REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table & Expo Presentation

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

Optimizing SCR Catalyst Utilization

Volker Rummenhohl
V-Tack, LLC
2018 NO_x-Combustion-CCR Round Table
St. Louis February 20,2018

Agenda

- General Topic Overview
  - New power industry situation
- Catalyst exchange strategy
- Importance of Reactor Potential VS Simply Activity Measurements
- Prioritizing Factors Affecting Catalyst Management
- Catalyst Testing and Benchmarking
- Regenerated Catalyst Considerations
- Comparing New and Regenerated Catalyst
  - Evaluation concepts

General Topic Overview

General Topic Overview

- Renewables on fast pace taking over
- XCEL Energy received 400 bids for wind plus storage and solar plus storage
  - Average price for wind plus storage 2.1 cents/kWh
  - Average price for solar plus storage 2.7 cents/kWh
- APS signed a 15-year PPA with First Solar for a 65 MW solar farm and 50 MW, 135 MWh battery
- Apple Campus 2 off the grid

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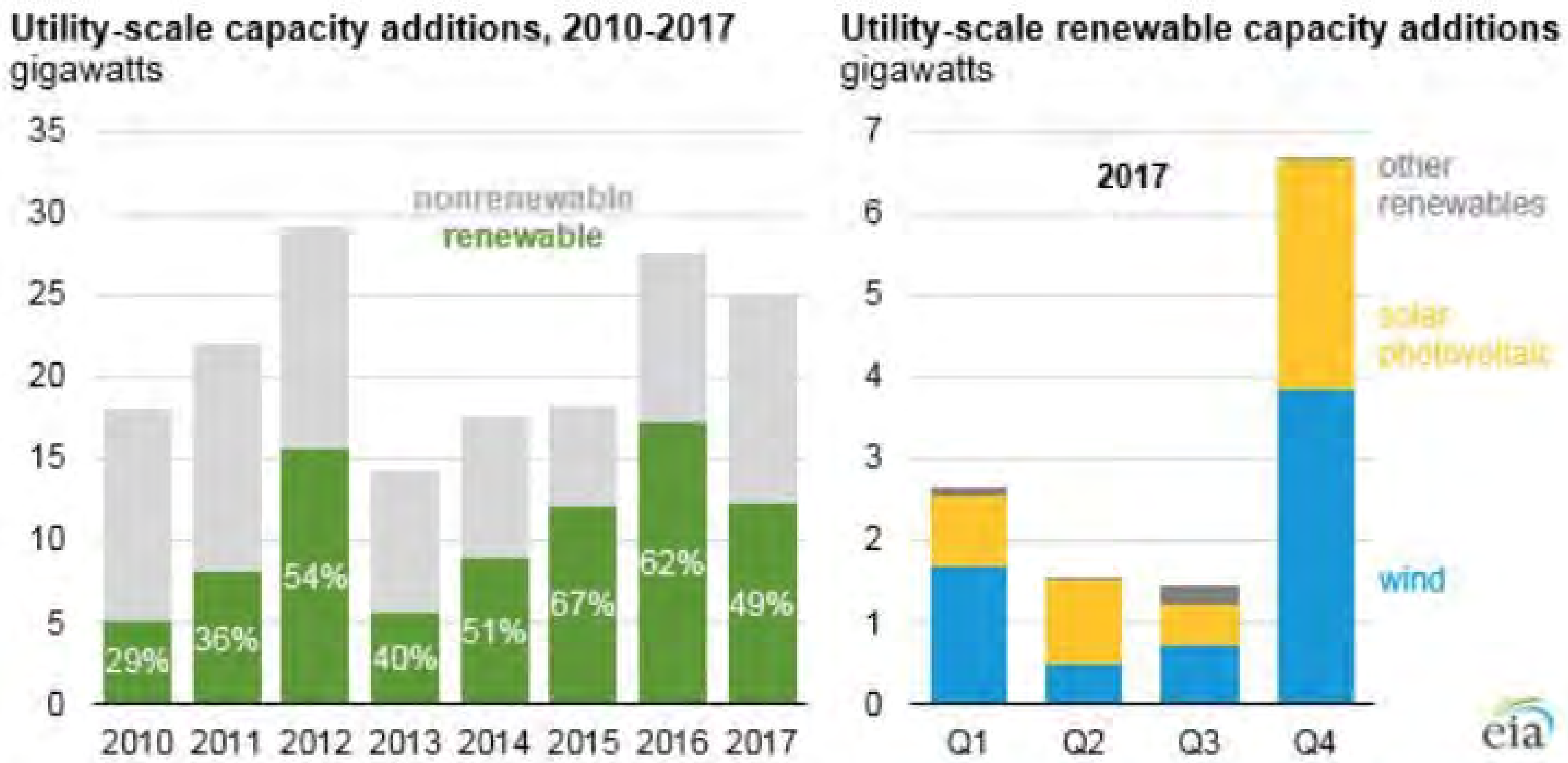
General Topic Overview



Source: U.S. Energy Information Administration, Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*

General Topic Overview

- Natural gas price remains low
- Former base loaded coal units are now frequently cycling
- Reduced operating hours, but in many cases higher catalyst deactivation

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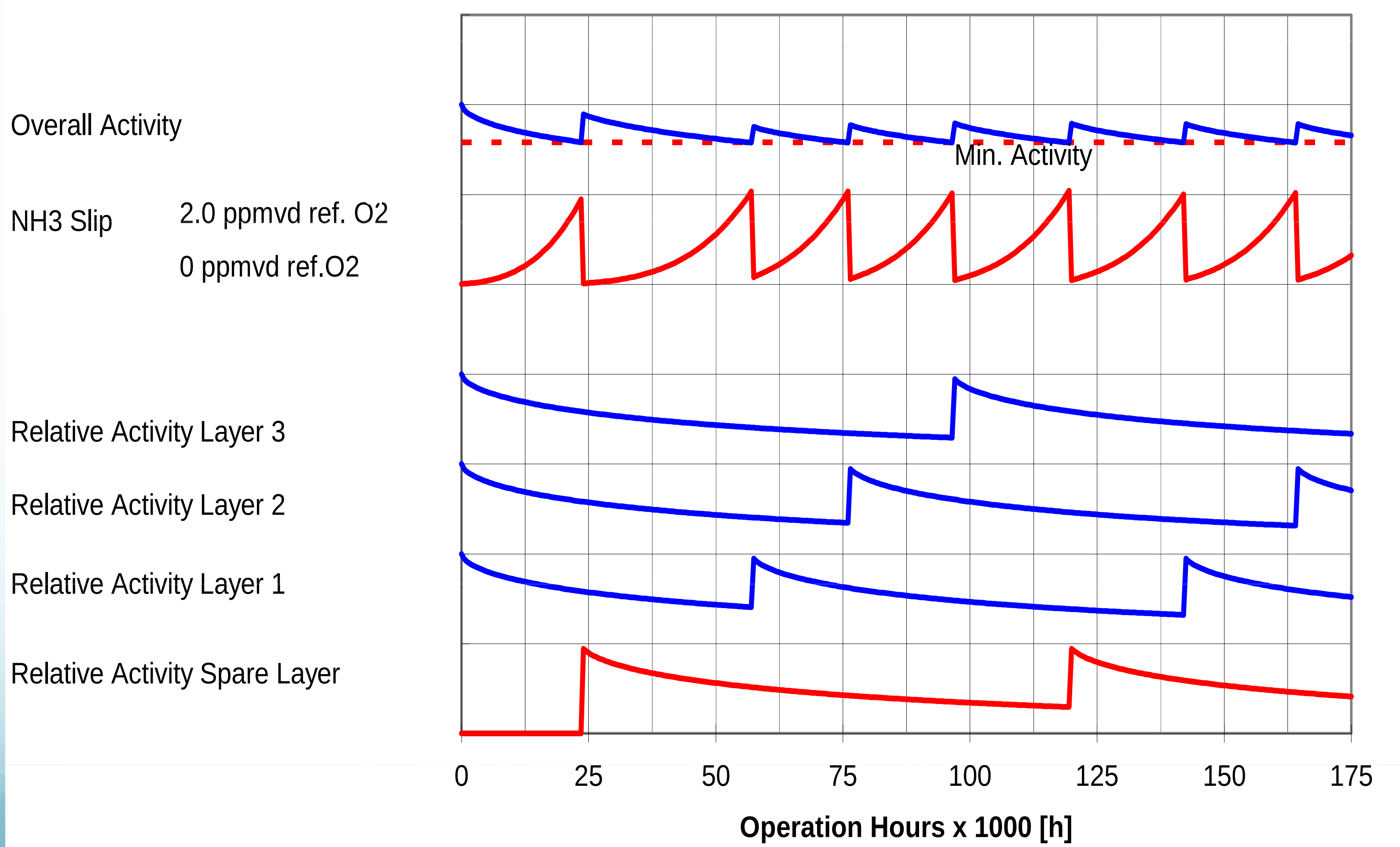
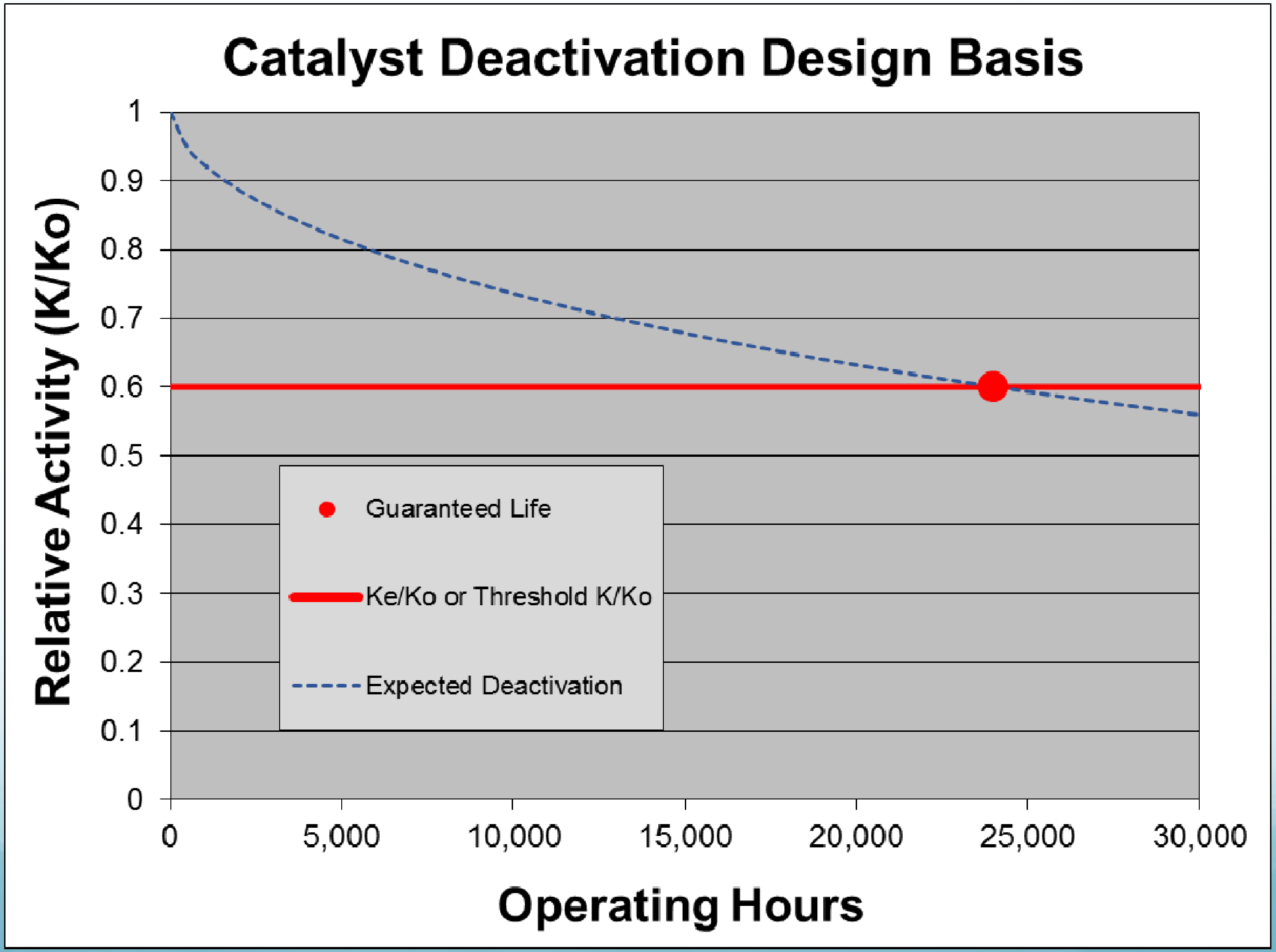
Catalyst Exchange Strategy

Catalyst Exchange



Expectation



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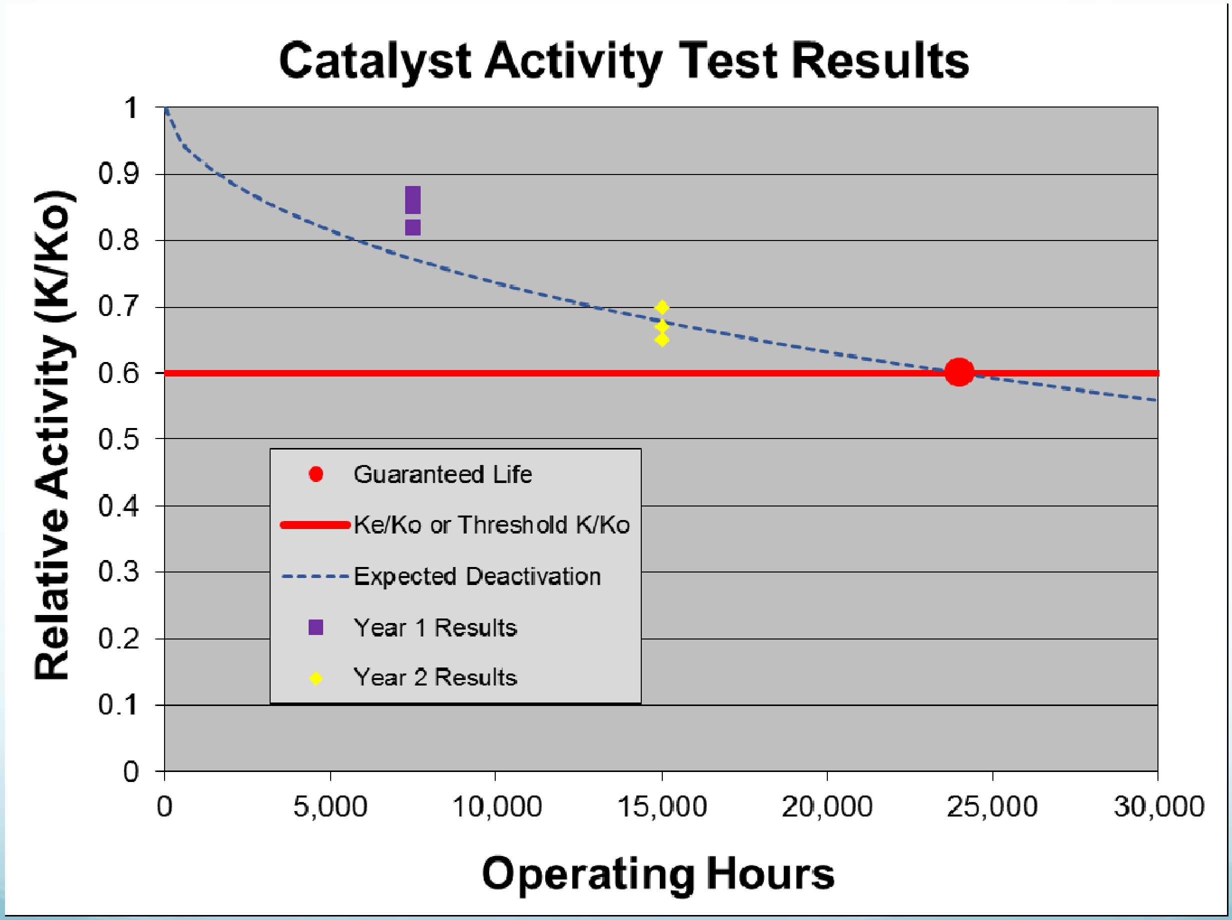
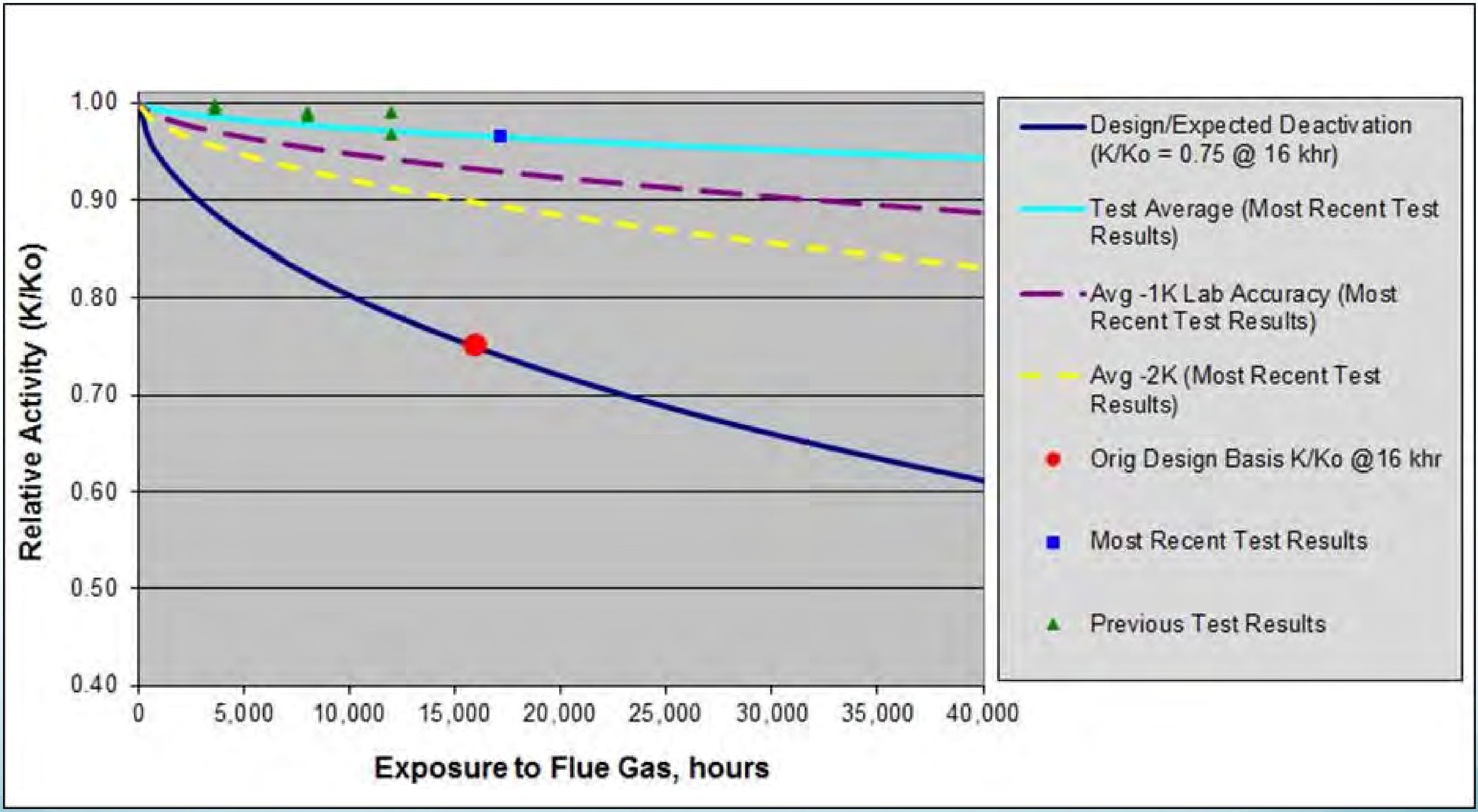
On Track


Catalyst Activity Test Results
Relative Activity (K/Ko)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Operating Hours
Guaranteed Life
Ke/Ko or Threshold K/Ko
Expected Deactivation
Year 1 Results
Year 2 Results

Positive Deviation



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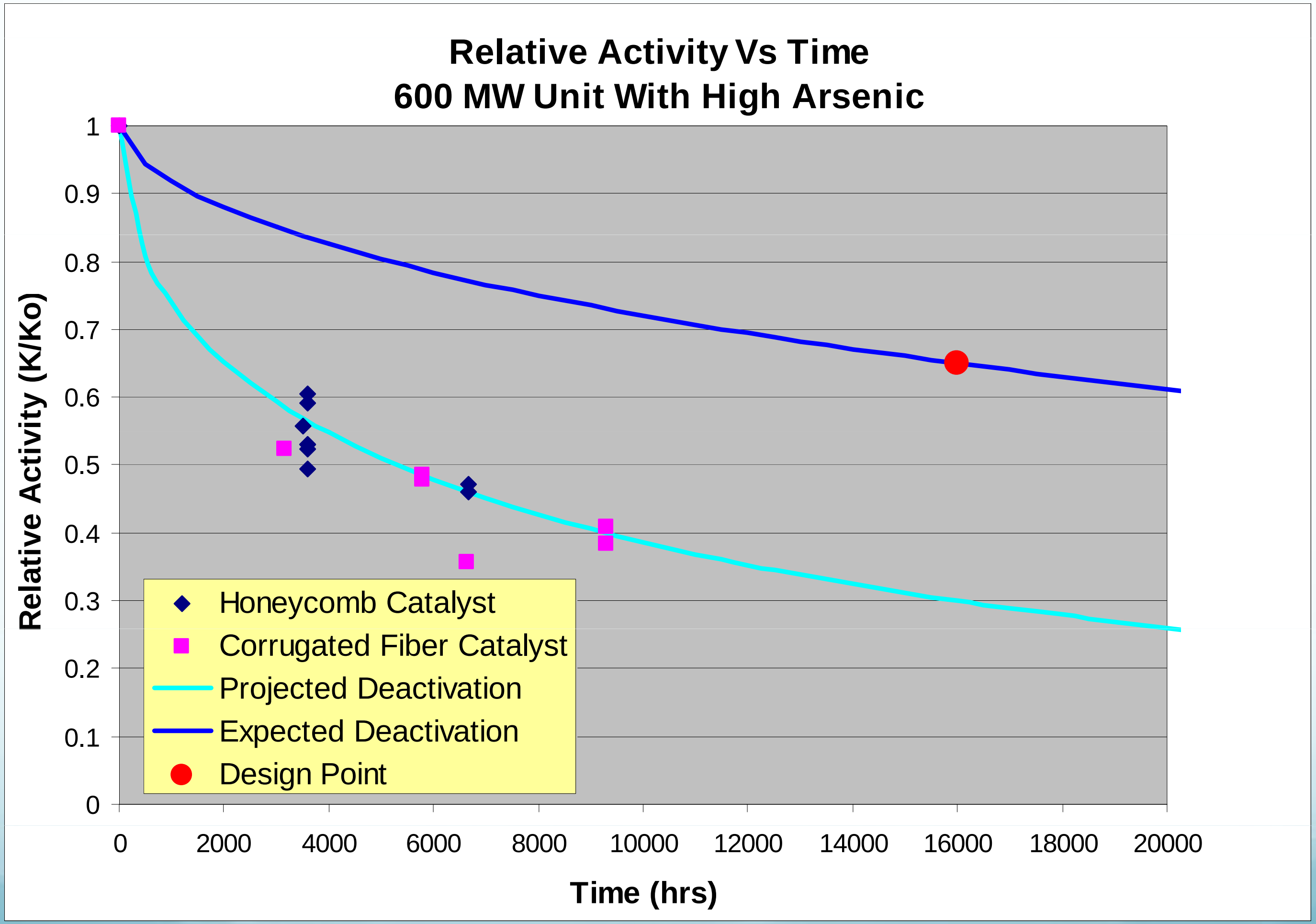
Negative Deviation



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Impacts on Catalyst Strategy

- Fuel
- Operating conditions
- Ammonia Flow Control System
- Plugging/Erosion/Corrosion(Plate)
- Additives
- Catalyst test conditions
- Catalyst laboratory
- Calculation
- Actual flue gas data VS design data
- Catalyst selection

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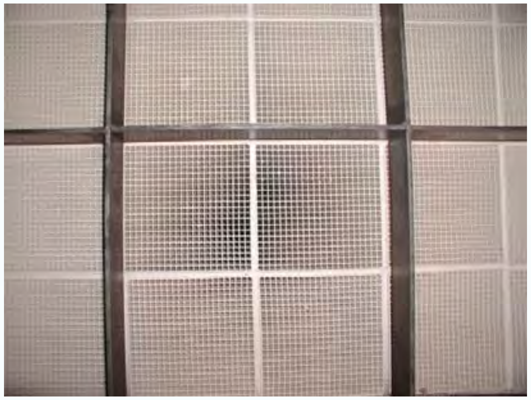
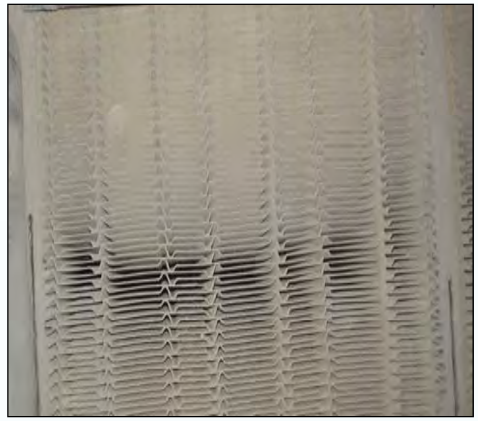
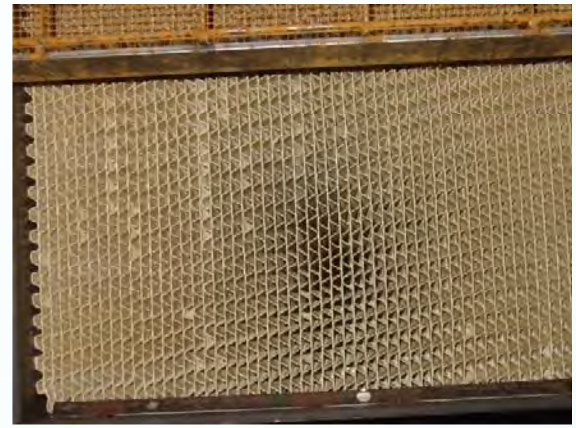
Catalyst Potential

Catalyst Potential







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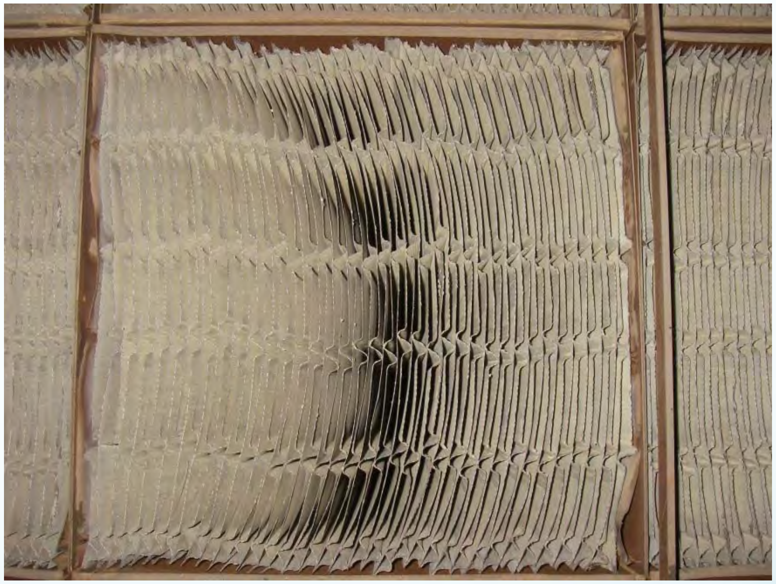
Critical Catalyst Management Planning Consideration

If Your Laboratory Element Looks Like This…

…But Your Operating Catalyst Looks Something Like This…



Things Are Not As Good As You Think!

K Measurement ≠ Reactor Potential

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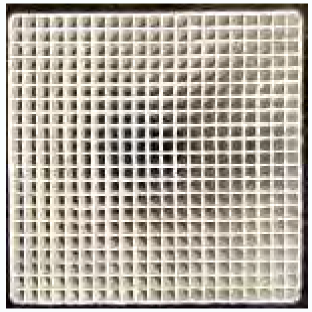
Critical Catalyst Management Planning Consideration

If Your Laboratory Element Looks Like This…



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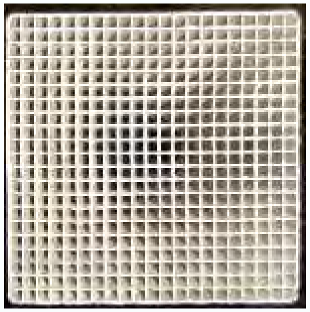

…But Your Operating Catalyst Looks Something Like This…

Things Are Not As Good As You Think!

K Measurement ≠ Reactor Potential

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Catalyst Activity VS Potential

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Catalyst Activity VS Potential

- Catalyst Potential

  $P = k/Av$

- Factors
  - NO_x removal efficiency
  - Ammonia slip
  - Velocity, Temperature and NH_3/NO_x distributions
- The effective catalyst potential must be at all times above the catalyst potential calculated at the end of the catalyst lifetime

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Critical Catalyst Management Planning Consideration

To Accurately Assess Reactor Potential

- Annual Catalyst Activity Testing
- Annual Catalyst Mechanical Assessment
  - Pluggage
  - Erosion (Open Holes = Flow Diversion)
  - Mechanical Condition
    - Plate Especially - Consistent Spacing
  - Seal Effectiveness
- Annual Operating Condition Assessment
  - Operated Like Design? (e.g., delta T = delta K)

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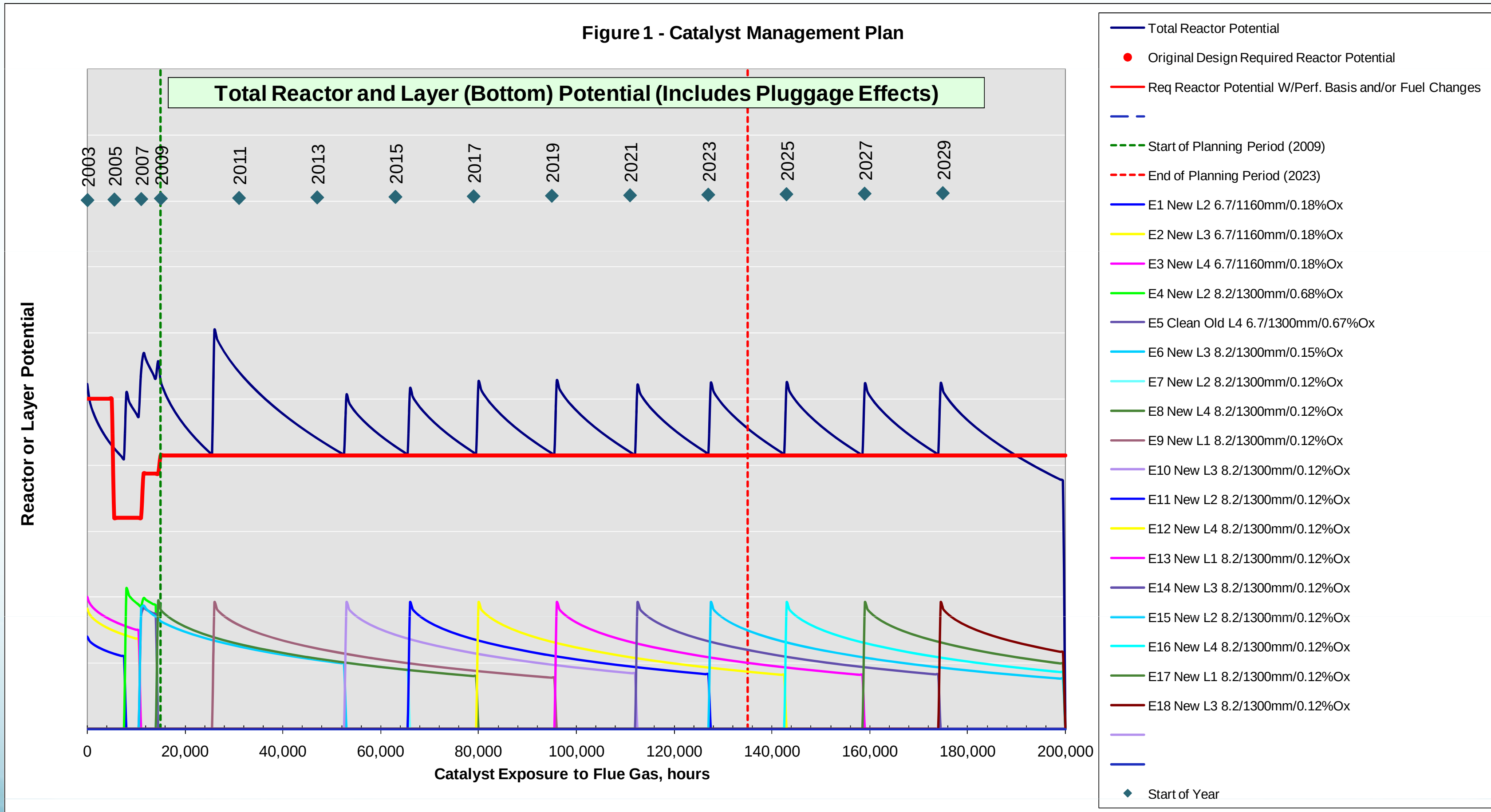
Catalyst Potential



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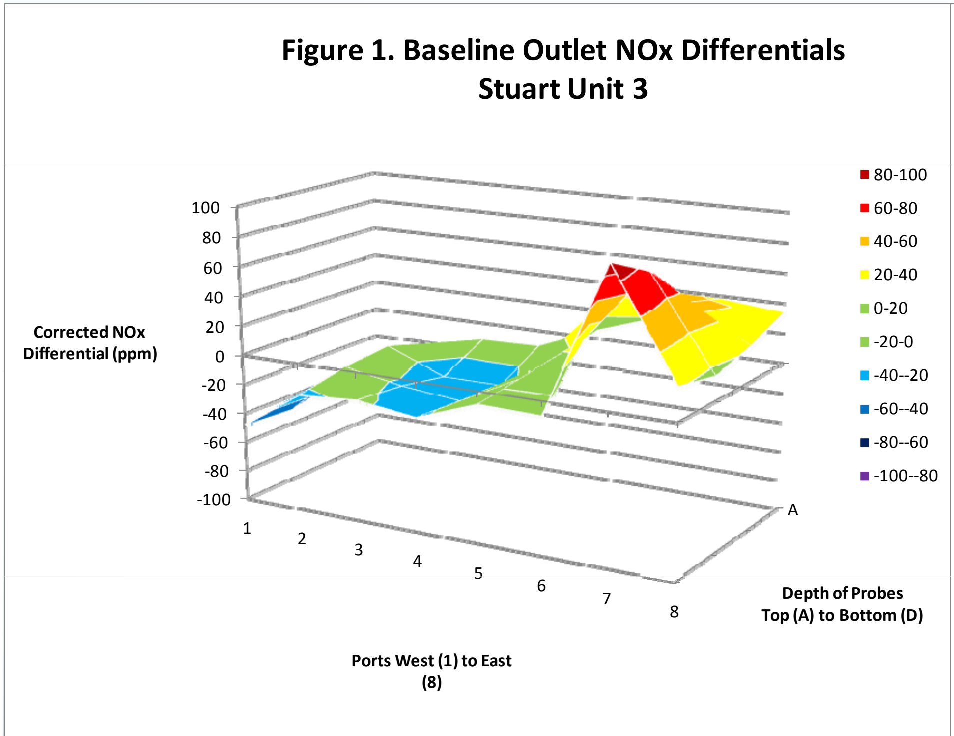
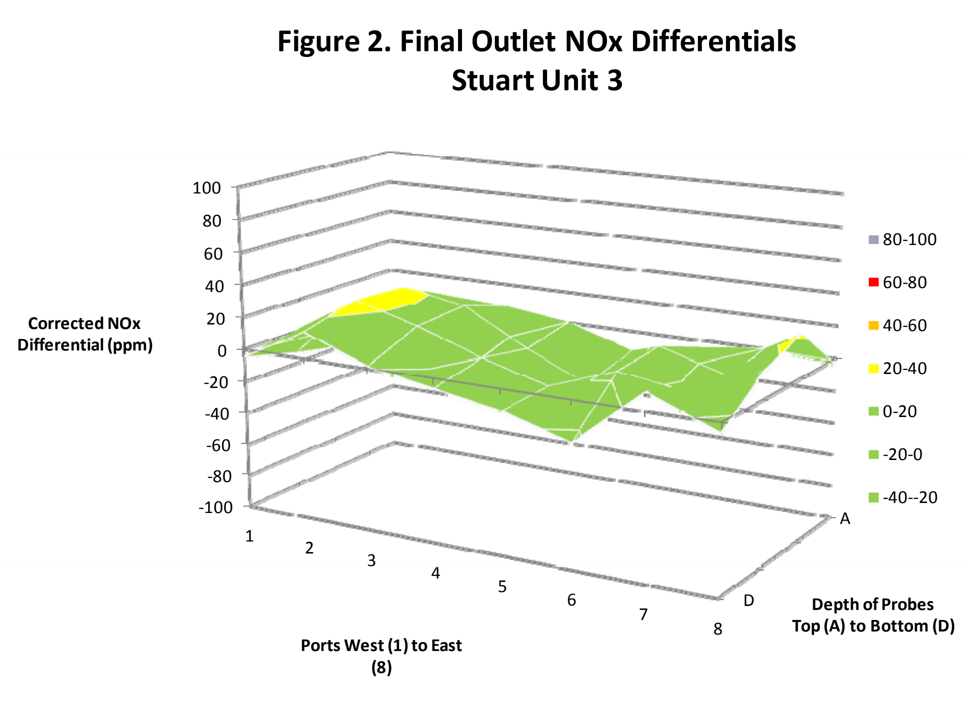
Flue Gas Distributions

Flue Gas Distributions





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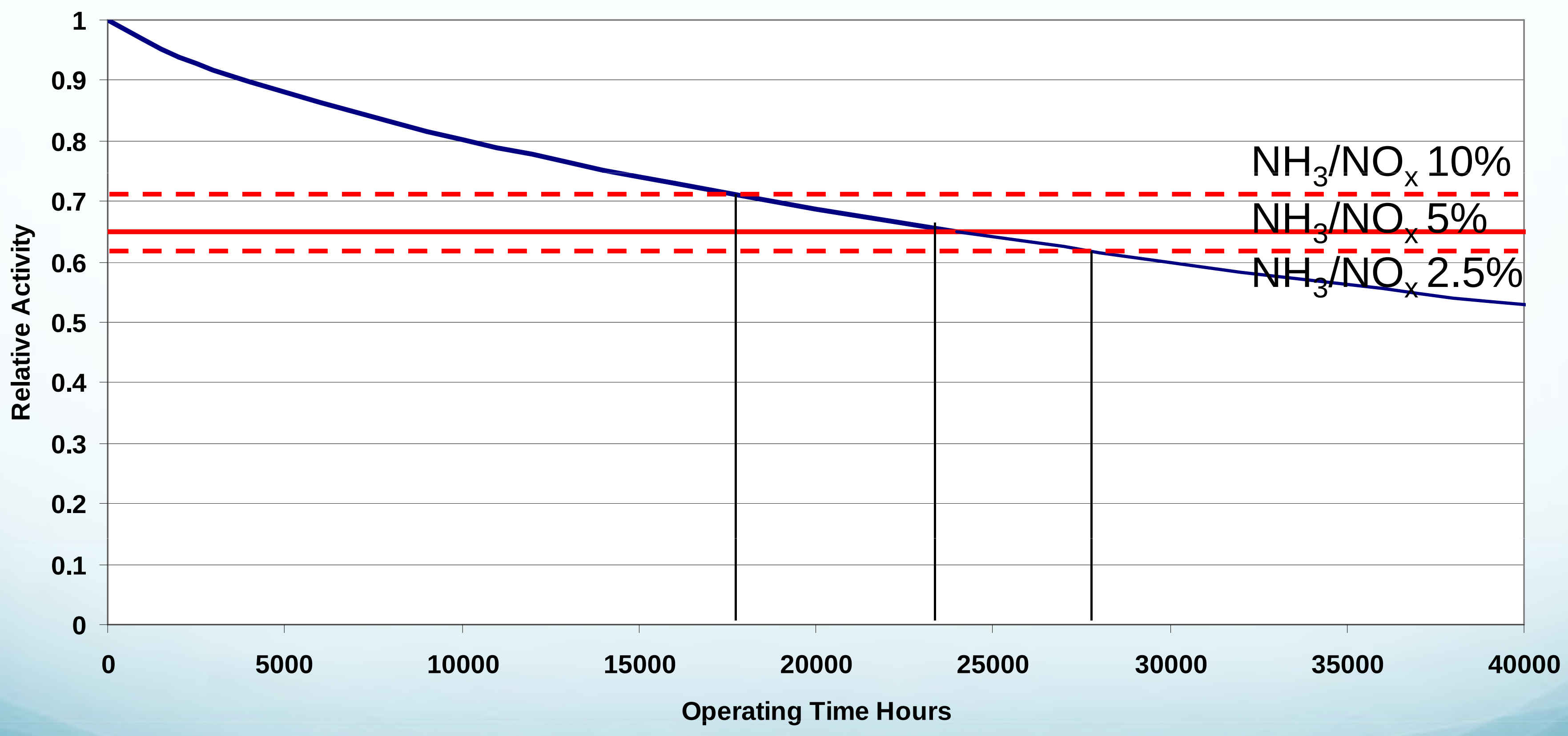
Flue Gas Distributions



Flue Gas Distributions

- 815 MW PRB fired boiler
- Original design allowed for extensive ash buildup/plugging in back of reactor which increased velocities elsewhere causing catalyst to erode.
  - Multiple catalyst change outs in five (5) years between 2007 and 2012.
  - Multiple annual shut downs to clean the reactor
- The goal of the project was to design flow distribution devices capable of improving the velocity distribution into the catalyst reactor by 40% from the baseline and eliminate recirculation areas in the reactor hood.

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Flue Gas Distributions
Original Design

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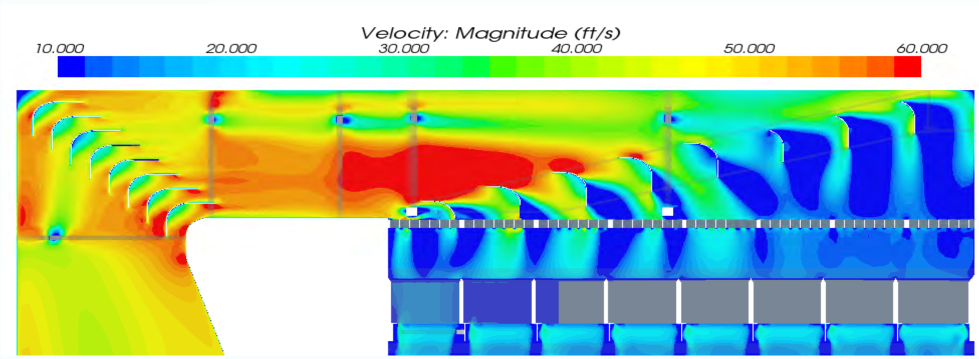
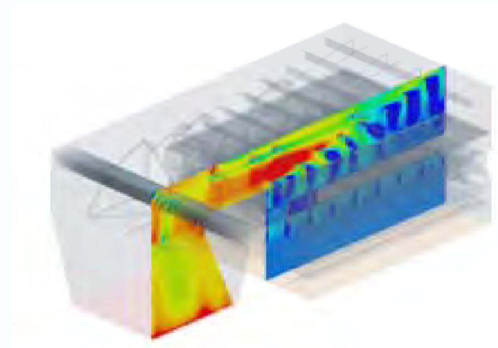
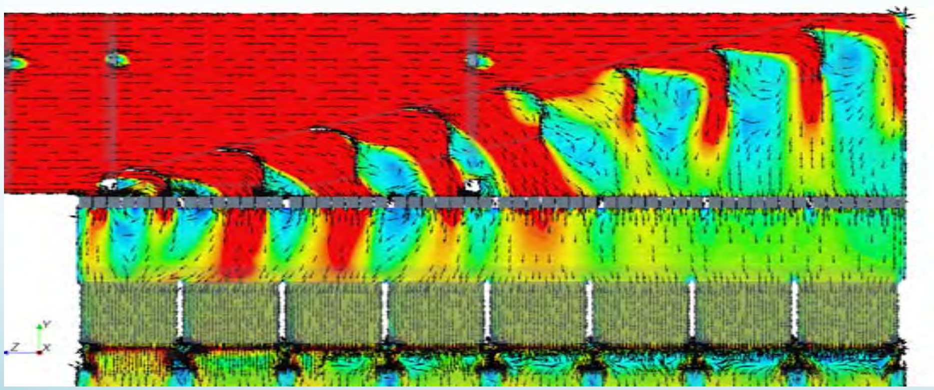
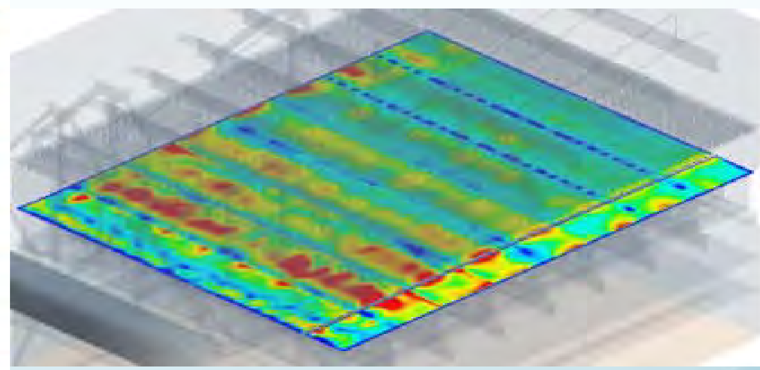
Flue Gas Distributions
Baseline CFD Results





High and low spots from the turning vanes are helped by the straightening grid and perforated plate but still yield a poor distribution into the 1st catalyst layer.





Vectors near vanes show recirculation areas where potential ash fallout can occur.

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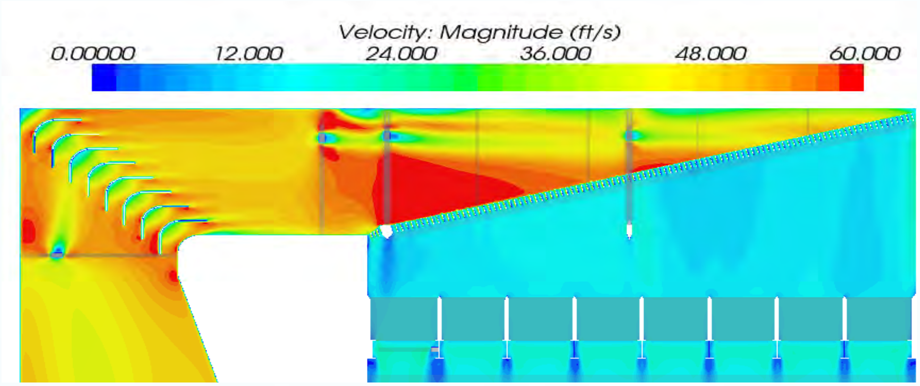
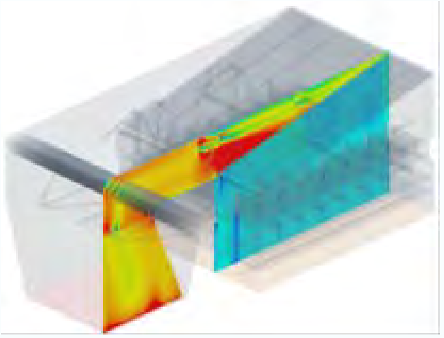
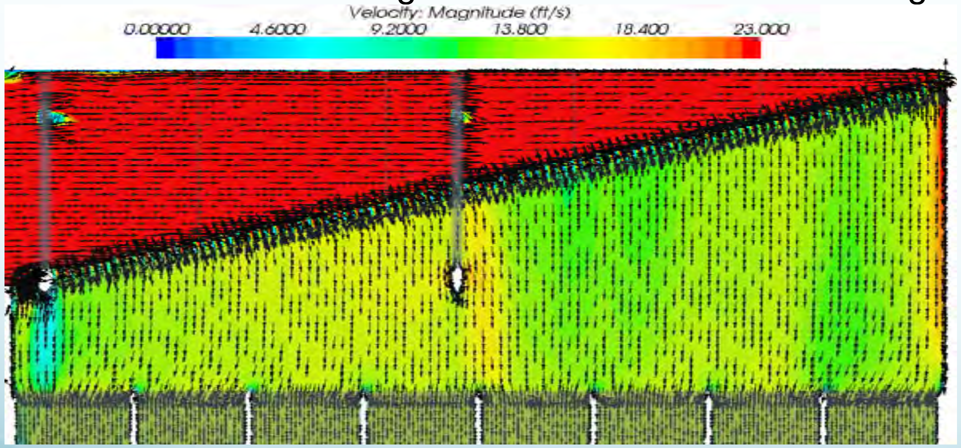
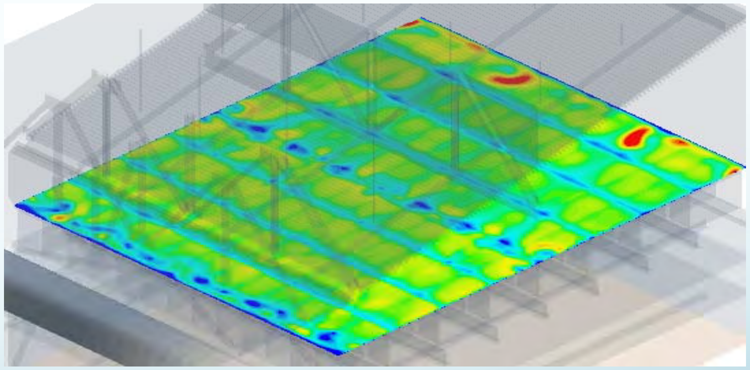
Flue Gas Distributions
Final CFD Results





Flow shadows from large truss reduced with new design.





Flow vectors all down, no recirculation

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Flue Gas Distributions
Final CFD Results

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Flue Gas Distributions

- Baseline Catalyst Inlet Velocity Profile – 17.5% RMSE
  - % within +/- 15% of average = 57.9%
  - % within +/- 30% of average = 88.6%
- Final Catalyst Inlet Velocity Profile – 9.4% RMSE
  - o % within +/- 15% of average = 90.8%
  - o % within +/- 30% of average = 98.8%
- No outages for cleaning between planned outages
- Overall system pressure drop lower (clean condition) compared to original design

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Flue Gas Distributions

- 300 MW bituminous coal fired boilers
- Retrofit of Large Particle Ash LPA screen
- Pressure drop increase due to catalyst plugging with LPA and air heater fouling with ABS forced the units to be de rated after ten weeks
- Every boiler had to come every three months down to vacuum the dust of the catalyst.
- Very high catalyst consumption

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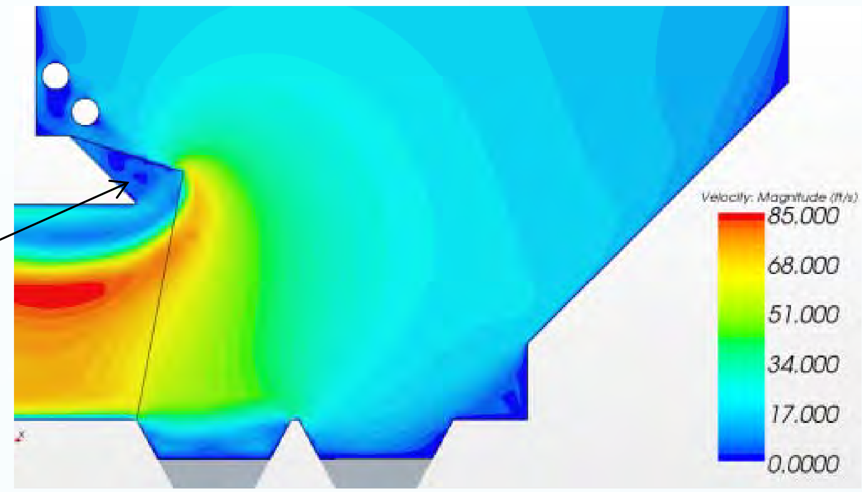
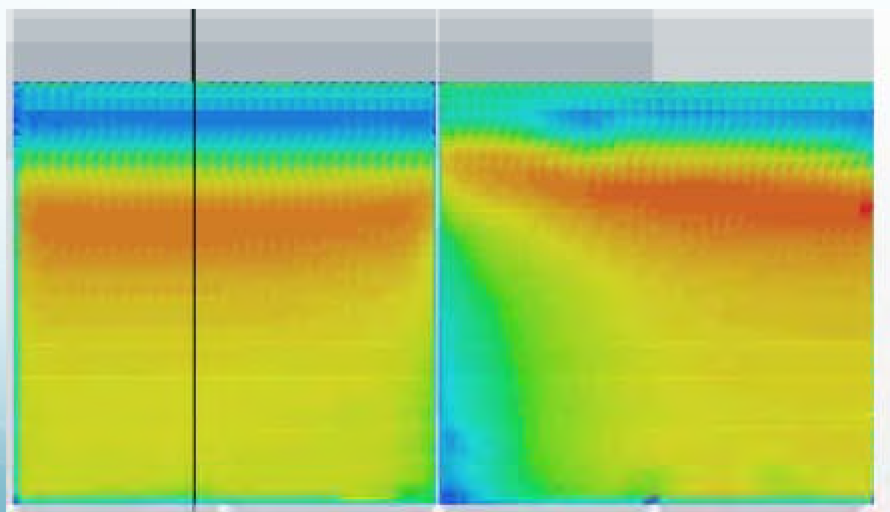
Flue Gas Distributions

Recommended Design

Average Velocity 61ft/s Max 85 ft/s

Low Angle may lead to ash deposition





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Flue Gas Distributions Statistical Comparison

Summary	Baseline	Recommended Design
LPA Screen velocity (ft./s)		
Min.	17.2	10.5
Max.	101.3	85.3
Average	71.7	61.1
RSME	26.2	20.4

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Flue Gas Distributions Results

- No more pressure drop increase
- No catalyst cleaning between scheduled outages
- 2.2 i.w.g. pressure drop improvement

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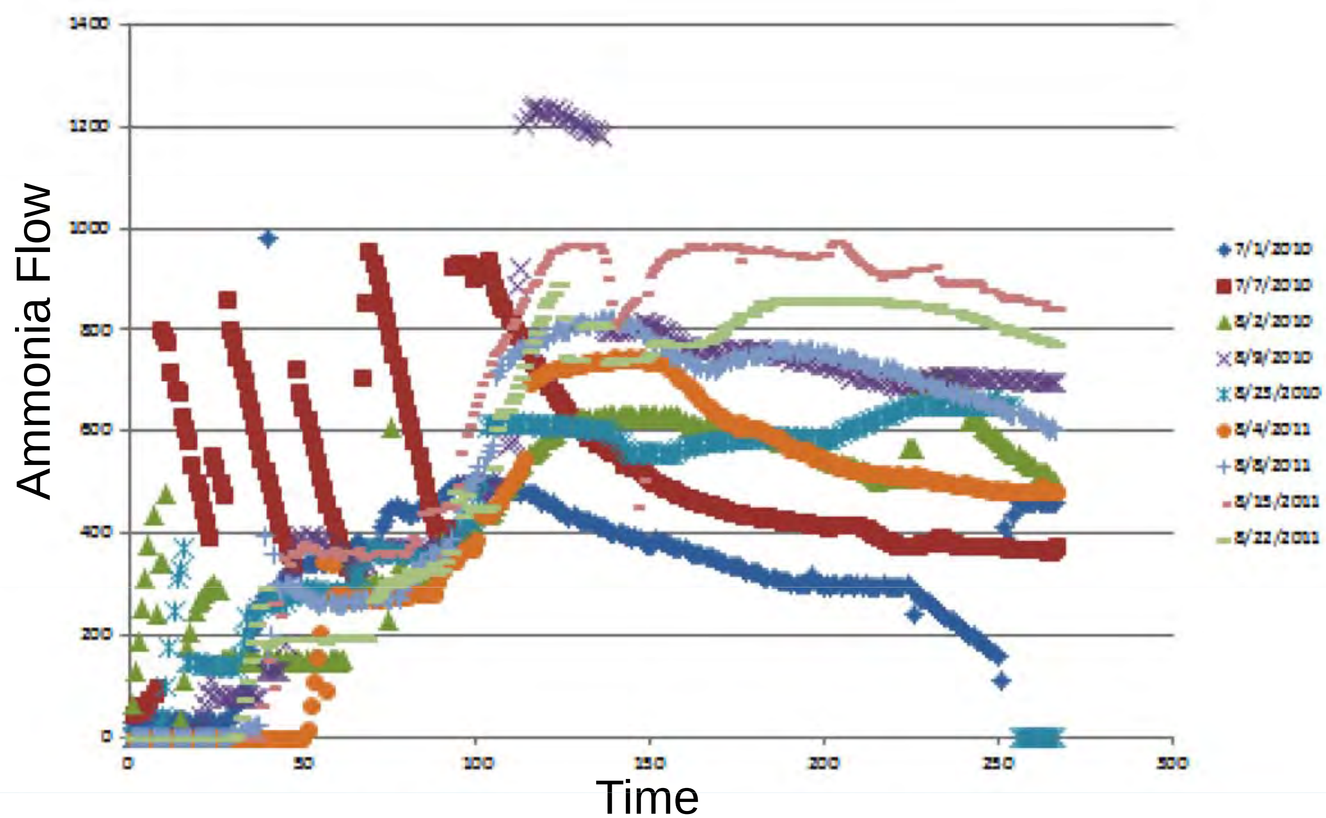
Control System

Ammonia Consumption



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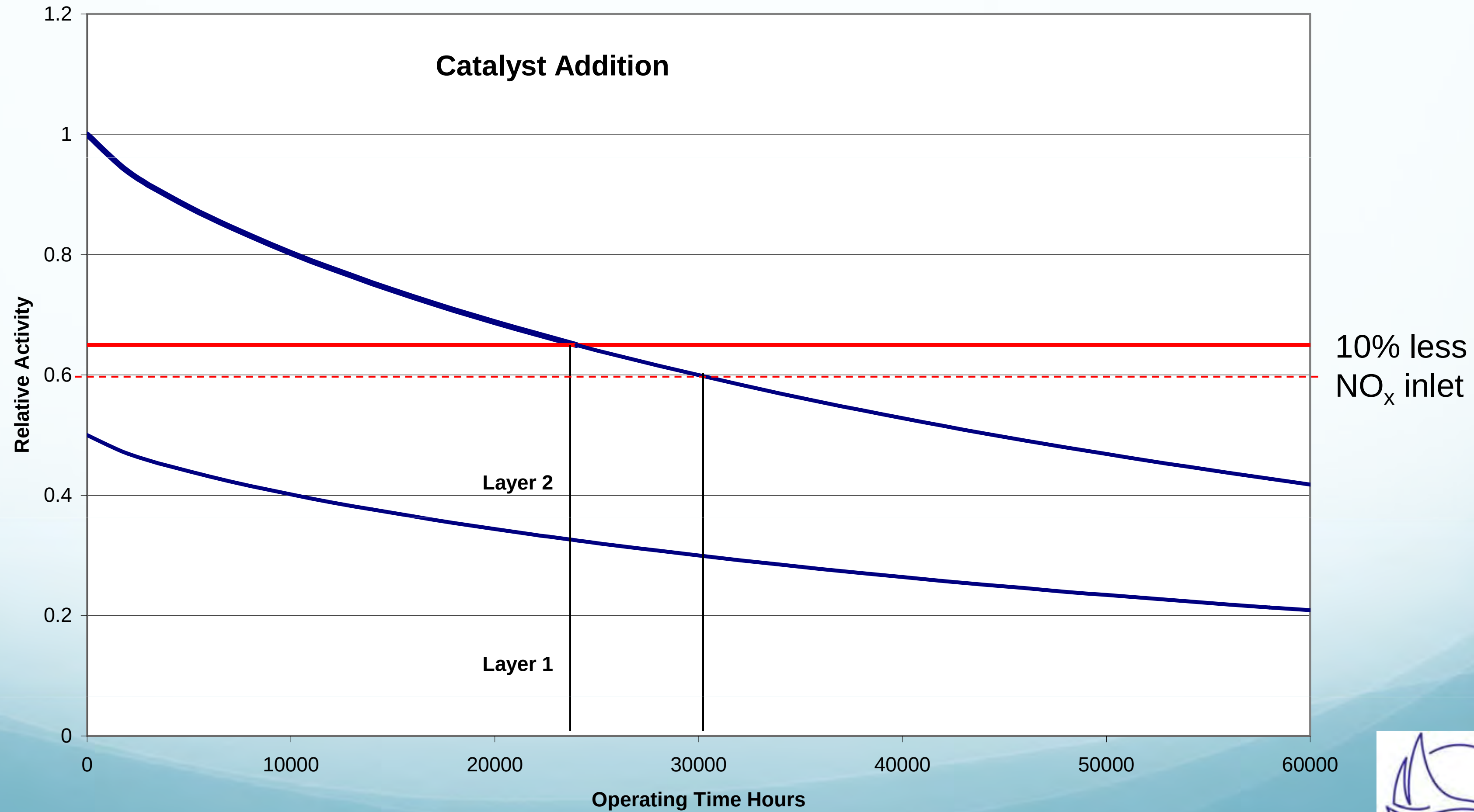
Boiler Operation

Operating Data



Accuracy

Round Robin 2012

Auswertung VGB-Ringversuch Benchreaktor 2009 – 2012
Plattenkatalysatorelement

Testbedingungen:

Volumenstrom	150 Nm^3/h
Temperatur	380 °C
Area Velocity	38,4 Nm/h
$\phi(NO_x)_{tr}$	300 ppmv
$\phi(SO_2)_{tr}$	500 ppmv
$\phi(O_2)_{tr}$	5 vol. %
$\phi(CO_2)_{tr}$	ca. 12 vol. %
$\phi(SO_3)_{tr}$	0 vol. %
$\phi(H_2O)$	15 $\pm$ 1 vol. %
$\alpha = n(NH_3) / n(NO_x)$	1

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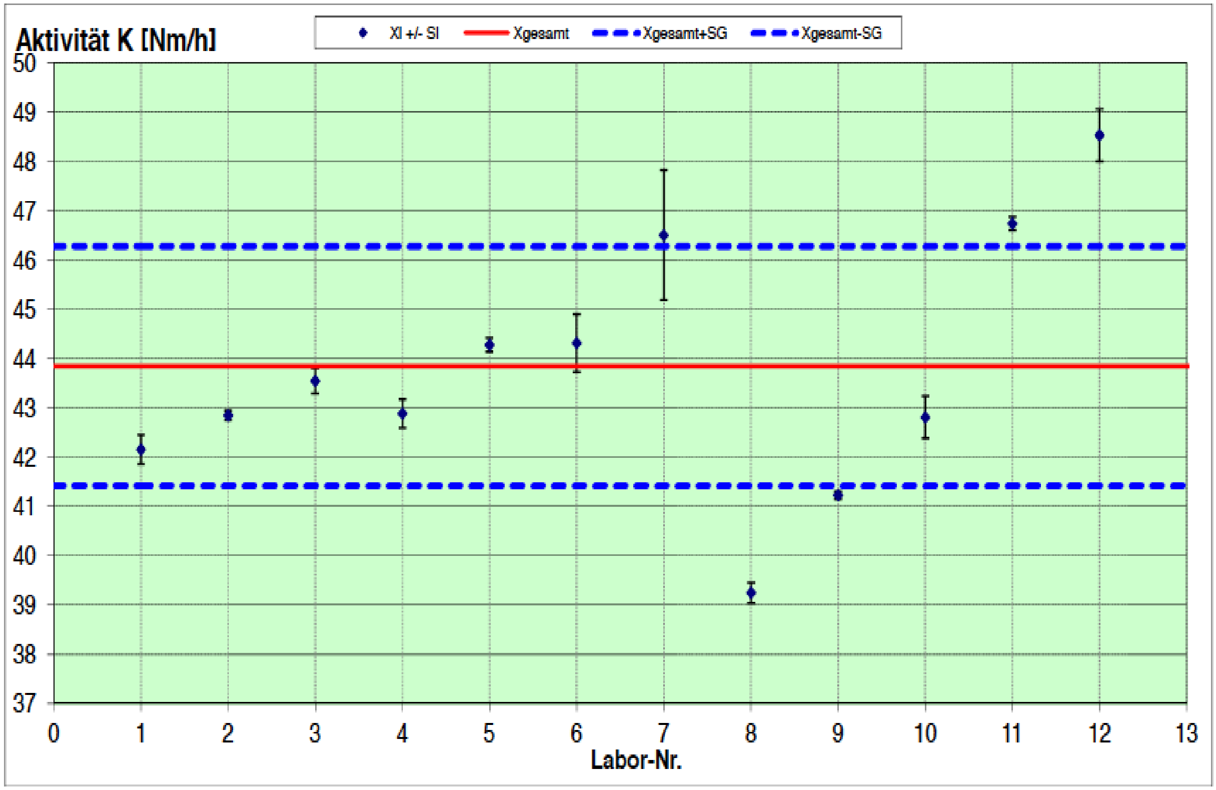
Round Robin 2012

Einzelwerte der Aktivitätsbestimmung:

Labor	Aktivität K [Nm/h]					
L1	41,8	42,7	42,1	42,2	42,1	42,1
L2	42,8	42,8	42,7	42,9	42,9	
L3	43,4	43,4	43,6	43,9	43,8	43,3
L4	42,4	43,1	42,8	43,0	43,2	
L5	44,5	44,1	44,2	44,3	44,3	
L6	44,1	43,5	44,5	44,4	45,1	
L7	48,2	47,7	47,0	45,4	45,7	45,1
L8	39,5	39,3	39,2	39,0		
L9	41,3	41,1	41,2	41,2	41,2	
L10	42,9	42,8	43,3	42,2	42,8	
L11	46,8	47,0	46,7	46,6	46,7	
L12	48,3	48,3	49,5	48,2	48,5	

Average 43.9 m/h

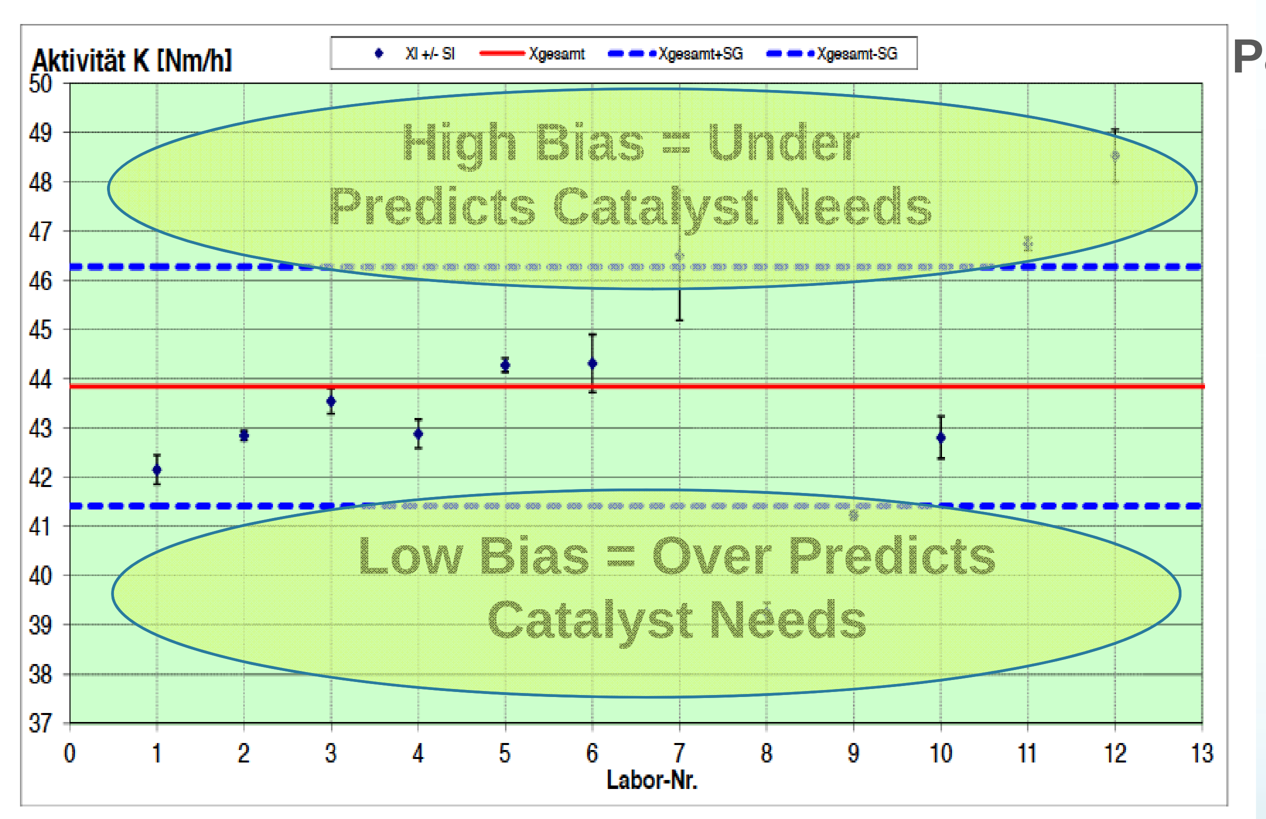
Round Robin 2012



Participating Laboratories

- BHK
- CERAM
- Cormetech (2)
- DKC (CN)
- E.ON (2)
- EnBW
- Evonik/STEAG (DE)
- Johnson Matthey
- STEAG (US)

Round Robin 2012



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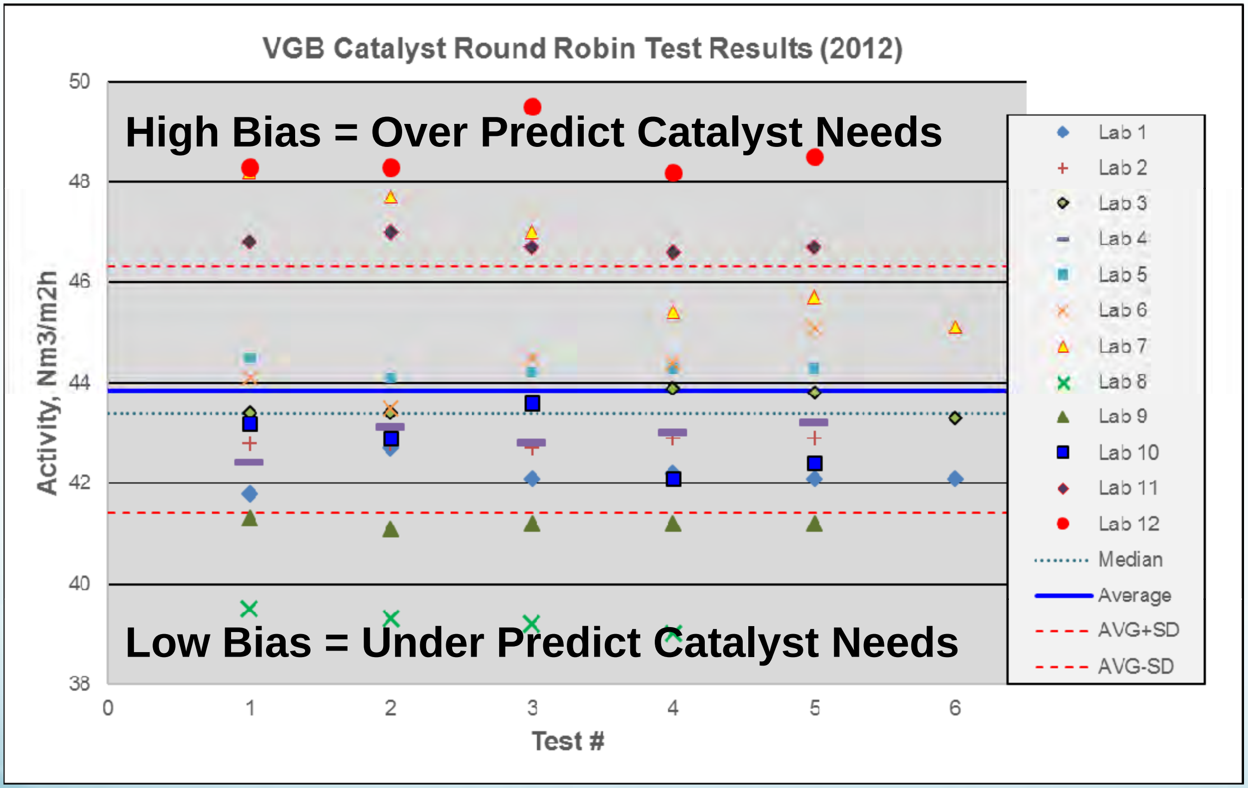
Round Robin 2012



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- Johnson Matthey
- STEAG (US)

Round Robin

VGB POWERTECH

Einzelwerte der SO_2-Konversionsrate

Labor	Konversionsrate [%]					
L1	0,36	0,31	0,31	0,31	0,36	0,32
L2	0,27	0,30	0,30	0,32	0,30	
L3	0,37	0,45	0,33	0,36	0,36	
L4	0,37	0,36	0,34	0,39	0,35	0,37
L5	0,38	0,38	0,39	0,42	0,39	
L6	0,32	0,25	0,29	0,28	0,29	
L7	0,30	0,28	0,31	0,29	0,28	0,29
L8	0,24	0,25	0,23			
L9	0,26	0,26	0,26	0,26	0,26	
L10	0,46	0,39	0,43	0,47	0,52	0,45
L11	0,37	0,36	0,37	0,36	0,36	
L12	0,42	0,34	0,41	0,41	0,41	

Average 43.9 m/h

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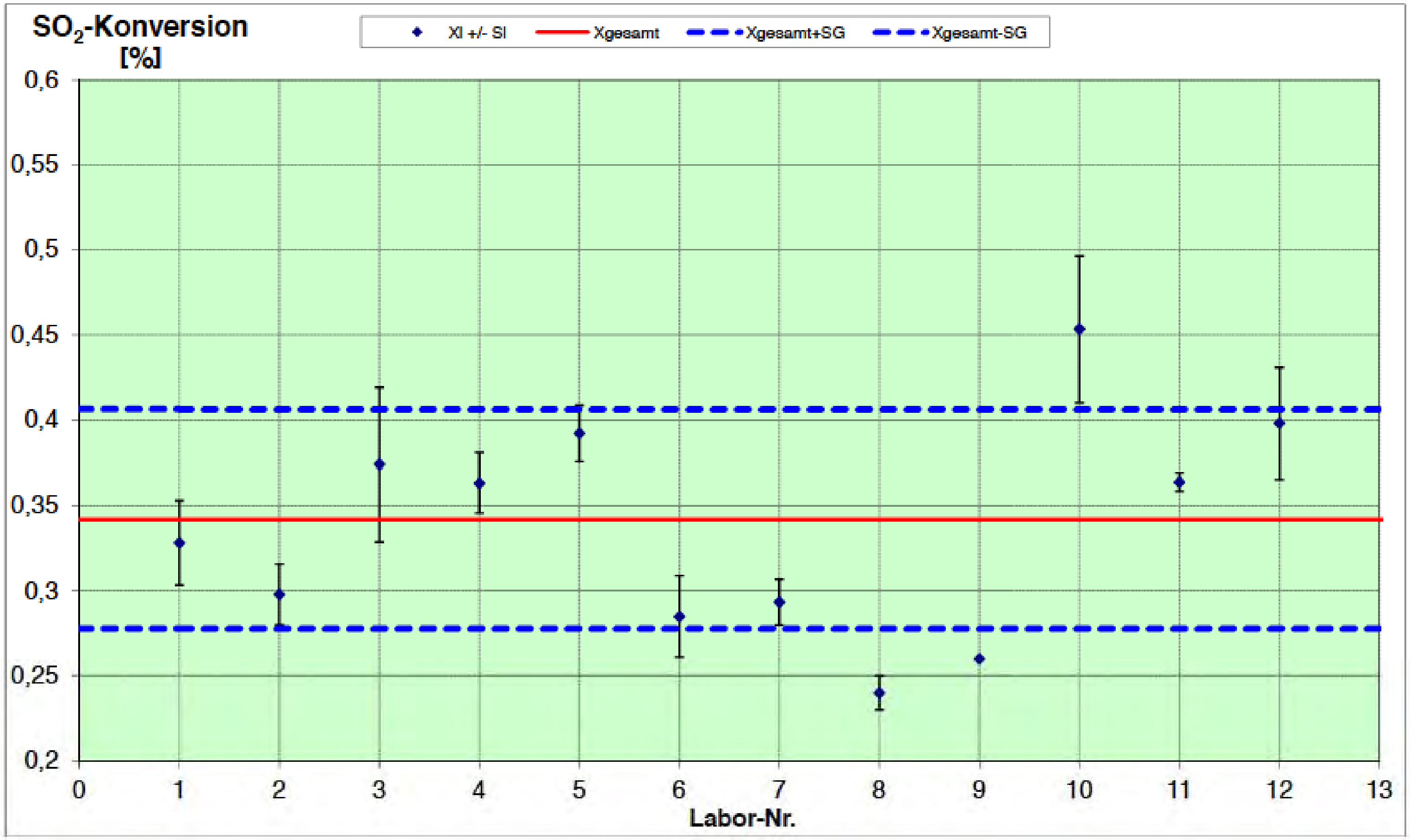
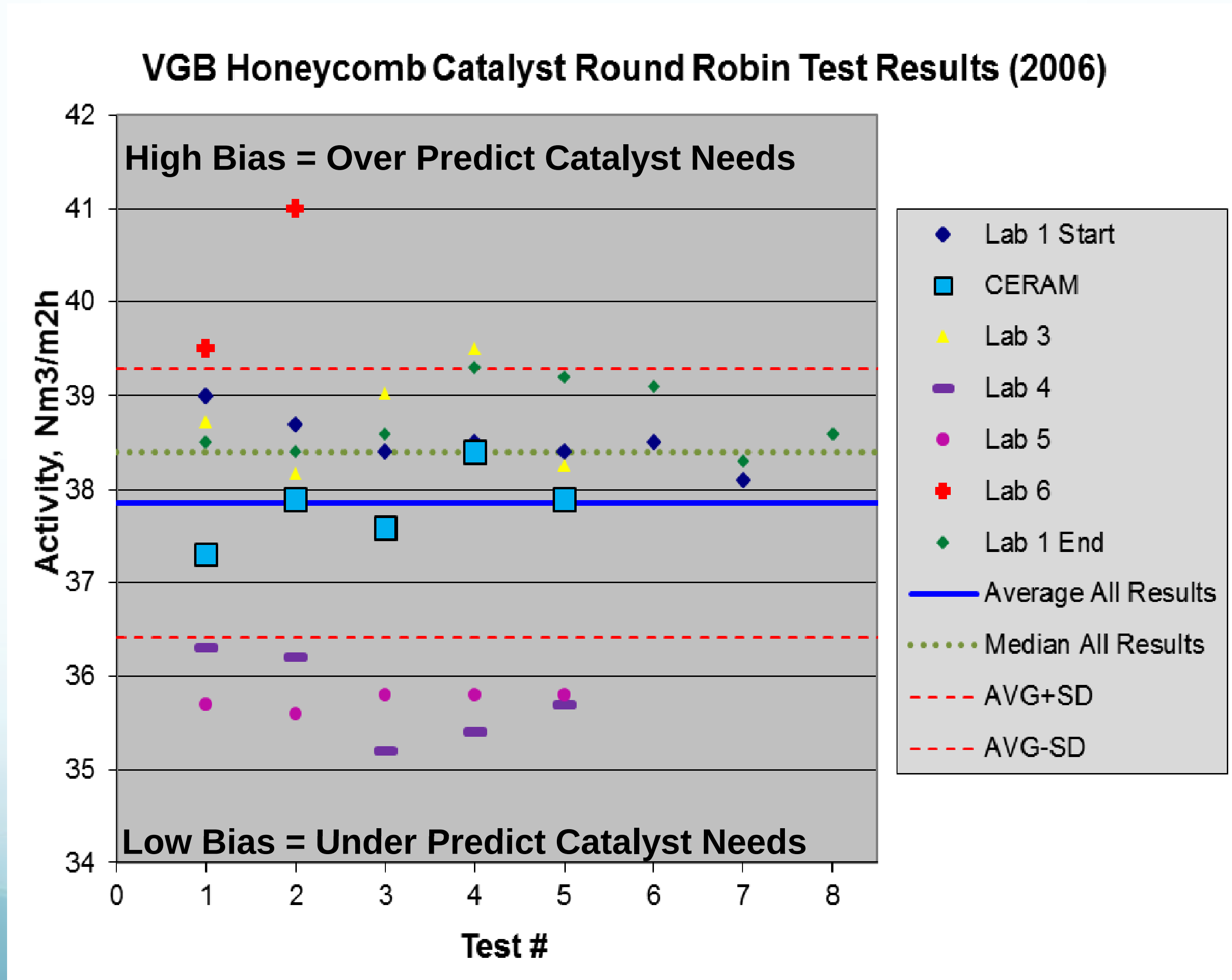
Round Robin


SO$_2$-Konversion [%]
Xi +/- Si
Xgesamt
Xgesamt+SG
Xgesamt-SG
0,6
0,55
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Labor-Nr.

Round Robin 2006



Sample Size

Micro- versus Bench Reactor

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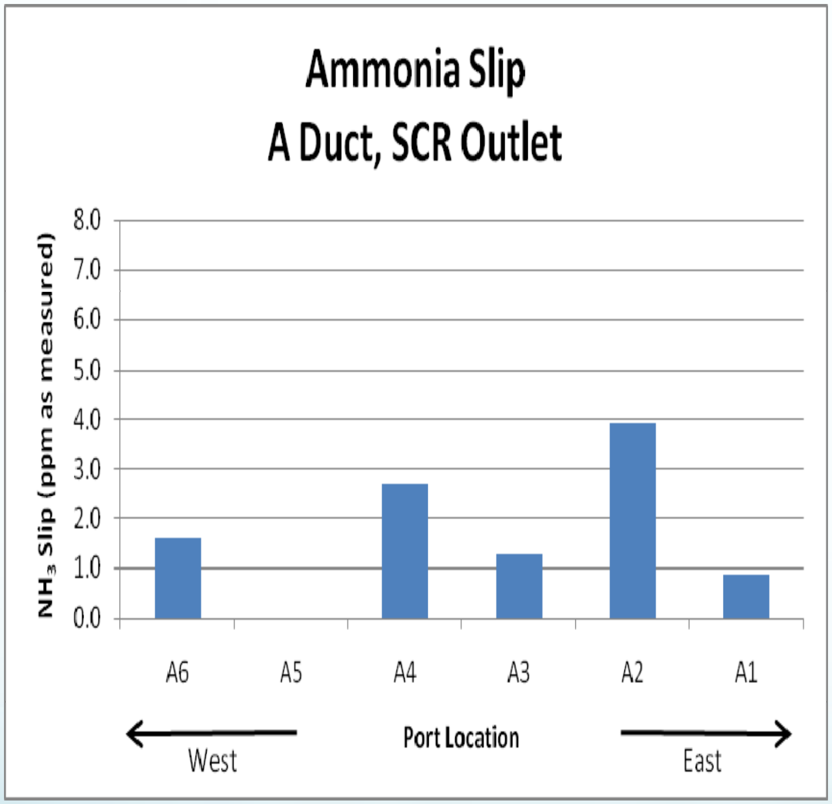
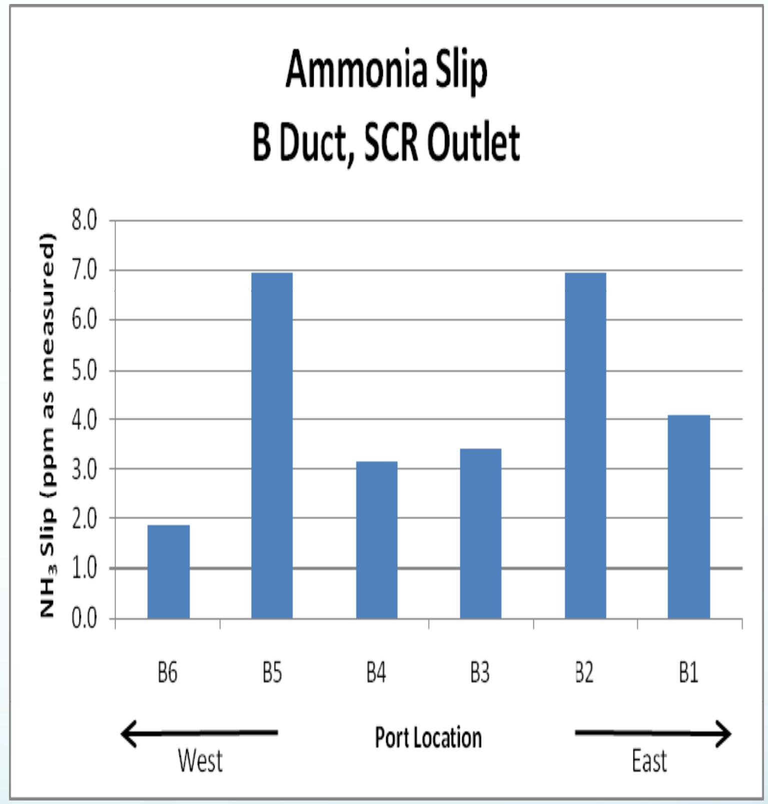
Additives

Additives

- Calcium or magnesium injection for ABS prevention
- Addition to the coal, injection in the furnace or before SCR
- Has been proven since the early 90s for SO_3 and arsenic mitigation

Additives





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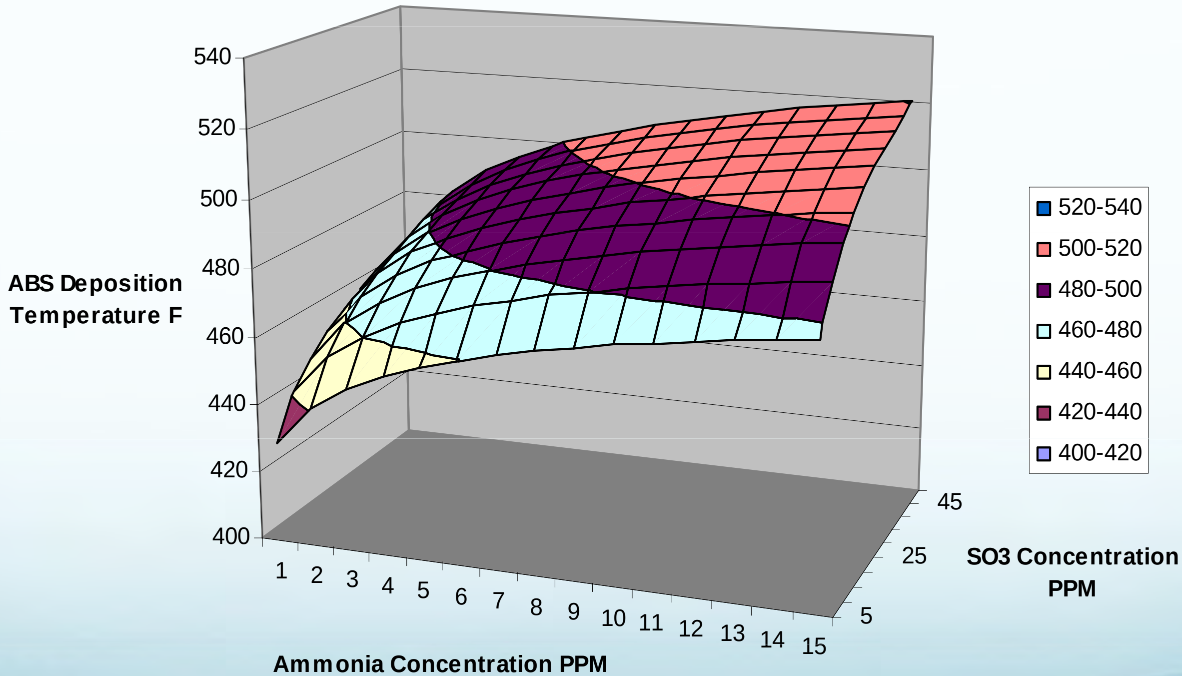
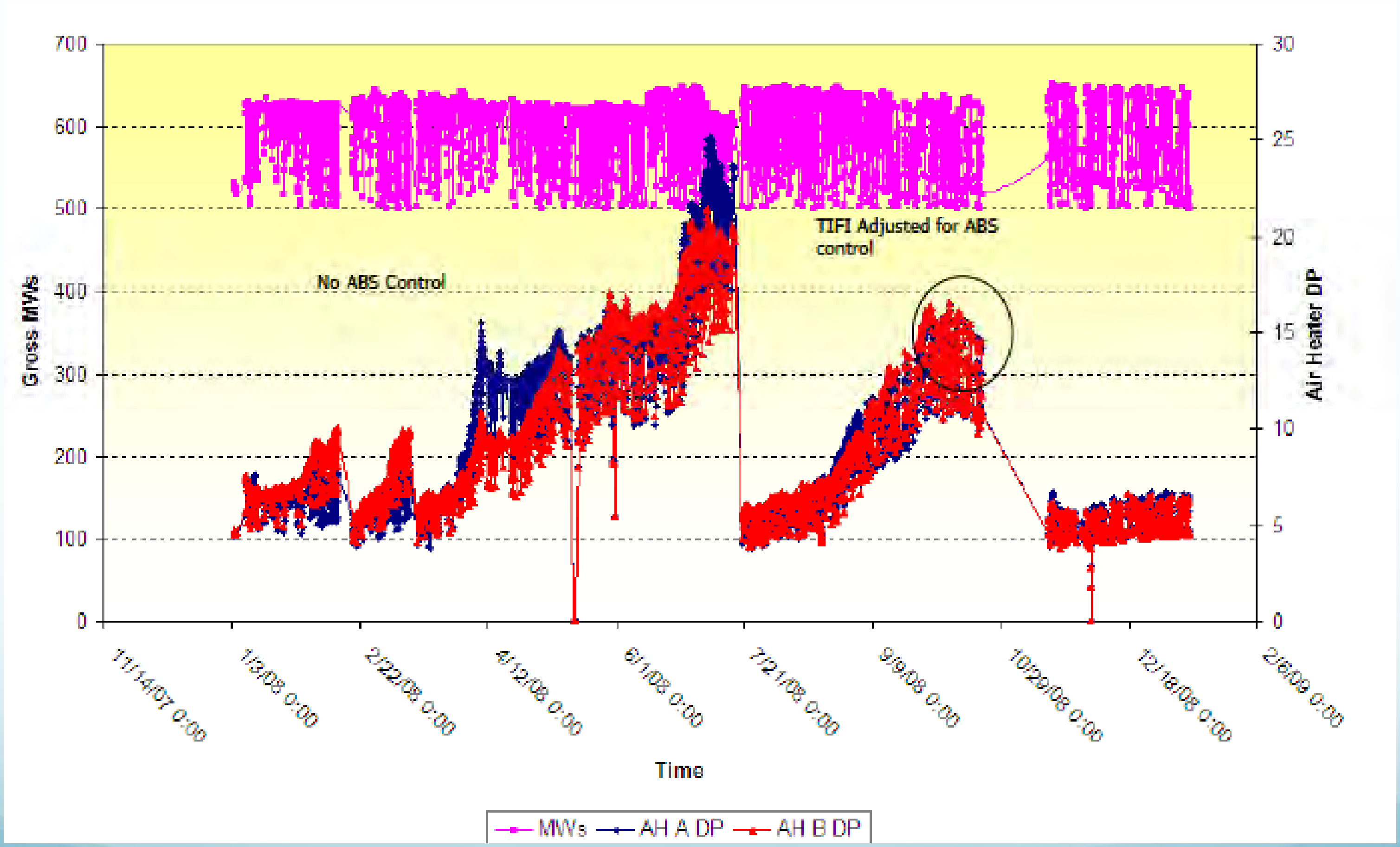
Additives

$NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4$

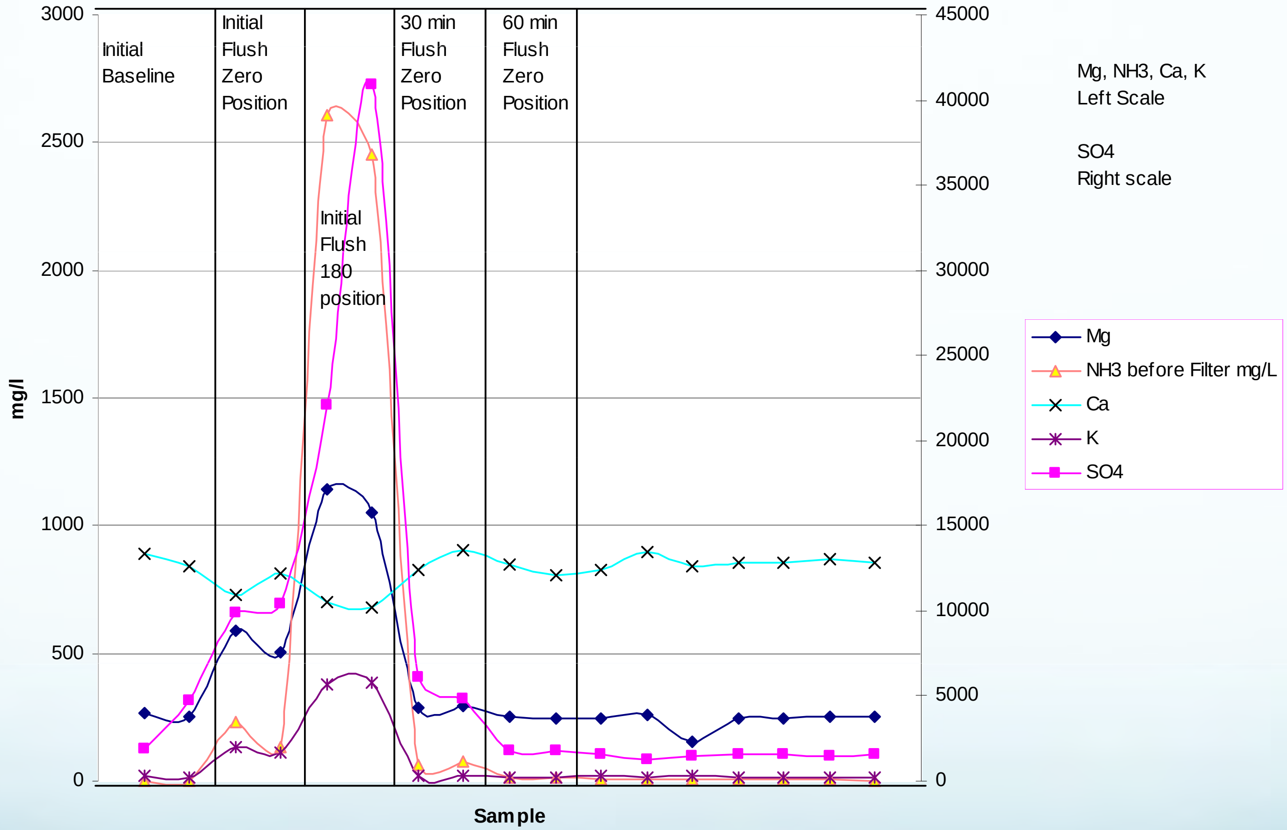


Additives



700
600
500
400
300
200
100
0
Gross MWs
30
25
20
15
10
5
0
Air Heater DP
No ABS Control
TIFI Adjusted for ABS control
11/14/07 0:00
1/3/08 0:00
2/22/08 0:00
4/12/08 0:00
6/1/08 0:00
7/21/08 0:00
9/9/08 0:00
10/29/08 0:00
12/18/08 0:00
2/6/09 0:00
Time
MWs
AH A DP
AH B DP

Additives


3000
2500
2000
1500
1000
500
0
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
mg/l
Sample
Initial Baseline
Initial Flush Zero Position
Initial Flush 180 position
30 min Flush Zero Position
60 min Flush Zero Position
Mg, NH3, Ca, K Left Scale
SO4 Right scale
Mg
NH3 before Filter mg/L
Ca
K
SO4

New VS. Regenerated Catalyst

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New VS Regenerated Catalyst

- Capital VS lifetime cost
- Deactivation over time
- Catalyst Potential
- History of regenerated catalyst
- Long time cost evaluation

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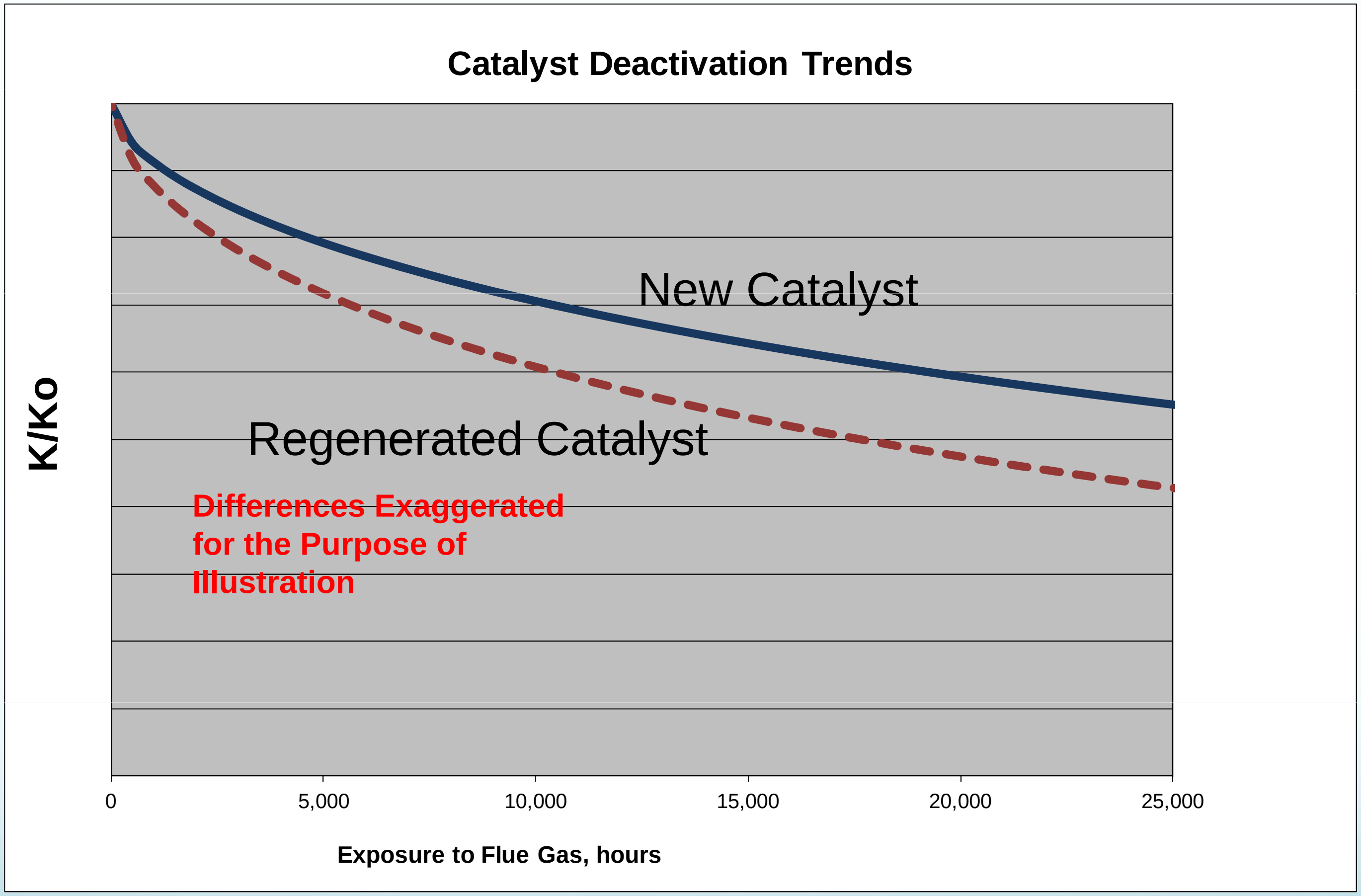
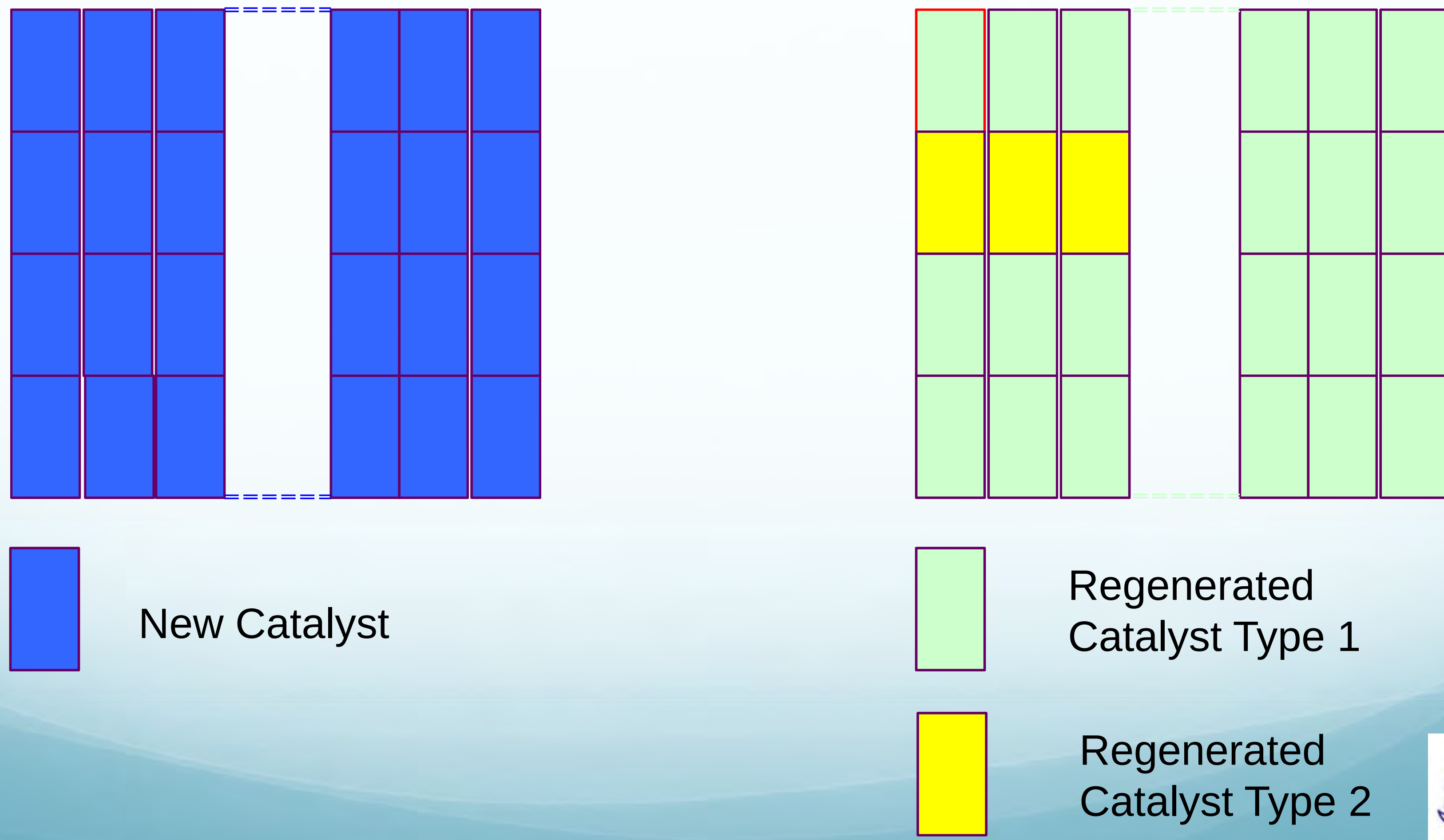
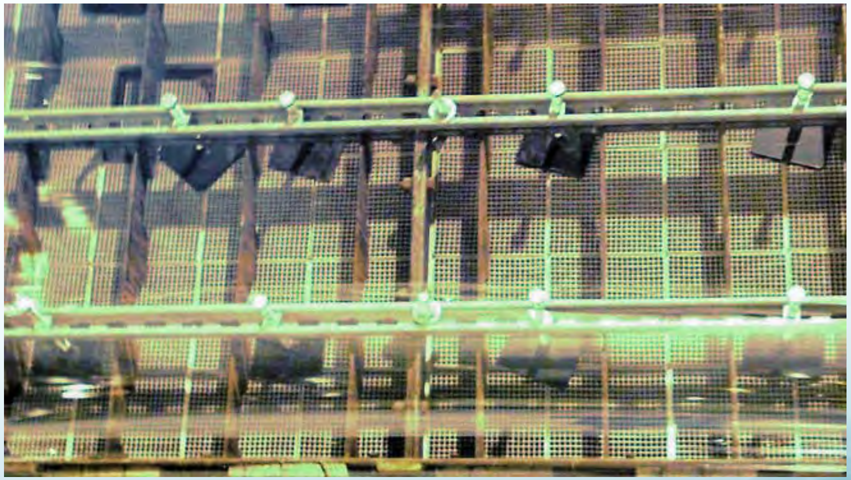
New VS Regenerated Catalyst



New VS Regenerated Catalyst



Catalyst Activity VS Potential



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Economic Example

600 MW Coal Plant Catalyst Management Plan

Past History **Future Plan**

Past

Future

Case 1 – New Catalyst For All Future Replacements (3 Year Outages)

Past

Future

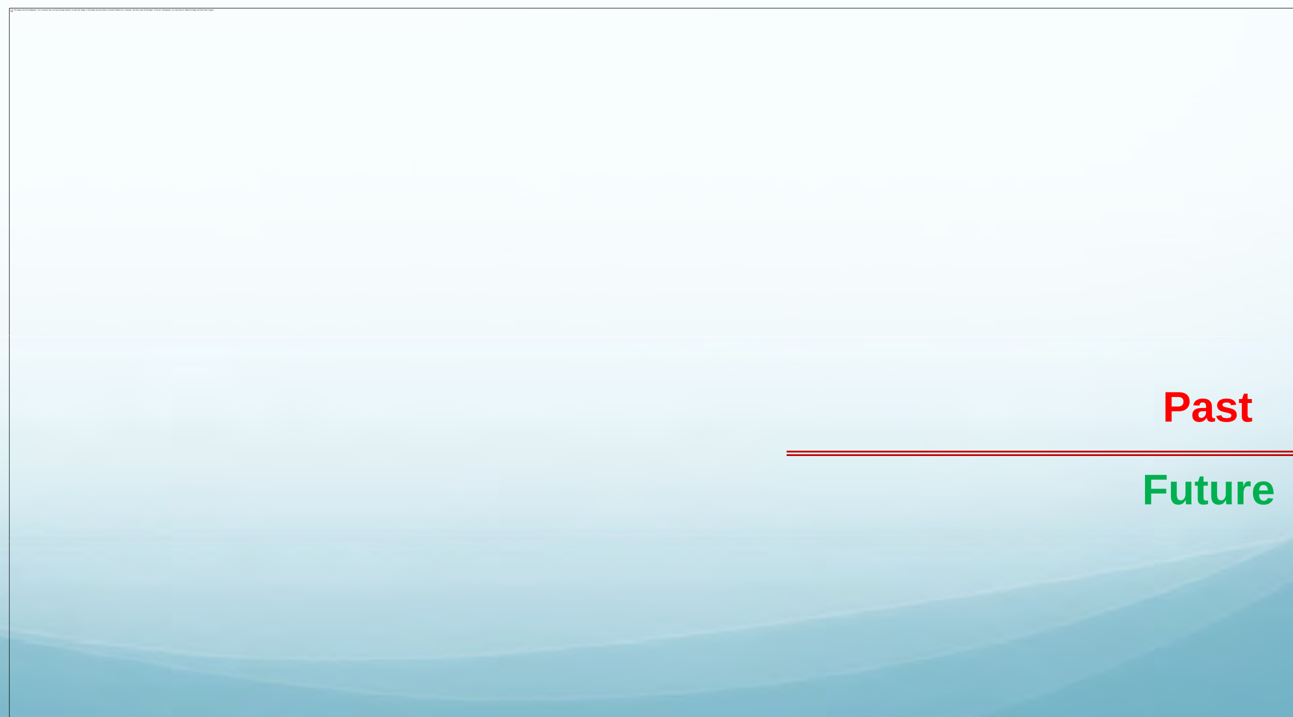
Three Year Outage Plan Achieved!

Case 1 – New Catalyst For All Future Replacements (3 Year Outages)

Net Present Value Analysis in 2018 Dollars	
Catalyst Related Expenditures	**$ 8,176,000**
Residual Catalyst Activity Value Remaining at End of Plan (2032)	**$ (16,000)**
Fan Energy Costs for Reactor Pressure Drop	**$ 3,613,000**
Total Net Present Value of Plan (2018 to 2032)	**$ 11,773,000**
NPV NOx Removal Cost of Plan (2018 to 2032)	**121 $/ton**

Analysis Assumptions

Escalation Rate	4.0%	New Honeycomb Catalyst Cost (2018)	$4500/m3
Present Worth Discount Rate	10.0%	New Plate Catalyst Cost (2018)	$3300/m3
Annual SCR Operation, hours/year	6,000	Catalyst Regeneration w/transport (2018)	$2400/m3
Capacity Factor	70%	Catalyst Removal Cost (2018)	$800/module
Fan Energy Cost (2018)	$0.06/kwh	Catalyst Installation Cost (2018)	$1000/module
		Catalyst Disposal Cost (2018)	$400/m3



Case 2 – Regenerated Catalyst For All Future Replacements

Regen Catalyst Assumptions (vs New):
+5% Pluggage
-10% Activity (equivalent SO2:3)
+5% Deactivation Rate
No Difference in Mechanical Quality (Realistic?)

Cannot Withstand Reduced Performance!

Not Possible to Maintain 3 Year Outage Plan!

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Case 2 – Regenerated Catalyst Requires More Frequent Replacements

Regen Catalyst Assumptions (vs New):
+5% Pluggage
-10% Activity (equivalent SO2:3)
+5% Deactivation Rate
No Difference in Mechanical Quality (Realistic?)

Replacements Required Every Two Years to Maintain Performance

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Case 2 – Regenerated Catalyst Requires More Frequent Replacements

Net Present Value Analysis in 2018 Dollars	
Catalyst Related Expenditures	**$ 7,597,000**
Residual Catalyst Activity Value Remaining at End of Plan (2032)	**$ 0**
Fan Energy Costs for Reactor Pressure Drop	**$ 3,782,000**
Total Net Present Value of Plan (2018 to 2032)	**$ 11,379,000**
NPV NOx Removal Cost of Plan (2018 to 2032)	**117 $/ton**

Analysis Assumptions			
Escalation Rate	4.0%	New Honeycomb Catalyst Cost (2018)	$4500/m3
Present Worth Discount Rate	10.0%	New Plate Catalyst Cost (2018)	$3300/m3
Annual SCR Operation, hours/year	6,000	Catalyst Regeneration w/transport (2018)	$2400/m3
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		Catalyst Disposal Cost (2018)	$400/m3

- Nearly Identical NPV to New Catalyst NPV
- Two Year Outage Interval Required
- 8 Events (Regen Cat) vs 5 Events (New Cat)
- <u>What is Indirect Cost of 2 vs 3 Year Outage Interval?</u>
- Reduced Mechanical Quality vs New = Reduced Interval

+5% Pluggage
-10% Activity (equivalent SO_2:3)
+5% Deactivation Rate

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Conclusions

- Catalyst activity and conversion rate test results over time must be comparable
- Catalyst lifetime is constantly changing
- Numerous tools are available to extend the catalyst lifetime
  - Boiler operation optimization
  - AIG tuning
  - Improve distributions
- Additives become economical, if other effects are considered
- Advantages of new versus regenerated catalyst depend on the criteria

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Thank you very much

Questions?

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