability

Hal Kruger, FirstEnergy
Scot Pritchard, Cormetech

Presentation Overview

- Mercury / DeNOx Interactions in SCR
- Mercury Capture from Boiler to Stack
- Evaluating Combined DeNOx and SCR Hg Oxidation
- Evaluation of Power Plant Fuel on Hg Emissions
- Mercury Capture Downstream of the SCR
- FirstEnergy's Approach to Evaluation of Combined DeNOx & Hg Oxidation in the SCR
- Case Studies
- Summary

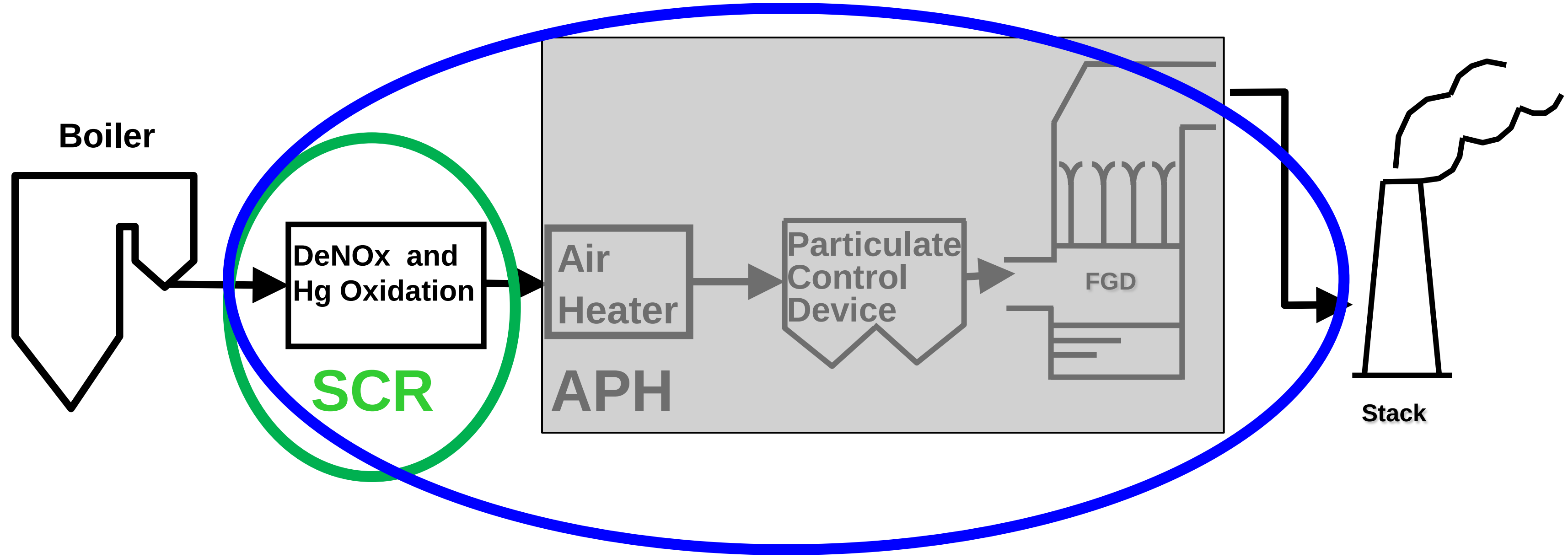
SCR Co-Benefits for Hg Removal



Key Differences for Hg vs. NOx

SCR is One Component of Overall System for Hg

- **DeNOx**
  - SCR Performance Requirements are well defined due to the dominant role of the SCR for NOx reduction
- **Hg**
  - Multiple systems may contribute to Hg control → SCR performance requirements are often not as well-defined yet may be essential for plant compliance



Key Differences for Hg vs. NOx

More Factors Influence Hg Oxidation in the SCR

DeNOx

- Key Factors
  - NOx inlet
  - Efficiency
  - Slip

  (NOx inlet, Efficiency, Slip → ***Performance Threshold***)

  - Temperature
  - O_2, H_2O, SO_2 (lower impact)
  - SO_2 conversion (formulation)
  - Fuel → contaminants → K/Ko
  - Reactor condition

Hg

- Key Factors
  - Hg oxidation → **Performance Threshold**
  - NOx inlet
  - Efficiency
  - Slip

  (NOx inlet, Efficiency, Slip → ***NH_3 (negative impact)***)

  - Layer position (NH_3)
  - Halogen (Fuel or additive)
  - Temperature
  - CO, hydrocarbons
  - O_2, H_2O, SO_2 (can be larger impact)
  - SO_2 conversion (formulation)
  - Fuel → contaminants → K/Ko
  - Reactor condition

Key Differences for Hg vs. NOx

Hg Ox Catalyst Potential, K/AV

- **Hg Oxidation K_{HgOx}/AV defines:**
  - Capacity for X% Hg oxidation
- **Activity, K_{HgOx}, depends on:**
  - Catalyst features and attributes
  - Flue gas conditions (+HCl, HBr, NH_3, CO, SO_2, HC)
- AV = Area Velocity = (Gas Flow) / (Total GSA)
- First order rate equation can be applied for Hg oxidation tests

→ This K value can be strongly condition and layer dependent

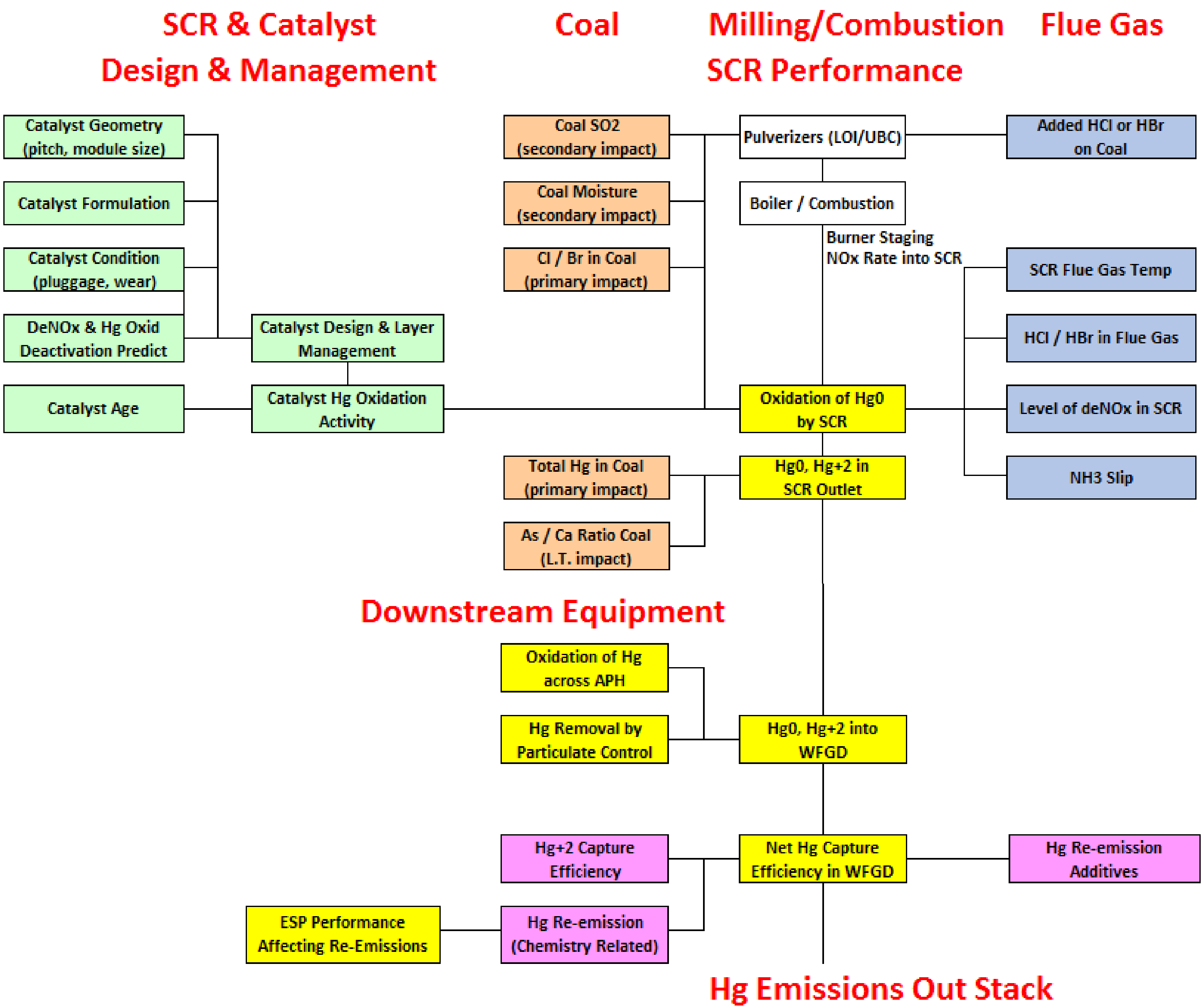
$$\frac{K_{HgOx}}{AV} = -\ln\left[1 - \eta_{HgOx}\right]$$

$$\eta_{HgOx} = fraction\ of\ Hg^0\ oxidation$$

Presentation Overview

- Mercury / DeNOx Interactions in SCR
- Mercury Capture from Boiler to Stack
- Evaluating Combined DeNOx and SCR Hg Oxidation
- Evaluation of Power Plant Fuel on Hg Emissions
- Mercury Capture Downstream of the SCR
- FirstEnergy's Approach to Evaluation of Combined DeNOx & Hg Oxidation in the SCR
- Case Studies
- Summary

Key Factors Impacting Hg Emissions with Co-Benefits



FirstEnergy's Mercury Oxidation & Capture Model

INPUTS **10.0** Coal Hg, lb/Tbtu

10% % Oxidized Hg Into SCR

ILLUSTRATIVE EXAMPLE: NOT AN ACTUAL UNIT

Coal Input | Catalyst Model | FE Empirical Data

SCR — AIR HEATER — ESP — WFGD

	SCR	AIR HEATER	ESP
Oxidation Efficiencies	90% (Hg^0 to Hg^{+2})	20%	10%

Hg Adsorbed on Ash - % Hg^0 **5%**

Hg Adsorbed on Ash - % Hg^{+2} **10%**

96% WFGD Scrubber Efficiency, Hg^{+2}

2% % Hg Re-emissions (MRE)

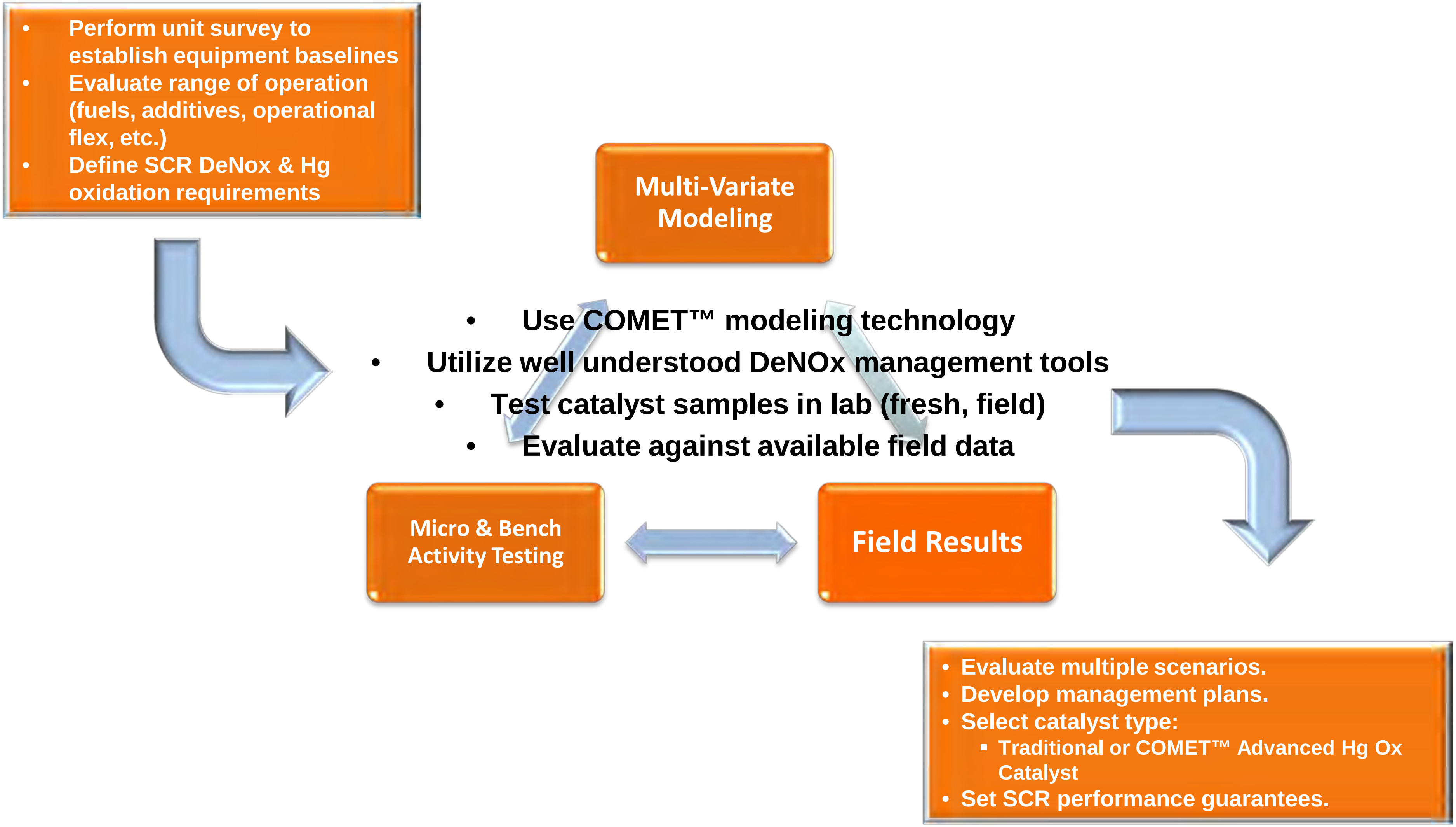
Flue Gas lb/Tbtu	SCR In	SCR Out	AH Out	ESP In	ESP Out	% Hg Total Oxid	WFGD Out (No MRE)	Stack (With MRE)
Hg^{+2}	1.00	9.10	9.28	8.35	8.42	93.2%	0.34	0.34
Hg^0	9.00	0.90	0.72	0.68	0.62		0.62	0.78
Hg^p	0.00	0.00	0.00	0.00	0.00		0.00	0.00
Hg^T	10.00	10.00	10.00	9.04	9.04		0.95	1.12
Hg^T in Ash				ash 0.96				

Presentation Overview

- Mercury / DeNOx Interactions in SCR
- Mercury Capture from Boiler to Stack
- Catalyst Management Methodology
  - Overview of Approach
  - Design requirements/options
  - Evaluation Tools
  - General Considerations
- Evaluation of Power Plant Fuel on Hg Emissions
- Mercury Capture Downstream of the SCR
- FirstEnergy's Approach to Evaluation of Combined DeNOx & Hg Oxidation in the SCR
- Case Studies
- Summary

COMET™

An Integrated Approach to Solutions



SCR Catalyst Design

Understand Needs and Options

- **Hg in Coal**
- **Halogen in coal**
- **Define Hg oxidation needed by the SCR, and assess vs. what can be achieved considering;**
  - **DeNOx and SO_2 oxidation targets**
  - **Temperature and gas composition**
    - Hg, NOx, NH_3, O_2, H_2O, CO, SO_2, HCl, HBr
  - **Catalyst selection/options (by layer)**
    - Traditional Catalyst
    - Advanced Hg Oxidation Catalyst
  - **Assess capability and impacts associated with reduction or addition of supplemental technologies**

SCR Catalyst Design

Understand Needs and Options

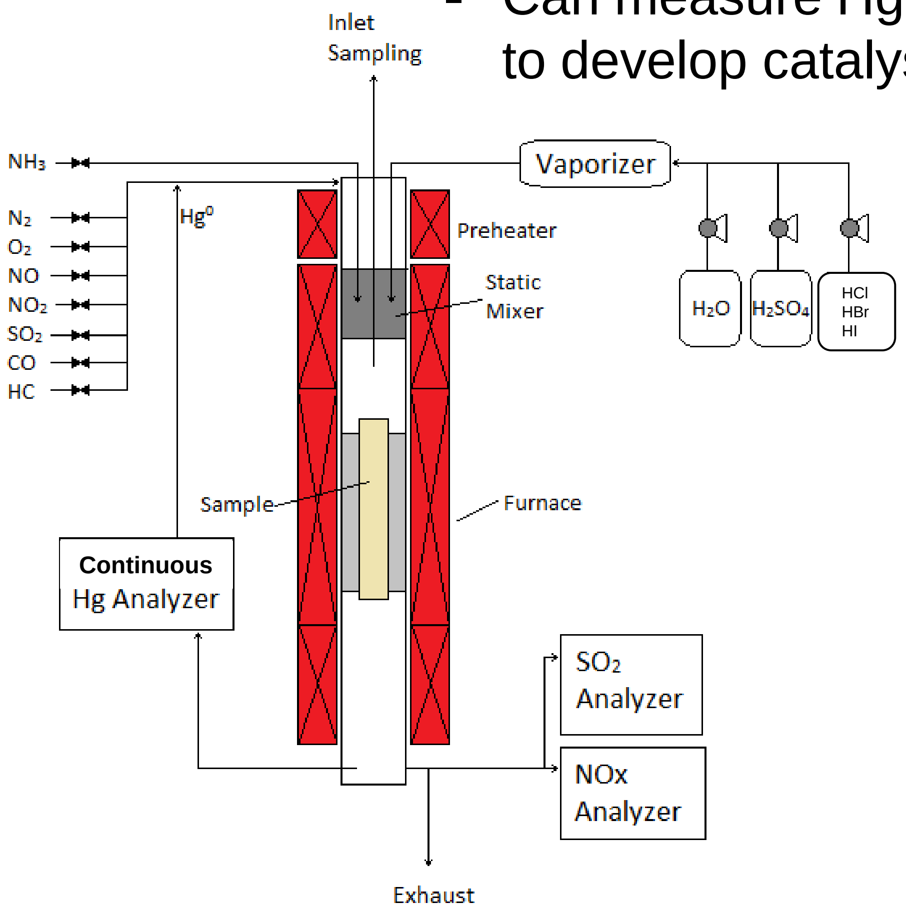
- **Hg can be Analogous to DeNOx…**
  - *With the caveats for K_{HgOx} previously outlined*
  - *f(NH_3, age, flue gas conditions, formulation, etc.)*
- **DeNOx or Hg oxidation may or may not be aligned**
  - *Depends on the relative catalyst potential and performance requirements for each reaction*

Tools for Evaluation

- **Laboratory Testing**
  - Fresh & aged catalyst characterization
  - Model development & Case study validations
- **Modeling**
  - Scenario analysis
- **Field Testing**
  - Qualify data
  - Compare/contrast with lab (DeNOx and Hg)
  - Assess applicability for future arrangements (reactor, additives, other equipment)

Multi-Variate Test Reactor

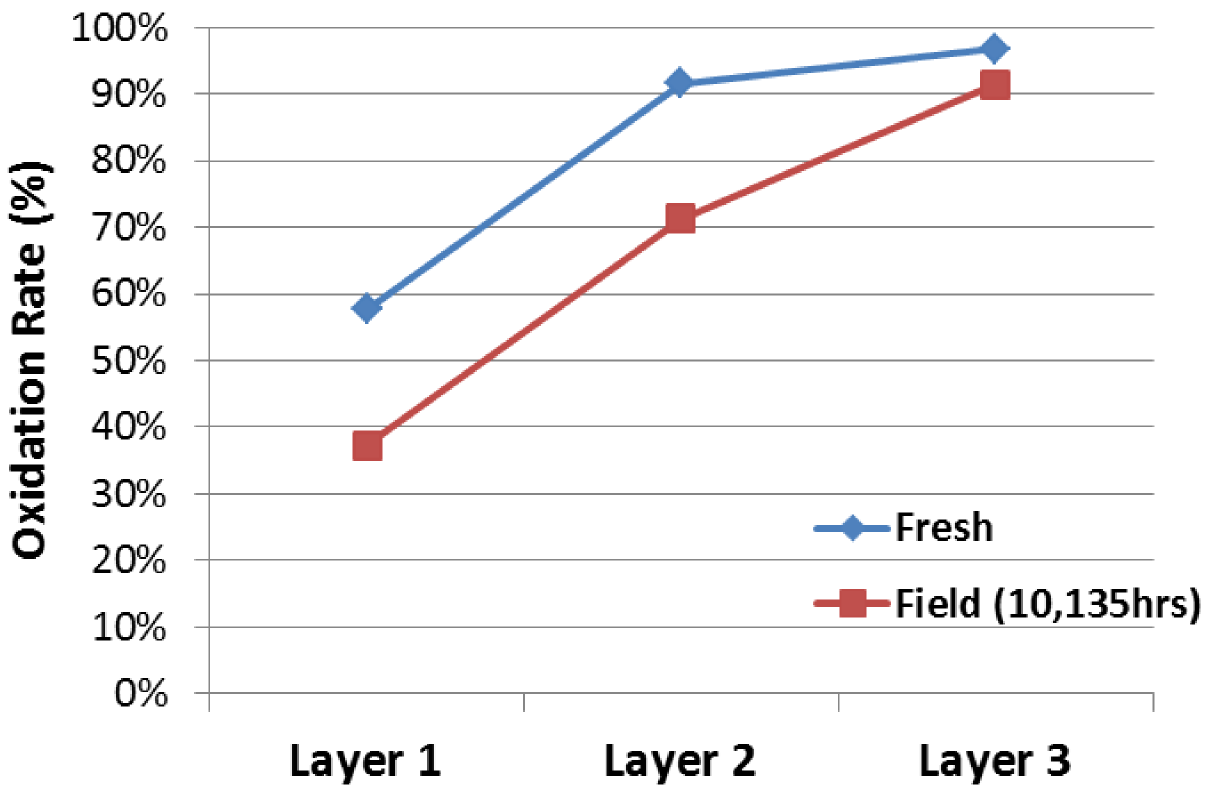
- Versatile and fully-automated for efficient data collection. CEMS for Hg, NO_x, SO_2.
- Can measure Hg oxidation under a full range of conditions to develop catalysts and assist w/ management strategies.



Full Bench Reactor
System Integrated Performance

- **Hg oxidation test capability**
  - Validation testing completed
  - Full size element testing
  - Individual element and multi-layer testing
  - Any catalyst type or combination
  - Any catalyst age
  - Controllable HCl/HBr, O_2, H_2O, SO_2, SO_3, NO_x, CO, HC

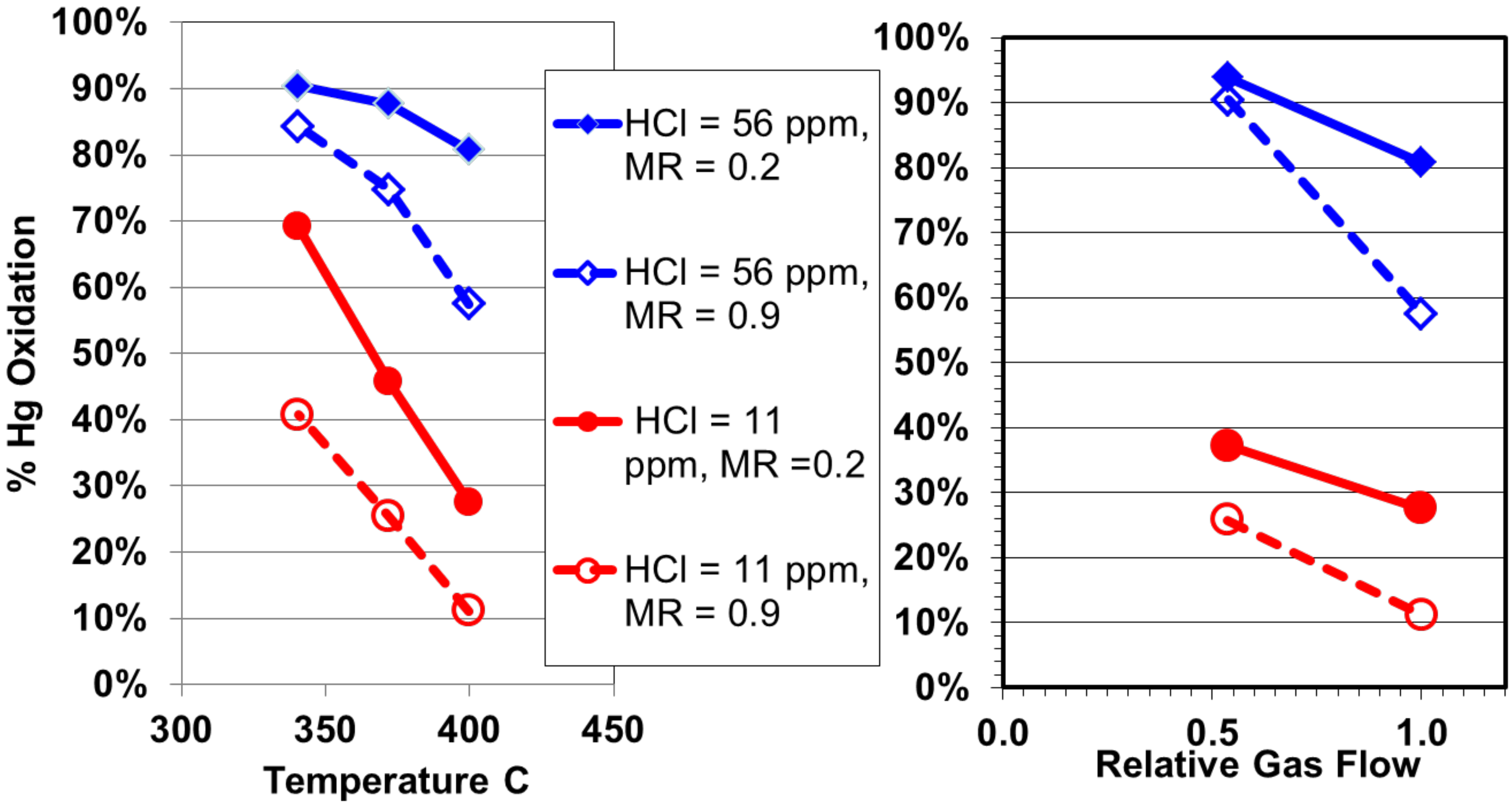
Full Bench System Testing



Integrated system performance and individual layer performance

Understanding Parameter Impacts

(Temperature, Flow, Halogens)



- Highest temperature with highest flow (i.e. Full load) typically design condition.
- Temperature impact more significant than for DeNOx and condition dependent
- Distribution of HCl content must be considered (May result in more than one design condition).
- Catalyst type can demonstrate different sensitivities to parameters

Hg Speciation Impacts

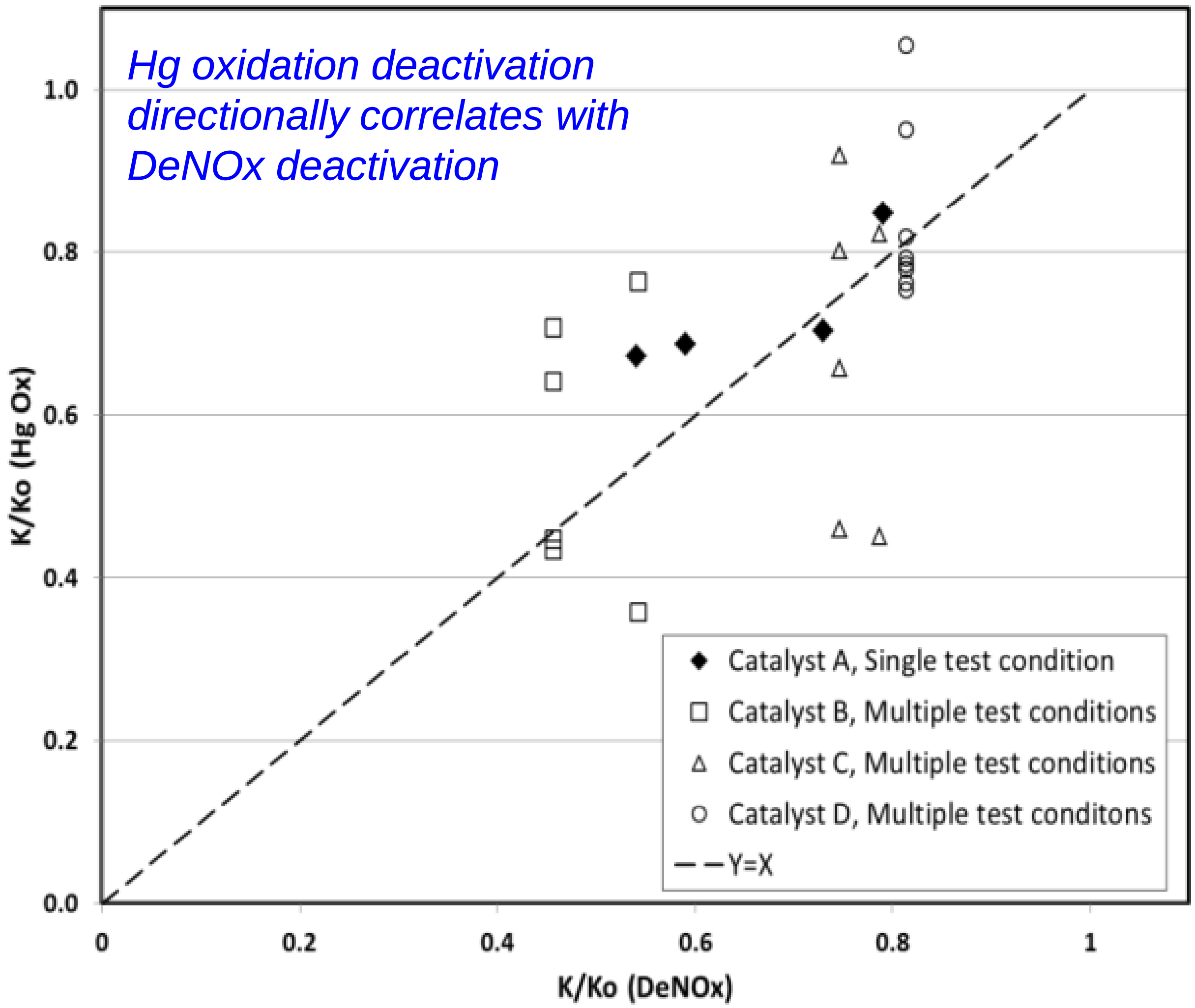
- Nomenclature can cause some confusion…

$$Oxidation\ Rate(\%) = \frac{(Hg^0{}_{in} - Hg^0{}_{out})}{Hg^0{}_{in}} \times 100$$

$$\%Oxidized\ Hg = \frac{Hg^{2+}}{Hg^T} \times 100$$

- Inlet (Hg^{2+} / Hg^T) can impact Hg oxidation rate
  - High (Hg^{2+} / Hg^T) may lower oxidation rate depending on NH_3, CO, SO_2, and Temperature.
  - Highest impact seen on first layer (high NH_3) but can be mitigated by catalyst type.
  - %Oxidized Hg at outlet unchanged or possibly higher.

Deactivation Studies



However, the extent of deactivation for the two reactions may not be equivalent:

K/Ko (Hg Ox.) is sensitive to operating conditions (especially *NH_3, HCl, Temperature*), and catalyst type

Field Measurement Considerations

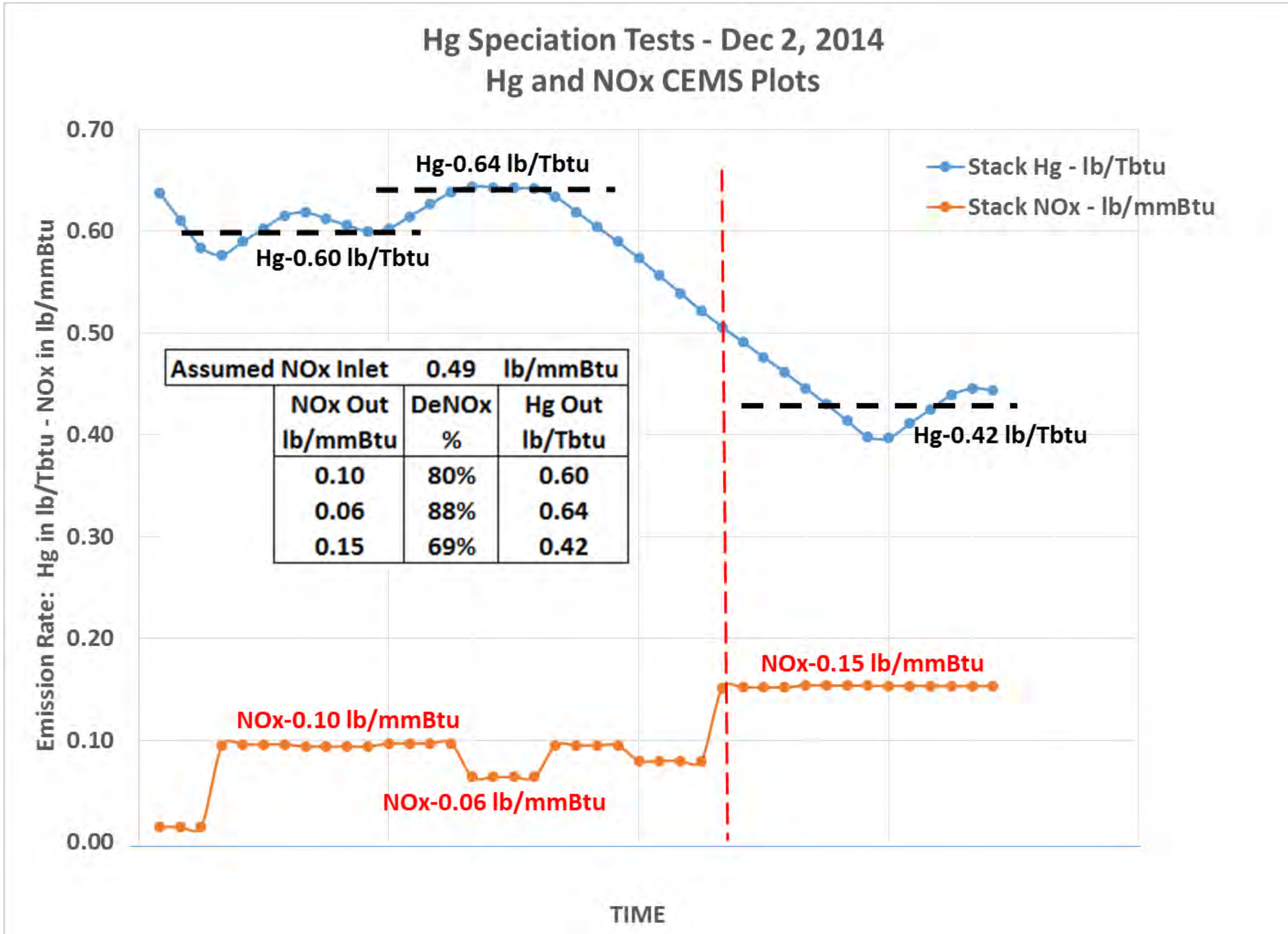
- Ideally, accurate speciated measurements from coal to stack would be obtained:
  - Coal
  - FGD inlet
  - Stack
  - SCR inlet
  - SCR outlet / APH inlet
  - APH outlet / ESP/BH inlet

  (Coal, FGD inlet, Stack:) ***More Reliable Measurements***

  (SCR inlet, SCR outlet / APH inlet, APH outlet / ESP/BH inlet:) ***More Difficult Measurements***

- In practice, accurate speciated measurements in dust laden environments is difficult. Alternate combined approach:
  - Field measurements: coal, ash, FGD retention, stack
  - Laboratory measurements: SCR and possibly APH

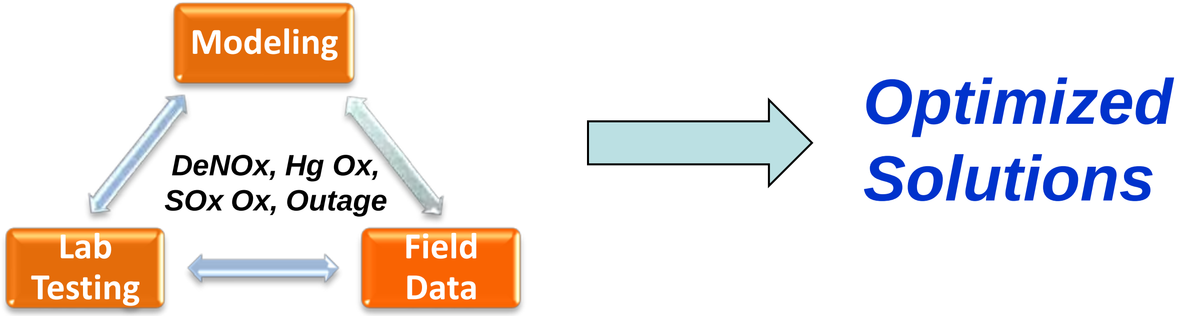
Hg Speciation for Various DeNOx



Assumed NOx Inlet	0.49	lb/mmBtu
NOx Out lb/mmBtu	DeNOx %	Hg Out lb/Tbtu
0.10	80%	0.60
0.06	88%	0.64
0.15	69%	0.42

COMET™ Summary

- **Hg oxidation and DeNOx must be co-managed**
  - Interdependent factors must be considered in setting design conditions
  - Catalyst features and attributes may not be applicable to both functions
- **Lab Testing & Field data improve Modeling Technology**
  - allows us to predict system performance and evaluate options for catalyst actions
- **Advanced Hg Oxidation Catalyst**
  - Option to help improve SCR co-benefit for Hg oxidation



Presentation Overview

- Mercury / DeNOx Interactions in SCR
- Mercury Capture from Boiler to Stack
- Evaluating Combined DeNOx and SCR Hg Oxidation
- Evaluation of Power Plant Fuel on Hg Emissions
- Mercury Capture Downstream of the SCR
- FirstEnergy's Approach to Evaluation of Combined DeNOx & Hg Oxidation in the SCR
- Case Studies
- Summary

Coal Impacts FE Units

Primary Factors Affecting Hg Capture

- Coal Hg (lower better)
- Coal Halogens – Cl, Br (higher better)

Secondary Factors (Can be significant)

- SO2 potential of fuel
- Moisture

Long Term Factor (catalyst poisons)

- Arsenic / Calcium Oxide ratio
- Other catalyst poisons

COLOR LEGEND

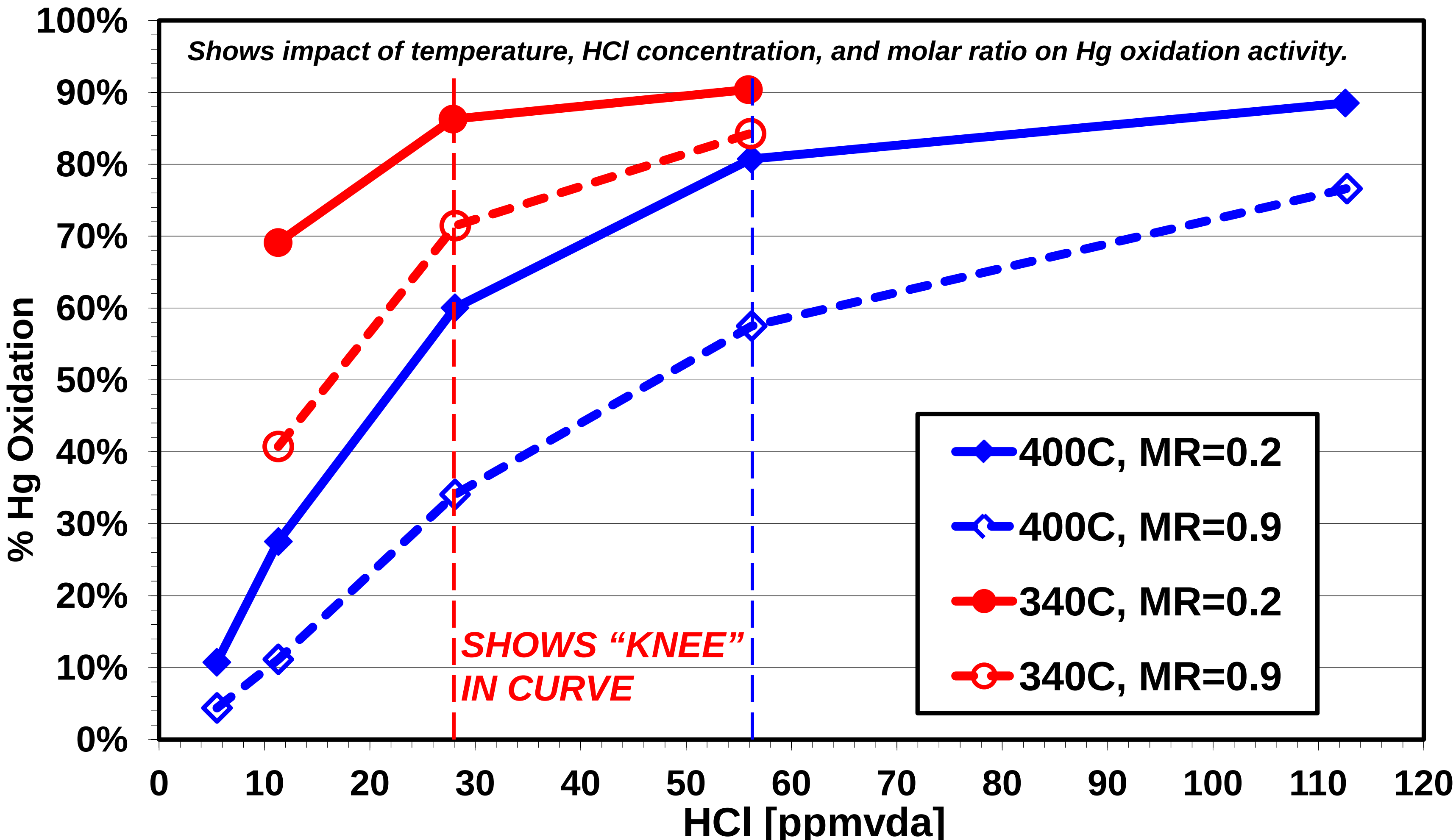
- Green: Good for Hg Capture
- Yellow: Average
- Pink: Potential Limitations for Hg Capture

Typical Coals

	Hg	Cl	HCl Equiv
Fuel Basis	Lb/Tbtu	ppmwd	ppmvd
Plant A	7.0 - 8.0	550-600	39 - 42
Plant B	9.0-10.0	650-750	46 - 53
Plant C	6.0	550	39
Plant D	7.7 - 8.7	600-800	42 - 56
Plant E	9.0 - 10.0	600	42
Plant F	7.5	650	46

Need to determine optimum HCl for good Hg Oxidation. For FE application, best to have at least 50 ppmvd HCl (715 ppm Cl in coal) into SCR. SCR Temp can influence grading

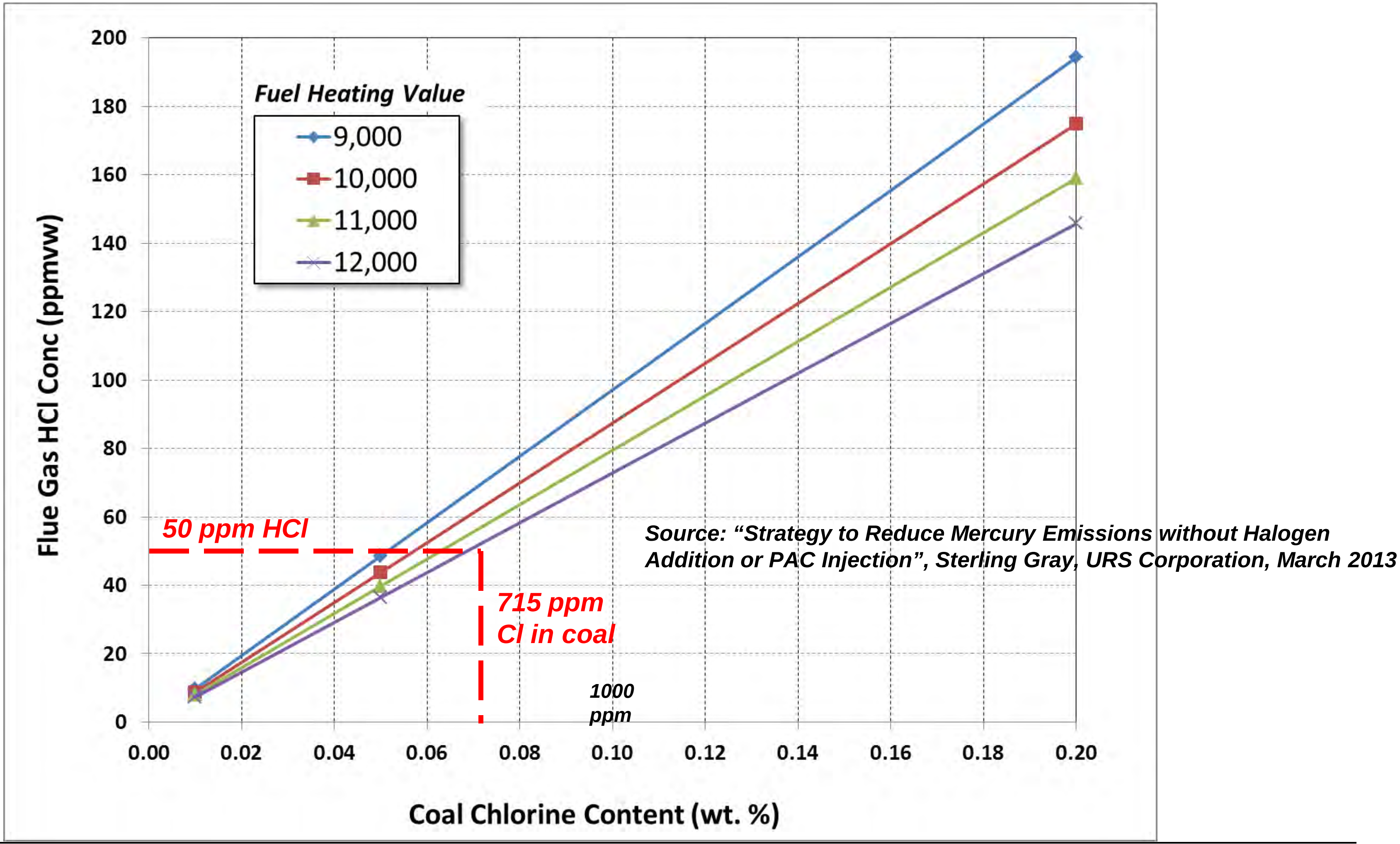
Catalyst Performance Example



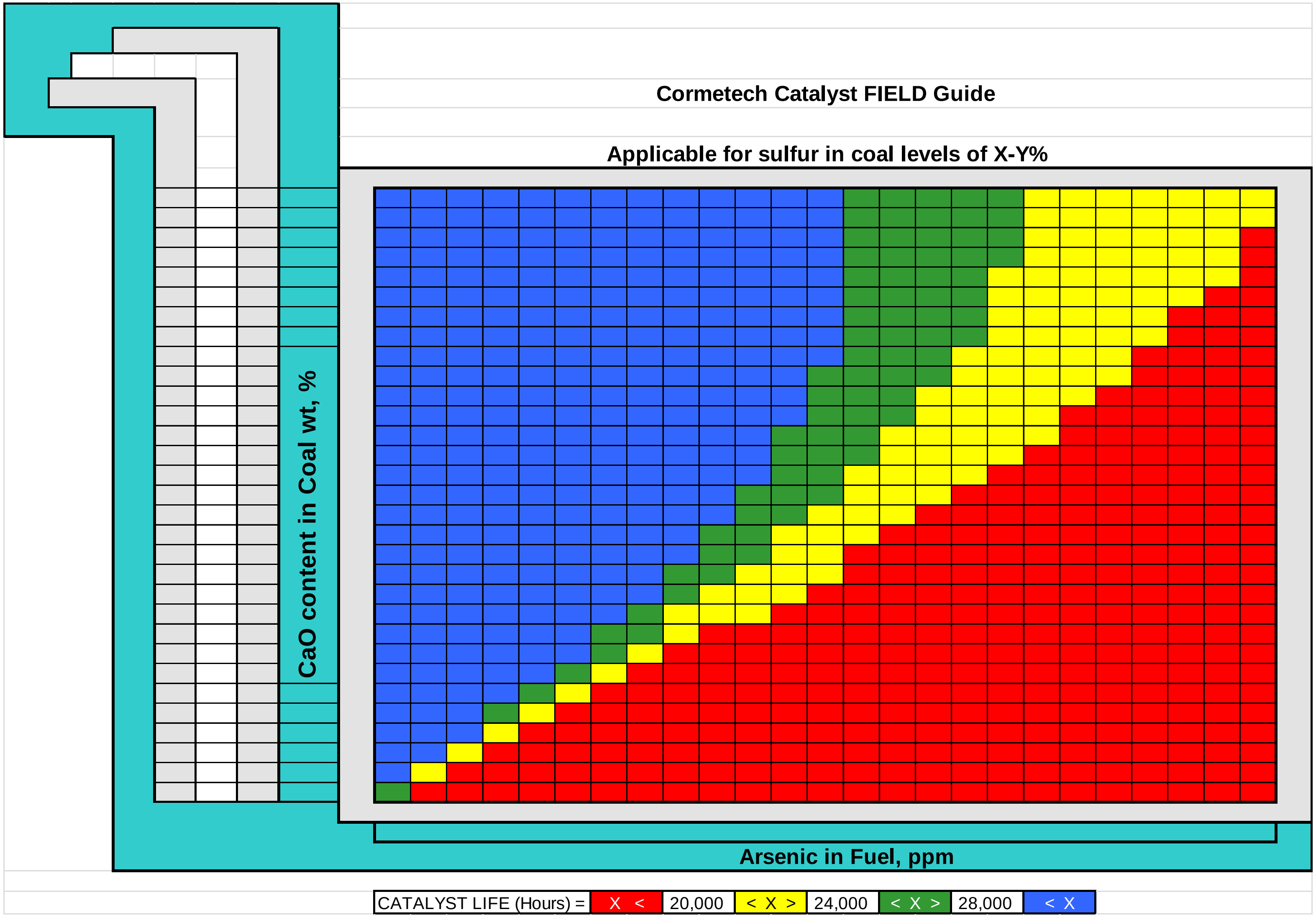
Layer Dependency: MR = 0.9 represents top layer
MR = 0.2 represents a lower layer

Flue Gas HCl vs Coal Chlorine

General Rule: 500 ppmwd Chlorine = 35 ppm HCl
715 ppmwd Chlorine = 50 ppm HCl



Arsenic Poisoning Analysis



Application of Curve Evaluating Arsenic/CaO in Fuel

Example of Analysis for a FirstEnergy Plant

	Coal Mine	SO2 lb/mmBtu	As ppm-dry	CaO in Fuel Wt%	Hg lb/Tbtu	Blend 1 %	Blend 2 %	Blend 3 %	Blend 4 %
HS	Coal A	6.2	7	0.3	7.2	33%		14%	20%
	Coal B	5.1	6	0.1	7.5		38%	39%	45%
	Coal C	3.3	50	0.1	25.5		14%		
LS	Coal D	3.7	5	0.3	8.7	40%	38%	24%	32%
	Coal E	3.4	12	0.1	22.2		7%	9%	
Other	Coal F	4.7	26	0.5	23.0		3%	3%	3%
	Coal G	0.7	1	1.0	7.4	27%		11%	
	Total					100%	100%	100%	100%
	DeNOx Catalyst Life - K-Hours				K Hrs	57	12	30	17
	Average Mercury in Fuel Blend				lb/Tbtu	8.0	12.0	10.8	8.3

A close working relationship between the catalyst team and Fuel Procurement is vital to optimize the combined catalyst/fuel plans

FirstEnergy's Mercury Oxidation & Capture Model

INPUTS **10.0** Coal Hg, lb/Tbtu

10% % Oxidized Hg Into SCR

ILLUSTRATIVE EXAMPLE: NOT AN ACTUAL UNIT

Legend: Coal Input (yellow) · Catalyst Model (green) · FE Empirical Data (orange)

SCR — AIR HEATER — ESP — WFGD

Oxidation Efficiencies	SCR	AIR HEATER	ESP
(Hg^0 to Hg^{+2})	90%	20%	10%

Hg Adsorbed on Ash - % Hg^0 **5%**

Hg Adsorbed on Ash - % Hg^{+2} **10%**

96% WFGD Scrubber Efficiency, Hg^{+2}

2% % Hg Re-emissions (MRE)

Flue Gas lb/Tbtu	SCR In	SCR Out	AH Out	ESP In	ESP Out	% Hg Total Oxid	WFGD Out (No MRE)	Stack (With MRE)
Hg^{+2}	1.00	9.10	9.28	8.35	8.42	93.2%	0.34	0.34
Hg^0	9.00	0.90	0.72	0.68	0.62		0.62	0.78
Hg^p	0.00	0.00	0.00	0.00	0.00		0.00	0.00
Hg^T	10.00	10.00	10.00	9.04	9.04		0.95	1.12
Hg^T in Ash				ash 0.96				

Mercury Capture Downstream of SCR

Areas Evaluated

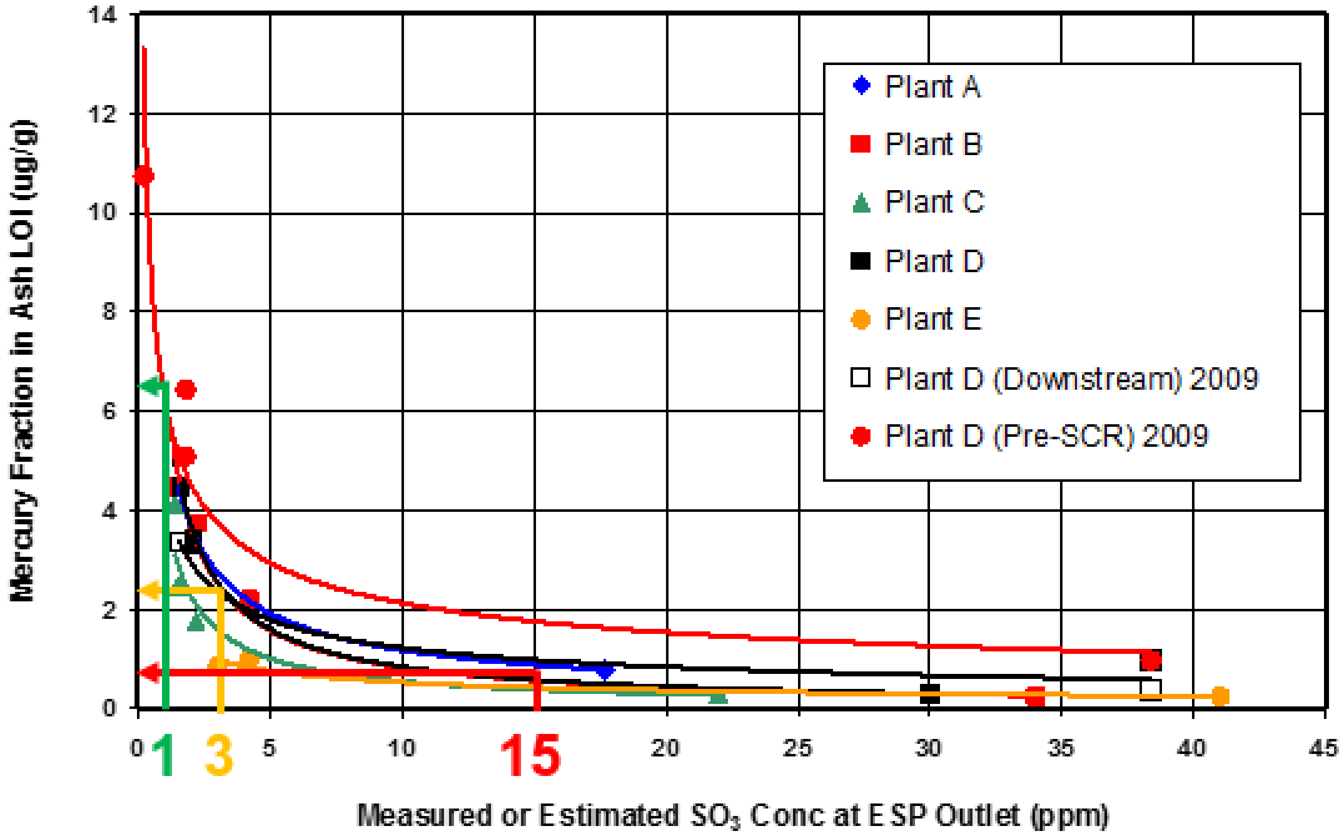
- **Oxidation of Hg across Air Heater & ESP**
- **Adsorption of Mercury on Fly Ash and Removal in ESP & WFGD**
- **Mercury Capture and Re-emissions in WFGD**

Hg Capture Across AH/ESP

- **The Air Heaters typically reduce the Flue Gas Temp from > 600F to 290-325 F depending on the Design and Condition**
- **As the flue gas cools, the following happens in the flue gas**
  - SO_3 is converted to H_2SO_4 and some is captured on the fly ash
  - Total Hg is reduced as Hg adsorbs on to fly ash
  - Oxidized Hg Increases
- **5 Factors affecting Hg capture on the fly ash**
  - **Need SO_3 < 5 ppm at Air Heater Outlet** - the lower SO_3 can give greater capture of Hg on the ash
  - **Need Gas Temps < 350 F** - lower temps can give greater capture of Hg on ash
  - **Need higher levels of LOI or Unburned Carbon** – “poor man’s ACI”
  - **Volume of fly ash**
  - **Halogens (HCl, HBr) in Flue Gas**

Impact of Hg Capture on Ash

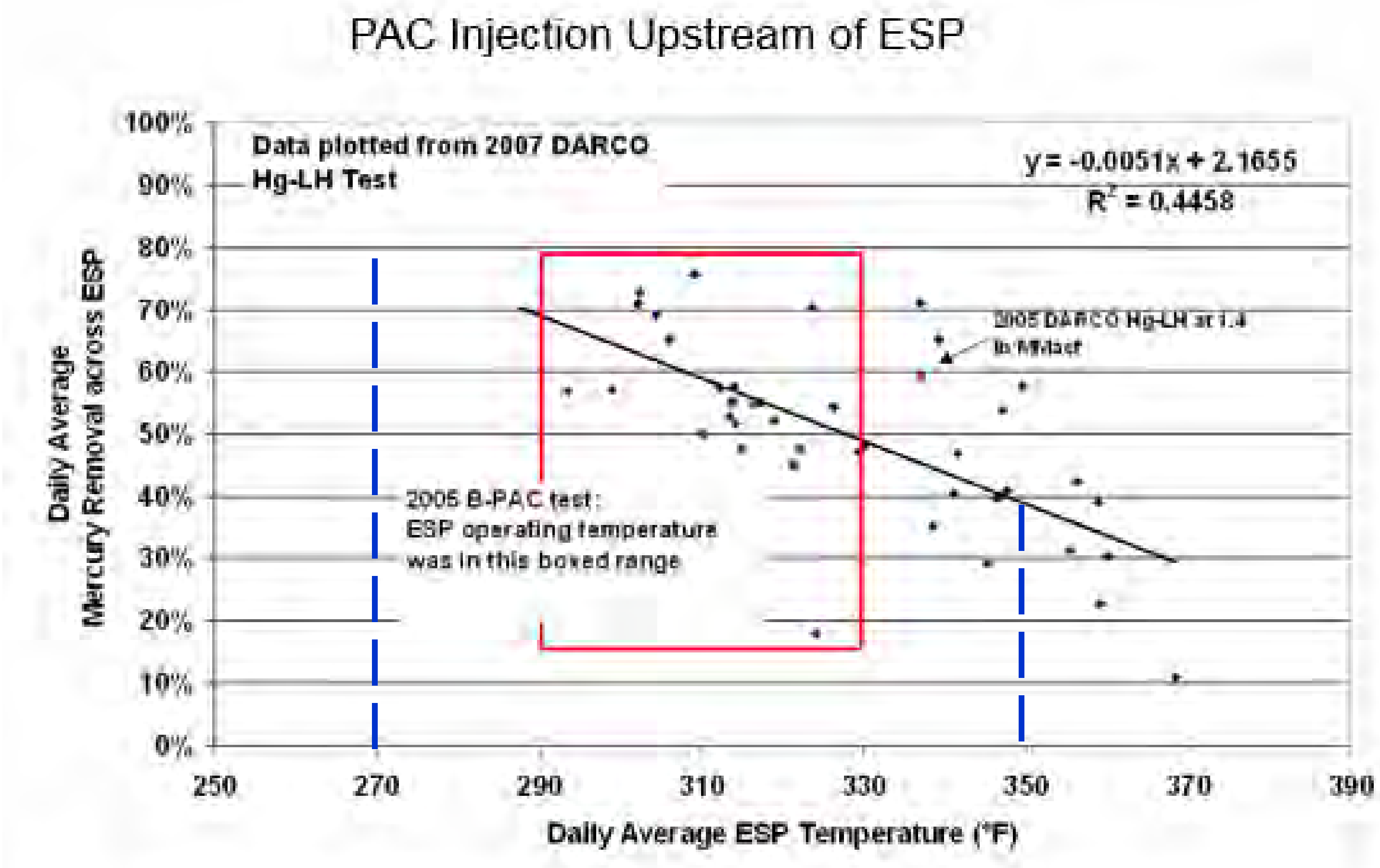
Hg capture improves below 5 ppm SO3 and is significant at 1-2 ppm SO3



Source: "Strategy to Reduce Mercury Emissions without Halogen Addition or PAC Injection", Sterling Gray, URS Corporation, March 2013

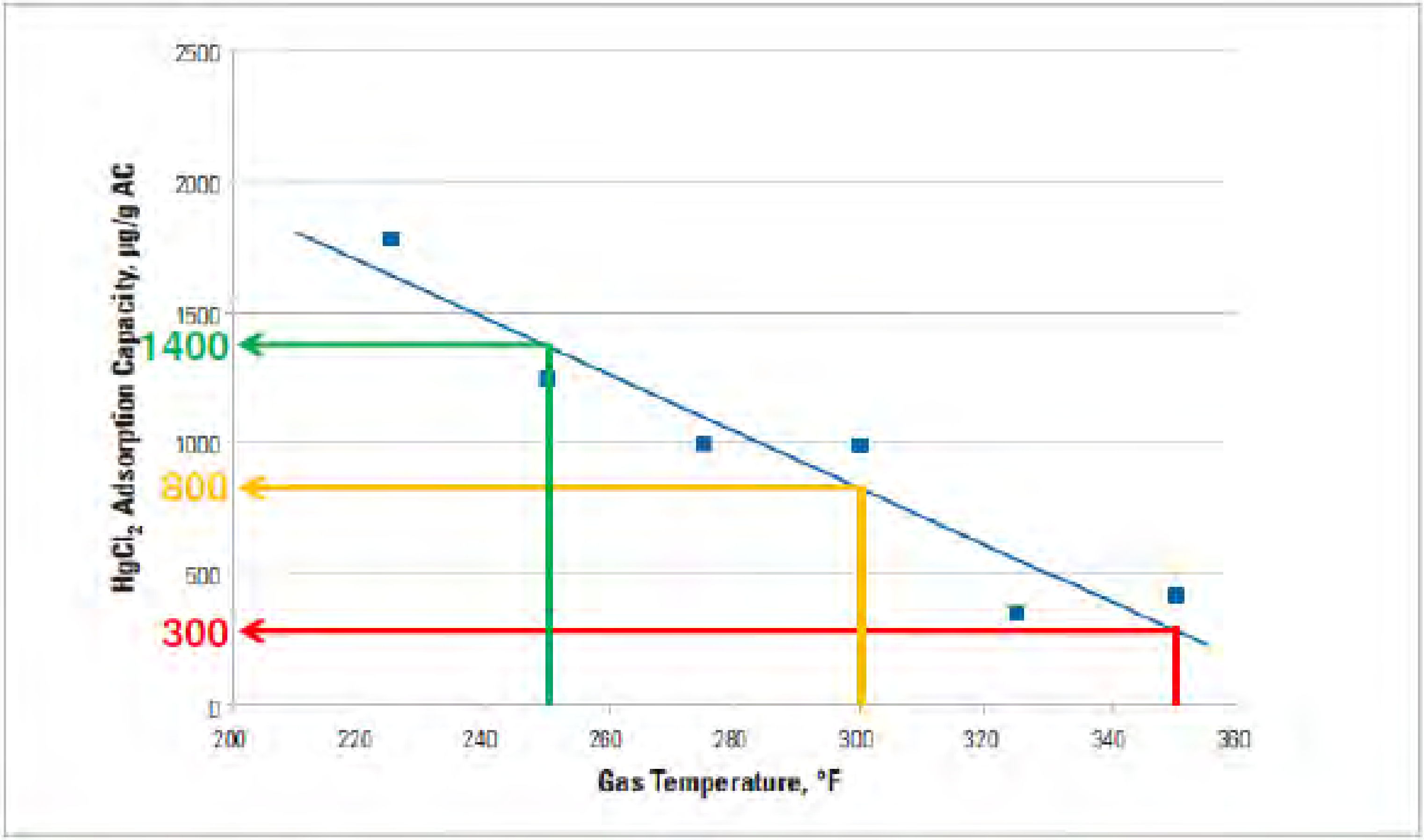
PAC Performance vs Temperature

Looking at Powdered Activated Carbon as a Surrogate for Unburned Carbon on Ash



Source: "Activated Carbon Injection at Stanton Station Unit 1", Richardson, URS, DOE Report, 2008

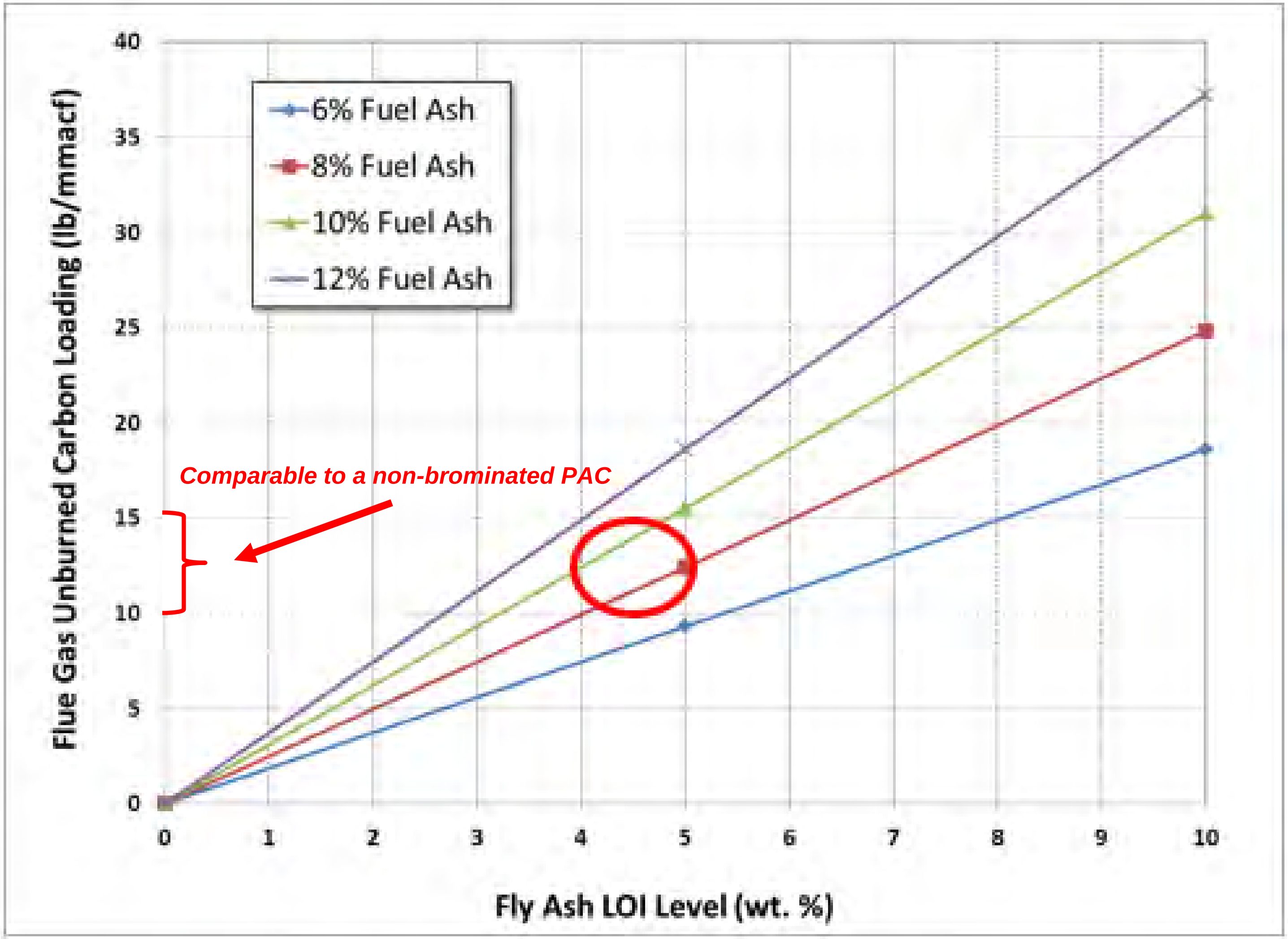
PAC Performance vs Temperature



Adsorption capacity of PAC increases at lower temperature

Source: "Strategy to Reduce Mercury Emissions without Halogen Addition or PAC Injection", Sterling Gray, URS Corporation, March 2013

UBC Loading vs Fly Ash LOI



Source: "Strategy to Reduce Mercury Emissions without Halogen Addition or PAC Injection", Sterling Gray, URS Corporation, March 2013

Hg Capture Across Air Heater/ESP

COLOR LEGEND

- Green: Good for Hg Capture
- Yellow: Average
- Pink: Potential Limitations for Hg Capture

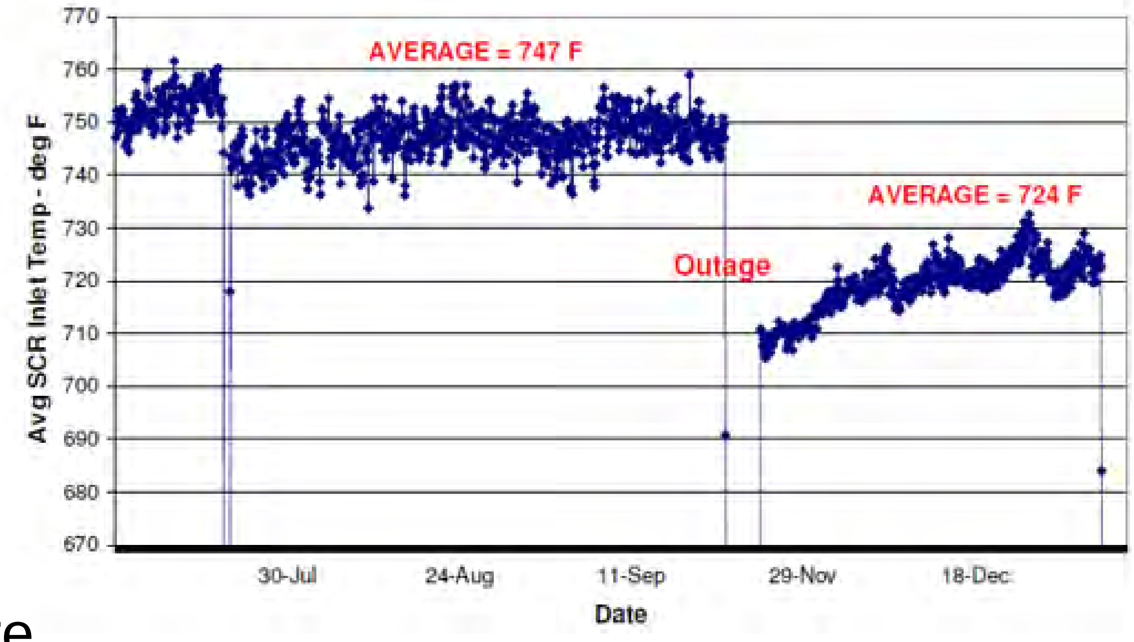
Air Heater Outlet Conditions

	AH Outlet Temp	AH Outlet SO3	AH Outlet LOI or UBC	Ash Loading in Coal	Carbon Loading	Halogens HCl in Flue Gas	Net Effect
	deg F	ppmwd		lb/mmBtu	lb/mmACF	ppmvd	
Plant A	300-340	<5	3-5%	6.6-7.4	8	38-41	Cannot get to 1-2 ppm SO3
Plant B	290-320	> 5	2-6%	9.0-10.0	11	46 - 53	SO3 Limiting
Plant C	290-300	>> 5	5-10%	9.7	20	39	Low HCl-High SO3
Plant D	320-325	<< 5 *	4-7%	7.3-7.5	12	42 - 56	Winter, 1-2 ppm SO3
Plant E	290-300	< 5	3-25%	9.0-10.0	>30	38-43	High LOI, Moderate SO3
Plant F	290-300	< 5	3%	9.0-10.0	8	30-45	Cannot get to 1-2 ppm SO3

* Plant D - with Higher SBS rate can go << 5 ppm

Evaluate Changing Process Conditions

- **Plant conditions change over time affecting Hg capture. Examples:**
  - **Flue Gas Temp into SCR** – cleanliness of convection back pass
  - **Correction of air Inleakage** - raises flue gas temp, reducing Hg capture



-- **Combustion Tuning** – may reduce LOI and reduce Hg capture on fly ash

Hg Capture & Hg Re-emissions in w/FGD

- **Hg Re-emissions**
  - Occurs when oxidized mercury captured in the scrubber liquor converts back to elemental mercury, Hg0.
  - Hg0 has low solubility in the scrubber liquor and is re-emitted.
  - Observed when Hg0 Stack > Hg0 into FGD
- **Hg Capture is a two step process in the scrubber**
  - Step 1: Scrub Oxidized Mercury, Hg+2, from flue gas and collect Hg in scrubber liquor
  - Step 2: If re-emissions occur, add chemicals or sorbents to move Hg from liquor into FGD solids.
  - Tell Tale Signs … Look for higher levels of dissolved Hg in the liquor or higher ORP levels in the FGD.

FirstEnergy's Catalyst Management Team & Approach

FirstEnergy

* Catalyst Program Management
* Field Testing for Hg Speciation
* Optimization of Fuel Blend / SCR Performance
* Evaluate Hg Capture after Air Heater
* Specify Minimum % Hg Oxidation from SCR
* Catalyst Procurement

Coalogix

* Catalyst Management Support
* Catalyst Field Inspection & Services
* Obtains / Manages Catalyst Samples
* Develops NOx Performance Curves

Cormetech

* Catalyst Lab Testing for NOx & Hg Oxidation
* Develops Catalyst Hg Performance Curves Based on Specified NOx Curves

Presentation Overview

- Mercury / DeNOx Interactions in SCR
- Mercury Capture from Boiler to Stack
- Evaluating Combined DeNOx and SCR Hg Oxidation
- Evaluation of Power Plant Fuel on Hg Emissions
- Mercury Capture Downstream of the SCR
- FirstEnergy's Approach to Evaluation of Combined DeNOx & Hg Oxidation in the SCR
- Case Studies
- Summary

Case 1

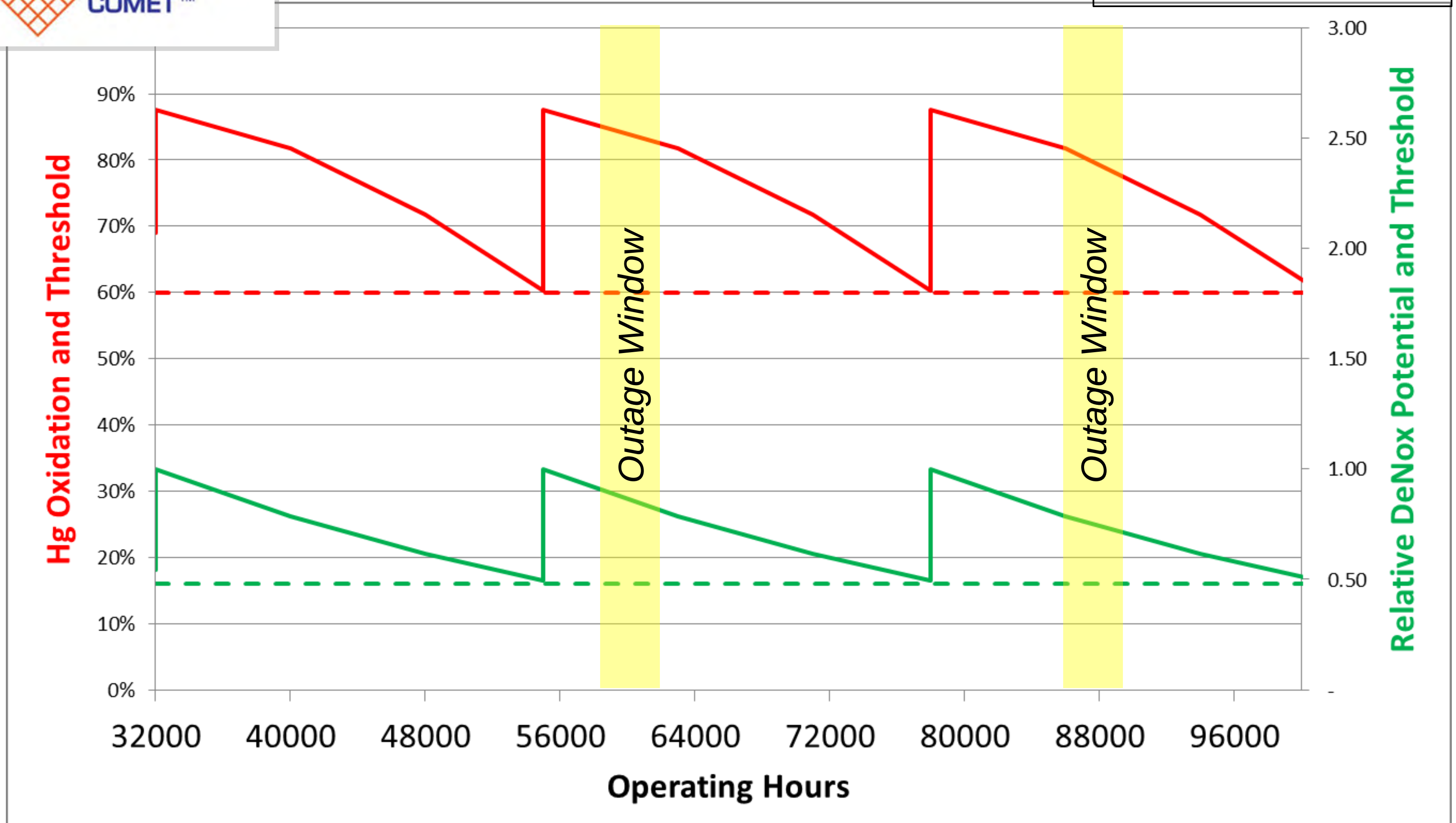
- Background/Input
  - Plant Info
    - E-Bit./PRB, SCR, 2L APH, ESP, LSFO FGD
    - Fuel blending capable, sell ash, moderate LOI, no NOx flex., No ACI
  - SCR
    - 4 layer reactor managed as a 3+0
    - All Catalyst OEM HC – age ~ 32,000 hrs
    - Layer 1 fouling from LPA
  - Targets
    - Based on FE assessment of BOP plant equipment capability, the SCR Hg oxidation target established at 60%
    - DeNOx target established at 84% (could flex to 82%)
    - Target outage cycle established at 3-1/2 years

Case 1

- Analysis
  - New fuel w/ and w/o additive (limestone on coal) to mitigate As poisoning
  - Multiple scenarios analyzed utilizing model & catalyst testing utilizing new and regen catalyst
  - Selected option validated via testing

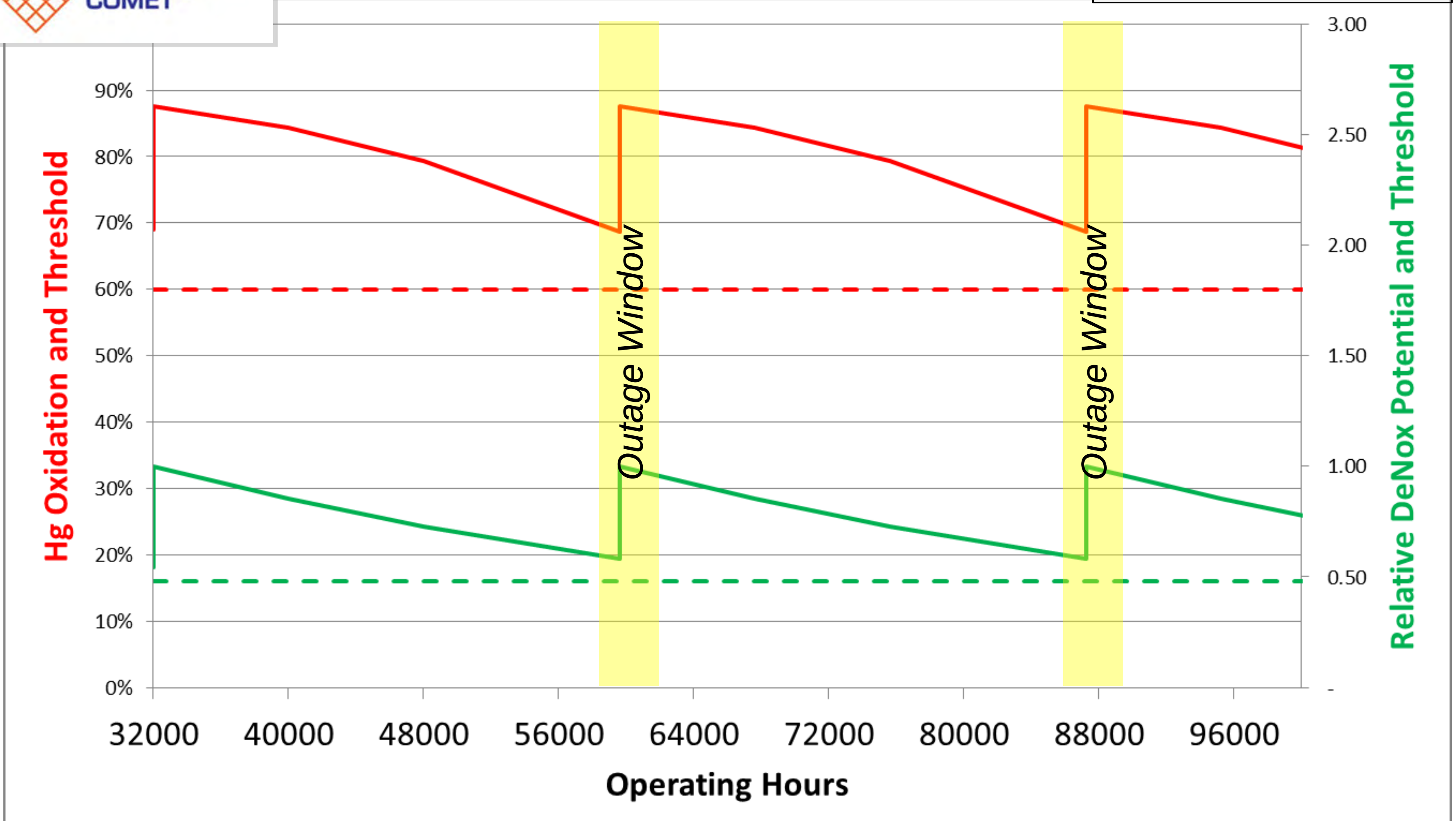
Baseline Management Plan w/ DeNOx Potential & Hg Oxidation

- *DeNOx = 84%*
- *New Fuel Basis*
- *HCl = 32 ppm*
- *3 - layer action*



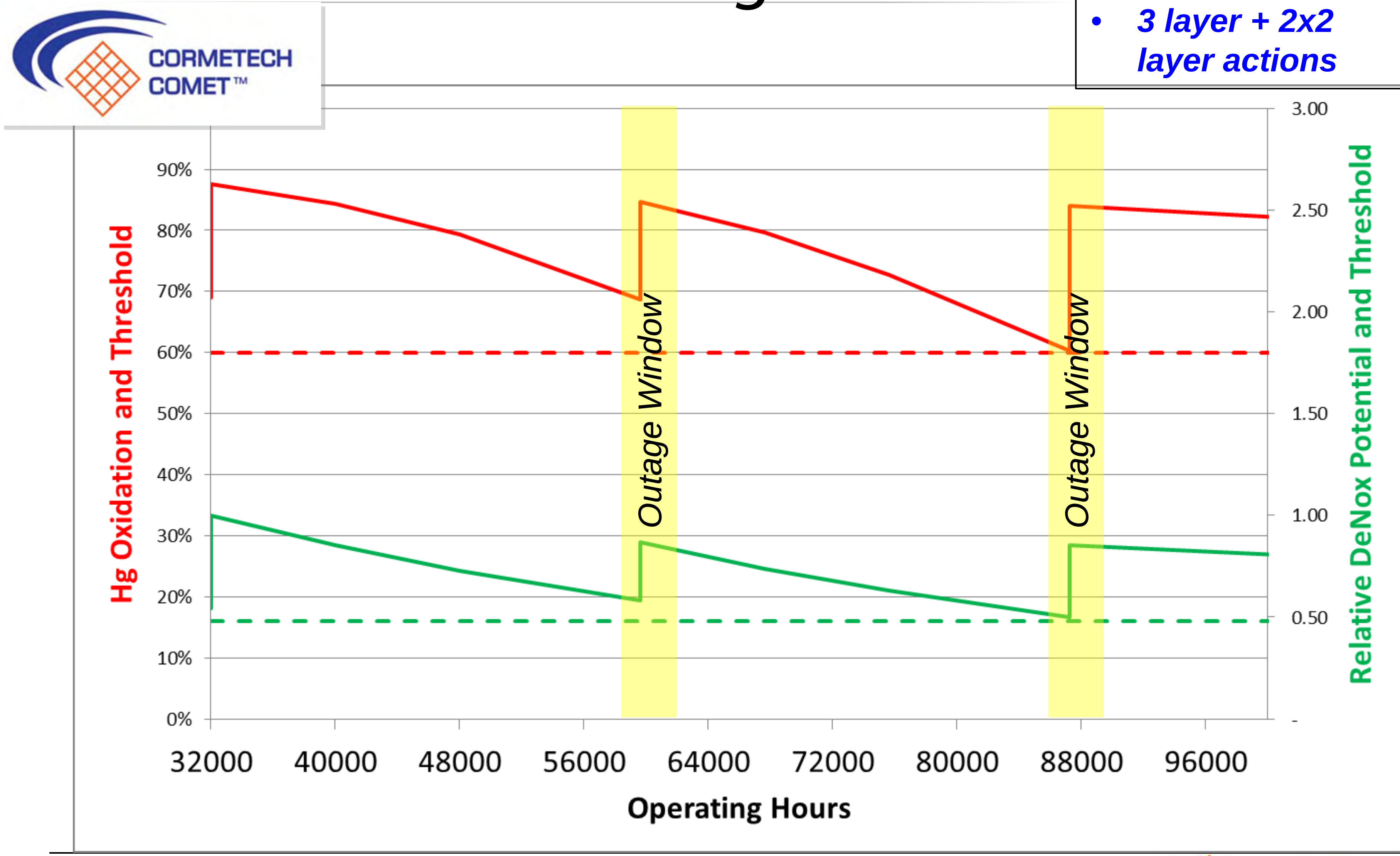
Scenario 1 Management Plan w/ DeNOx Potential & Hg Oxidation

- *DeNOx = 84%*
- *New Fuel Basis*
- *HCl = 32 ppm*
- *3 – layer actions*
- ***Add Limestone***



Scenario 2 Management Plan w/ DeNOx Potential & Hg Oxidation

- *DeNOx = 84%*
- *New Fuel Basis*
- *HCl = 32 ppm*
- ***Add Limestone***
- ***3 layer + 2x2 layer actions***



Case 1 Conclusions

- DeNOx and Hg requirements were reasonably matched, DeNOx controlled slightly
- Planned for 3 layer action (2 regen + 1 new)
- Each subsequent outage will require 2 layer action
- Limestone addition needed for worst fuel case
- System maintenance for improved LPA capture will provide higher assurance to meet the plan
- Strategies for managing alternate performance needs driven by fuel changes are in place
  - Load limits, fuel management, and/or utilization of layer 4

Case 2

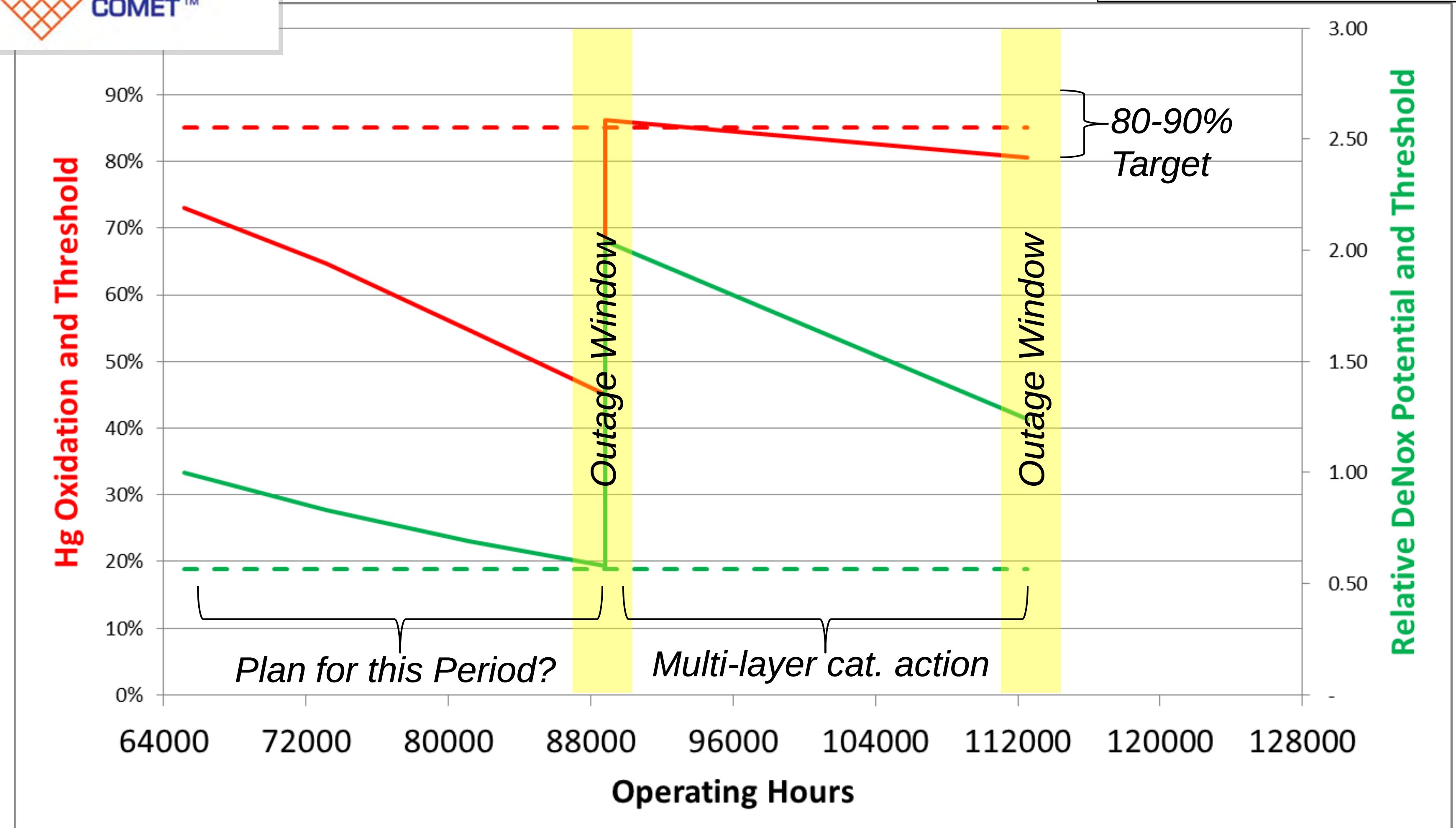
- Background/Input
  - Plant Info
    - 90/10 H/M S, SCR, 2L APH, SBS for SO_3, ESP, Mg/Enhanced lime FGD
    - Rudimentary blending, ash dispose or External Gypsum Plant, moderate LOI, NOx flex., No ACI, potential for Br.
  - SCR
    - L1 – regen plate, L2 – regen HC, L3 – OEM HC, L4 – new plate
  - Targets
    - Based on FE assessment of BOP plant equipment capability, the SCR Hg oxidation target established at 80-90%
    - DeNOx target established at 80%
    - Target outage cycle established at 3 years

Case 2

- Analysis
  - Impact of alternate temperature and Br addition
  - Lab Testing utilized to establish model applicability
  - Options under assessment – decision pending

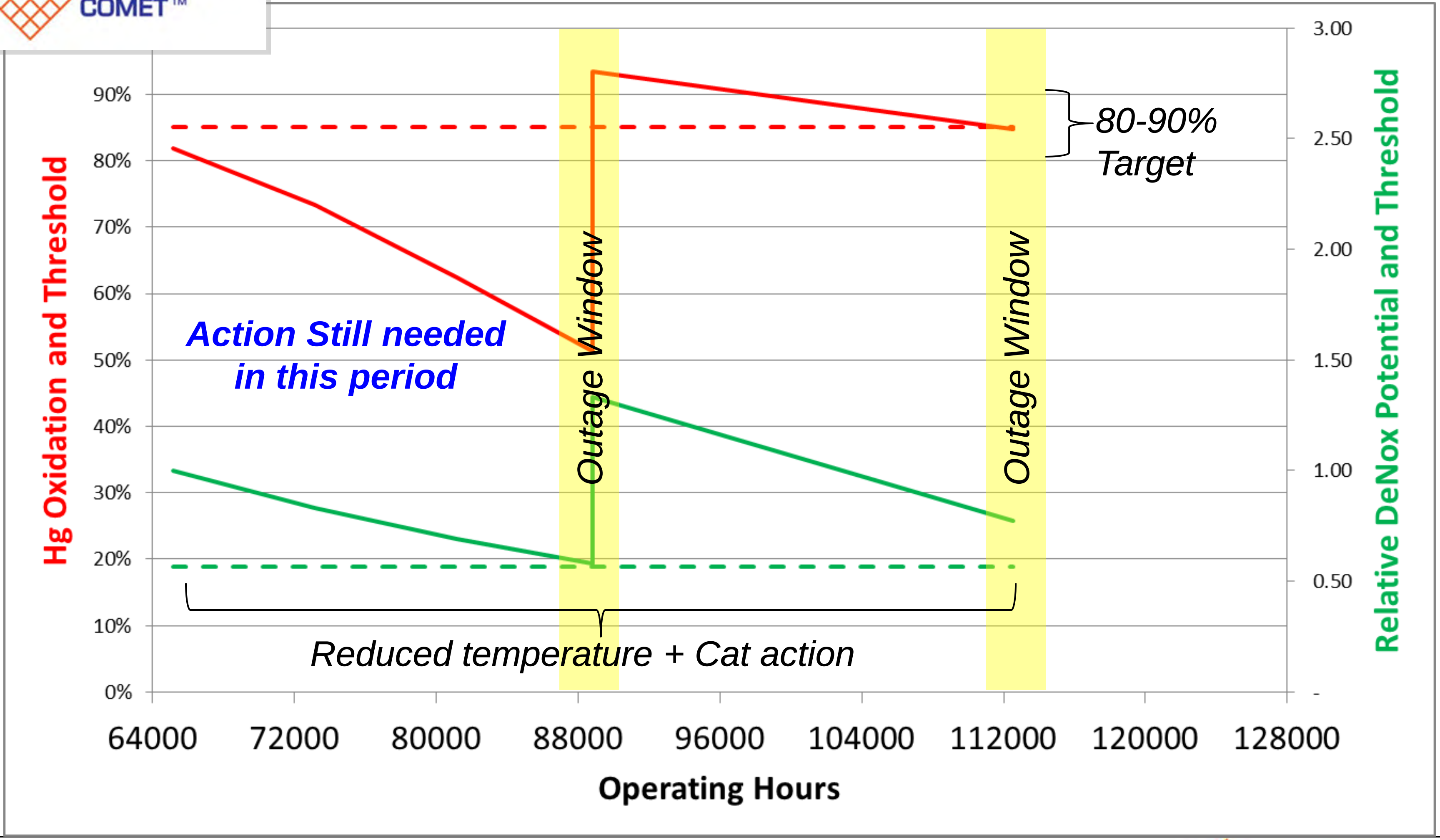
Baseline Management Plan w/ DeNOx Potential & Hg Oxidation

- *DeNOx = 81%*
- *Fuels stable*
- *HCl = 30 ppm*
- ***Multi-layer high potential action***



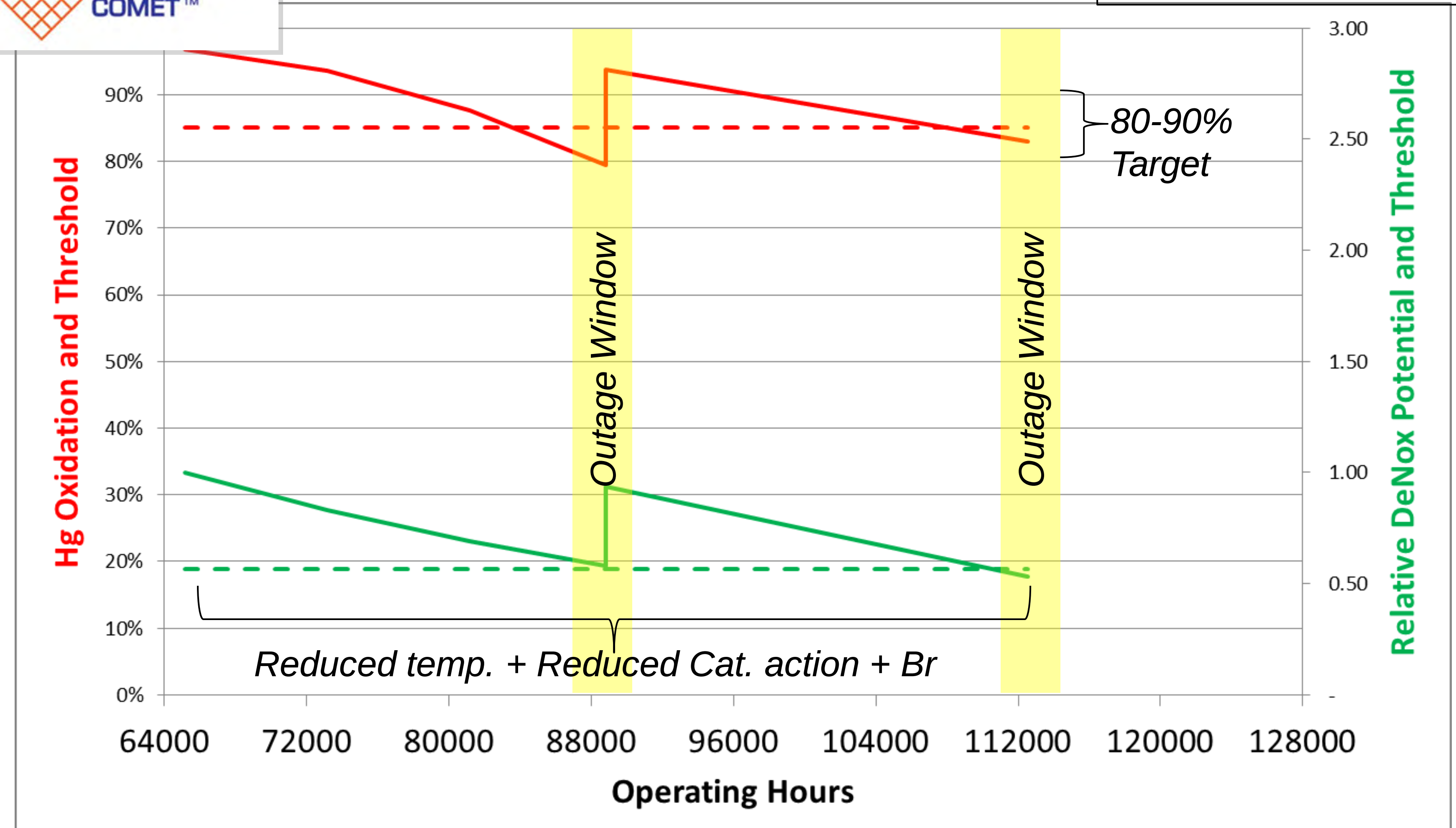
Scenario 1 Management Plan w/ DeNOx Potential & Hg Oxidation

- *DeNOx = 81%*
- *Fuels stable*
- *HCl = 30 ppm*
- ***Multi-layer action***
- ***Temp reduction***



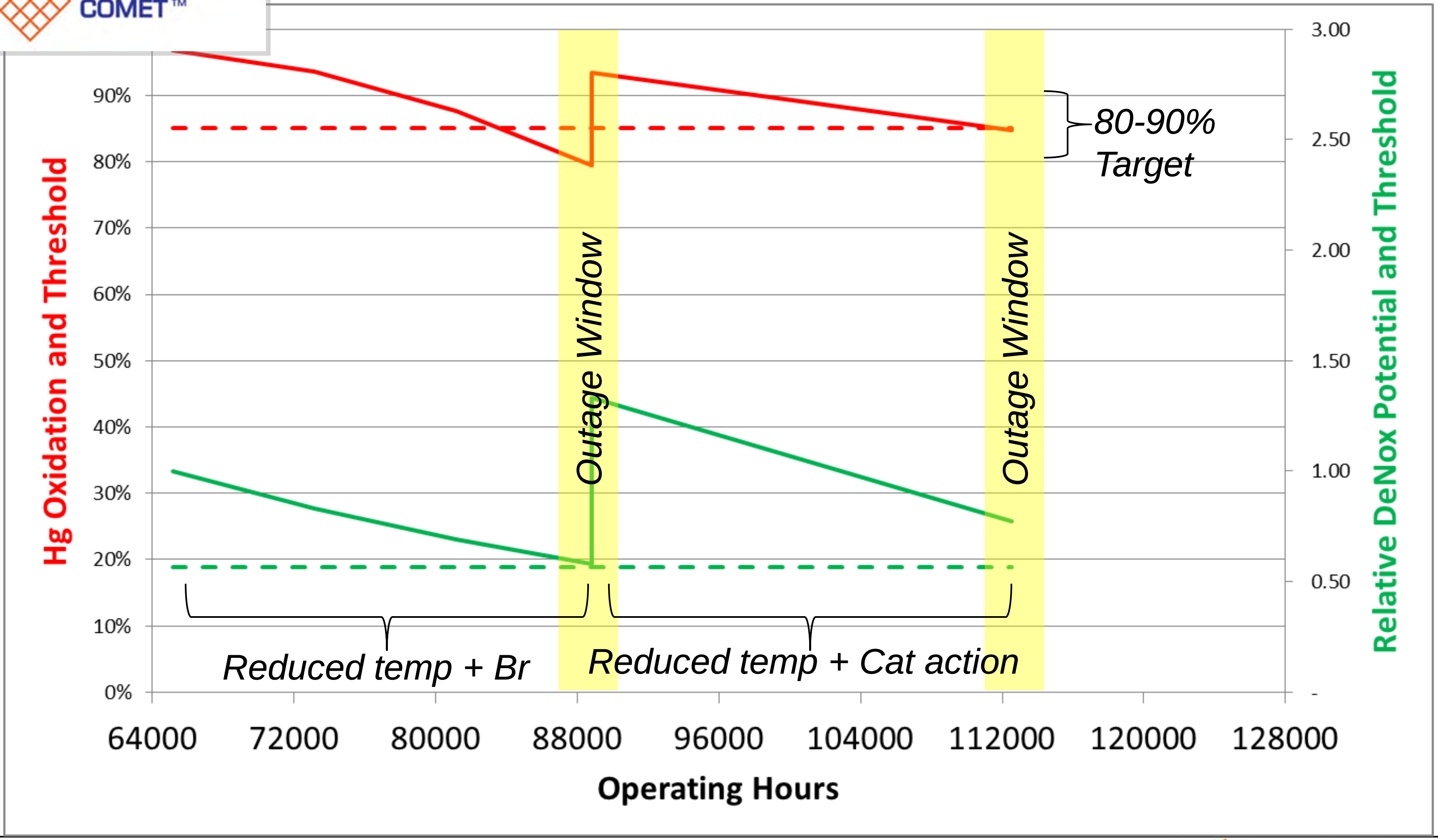
Scenario 2 Management Plan w/ DeNOx Potential & Hg Oxidation

- *DeNOx = 81%*
- *Fuels stable*
- *HCl = 30 ppm*
- ***Reduced layer action required***
- ***Br addition thru-out***



Scenario 3 Management Plan w/ DeNOx Potential & Hg Oxidation

- *DeNOx = 81%*
- *Fuels stable*
- *HCl = 30 ppm*
- ***Multi-layer action***
- ***Br addition 1st cycle***



Case 2 Conclusions

- Hg Ox. requirements control catalyst management and/or additive actions over DeNOx.
- Alternatives – Br addition with improved catalyst leading candidates.
- A concern associated with Hg re-emissions associated with the Br solution. Evaluation will be completed.
- Information being used to help evaluate “sister” units but need to consider differences in downstream equipment and current catalyst load.

Presentation Overview

- Mercury / DeNOx Interactions in SCR
- Mercury Capture from Boiler to Stack
- Evaluating Combined DeNOx and SCR Hg Oxidation
- Evaluation of Power Plant Fuel on Hg Emissions
- Mercury Capture Downstream of the SCR
- FirstEnergy's Approach to Evaluation of Combined DeNOx & Hg Oxidation in the SCR
- Case Studies
- Summary

Summary

- Understanding of DeNOx and Hg emissions are critical to plant success
- Each unit must be well understood
  - Equipment, fuels, additives, operating conditions, catalyst, outage planning, etc. and how they interact as a function of performance goals
- Tools exist to facilitate making educated decisions
  - BOP equipment impact data & understanding growing
  - Field testing & data assessment
  - Catalyst modeling & testing
  - Economic assessment

Thank You

Questions?