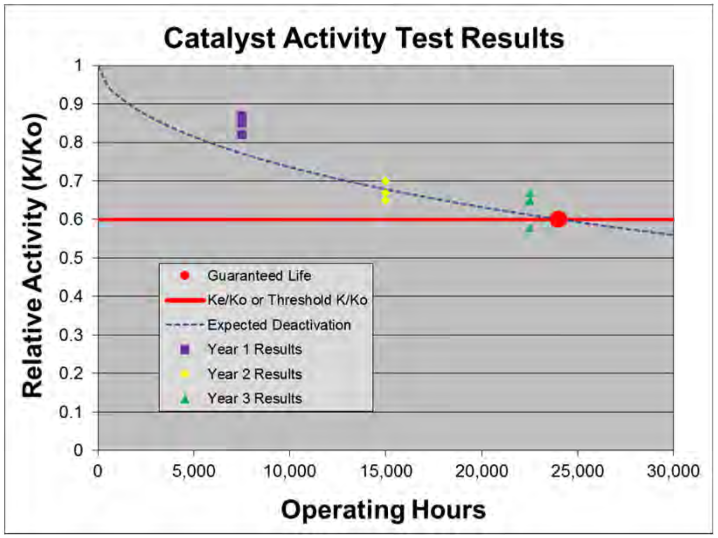
REINHOLD ENVIRONMENTAL Ltd.

2015 NOx-Combustion Round Table & Expo Presentations

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

Reinhold Environmental 2015 NOx-Combustion Round Table

Do Your Laboratory Activity Test Results Match Field Performance?



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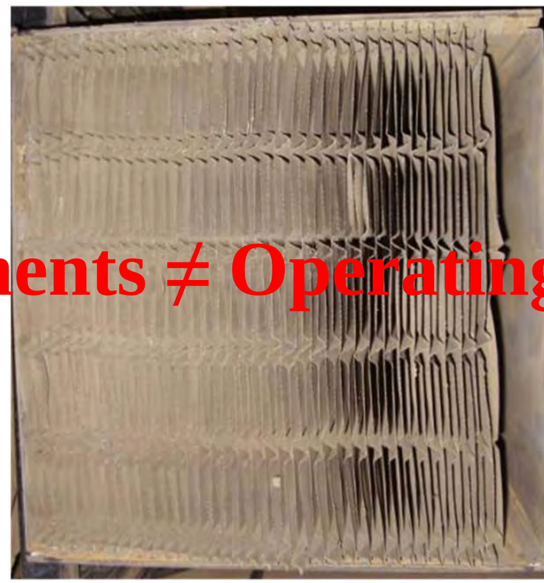
Presented by:
John Cochran & Noel Rosha
IBIDEN CERAM Environmental, Inc.

February 24, 2015

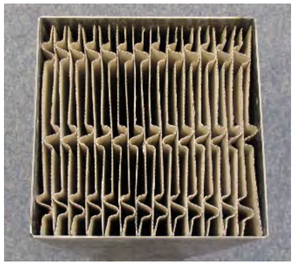
The Challenge For Catalyst Management Planning

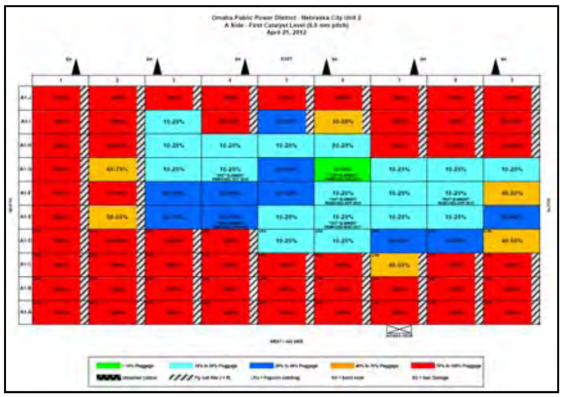
Does A Laboratory Activity Measurement Accurately Reflect Reactor Operating Conditions?

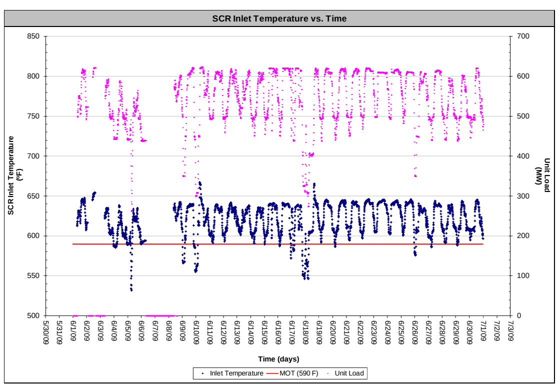


Activity Measurements ≠ Operating Reactor Potential

Key Aspects of Effective Catalyst Management Planning





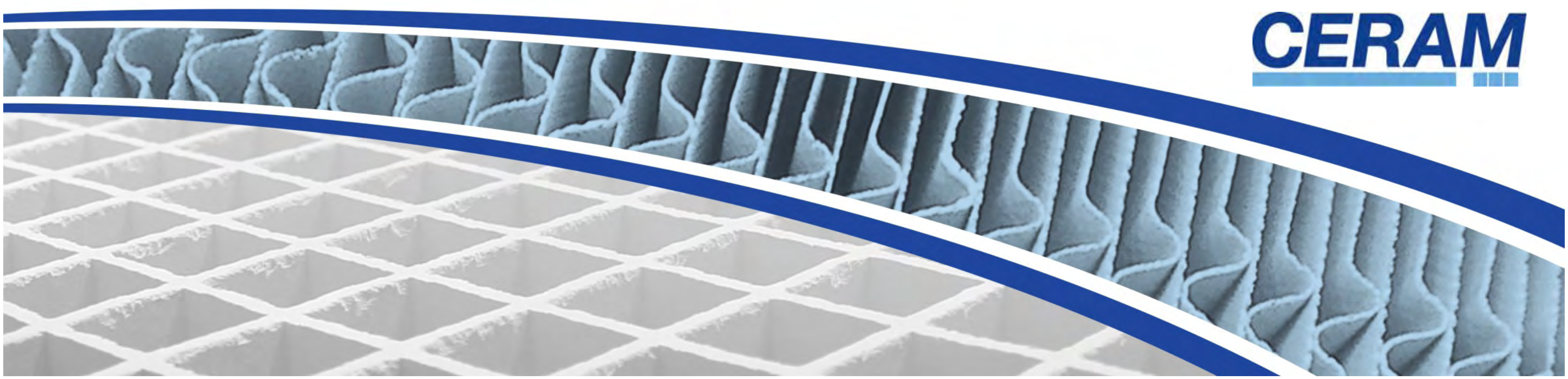


- Catalyst Testing:
  - Accuracy and Consistency
  - Benchmarking
  - Consider Activity Measurement Bias
    - Low – Premature Catalyst Additions
    - High – Increased Operating Risks/Costs
- Assessment of Mechanical Conditions
  - Pluggage
  - Catalyst Mechanical Condition
  - Seal Integrity
- Assessment of Operating Conditions
  - DeNOx Demand – SCR Process Requirements
  - Boiler Operations – Affecting "Operating" Reactor Potential

Presentation Topics

- Catalyst Testing Considerations
- Traditional Catalyst Management Planning
- Enhanced Catalyst Management Planning
- Recent Experience: Midwest Utility 810 MW Unit Burning PRB
  - Pluggage Problems and Upgrades
  - Dry Ice Blasting and Regenerated Catalyst (Plate and Honeycomb) Experience
  - Correlating Field Ammonia Slip Measurements to Operating Reactor Potential
  - Catalyst Management Course Changes Necessary to Accommodate Outage Schedule
  - Root Cause Analysis and Results

Catalyst Testing Considerations



The Most Important Factor: Accuracy

- There is No Direct Measurement of Activity
- Must Accurately Measure and Control….
  - NOx Reduction
  - NH_3 Molar Ratio
  - Gas Flow
  - Sample Geometry
  - Recreate Flue Gas Conditions

- Accuracy Determined by Benchmarking and Statistics
  - Internal Audits of Known Samples
  - External Benchmarking to Assess Accuracy and Bias
  - Benchmarking and Audit Goal – Unbiased Measurement
- Need to Correlate Laboratory Measurements to Field Results
- Without External Benchmarking is it Possible to Assure Accuracy?

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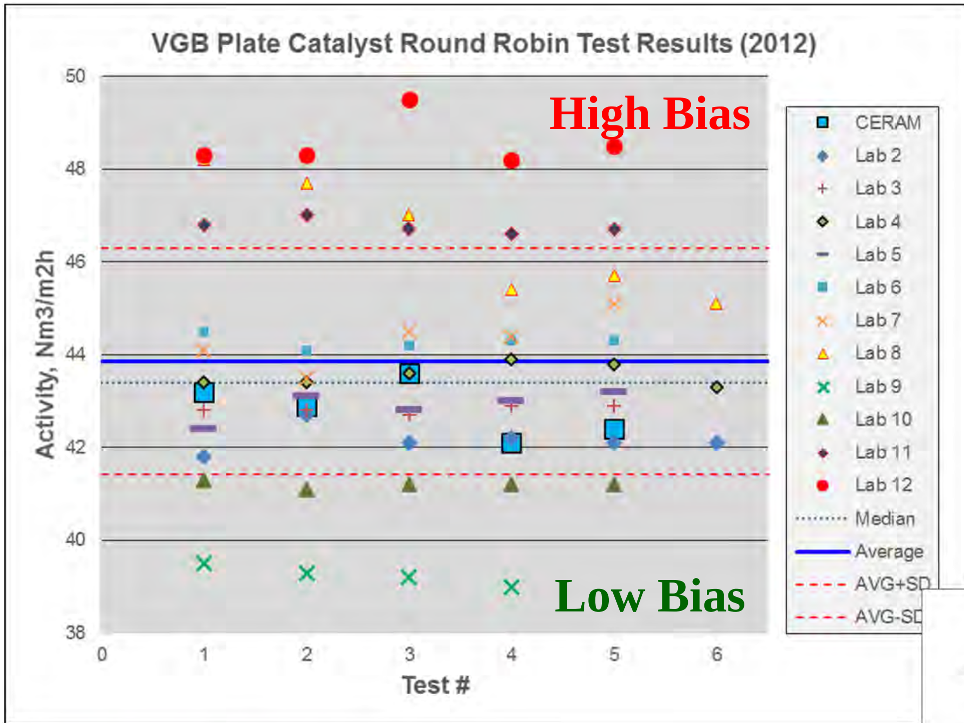
CERAM Laboratory Capabilities

- Performing >2300 Activity Tests Annually
  - QA/QC for New Production of Honeycomb and Plate
  - Aged Catalyst Samples of Honeycomb, Plate and Corrugated Fiber by All Predominant Suppliers
- >20 Full Bench and Semi Bench Reactors for Activity and Conversion Rate Measurements
- VGB Benchmarked Laboratory
  - 2006 Honeycomb Test – CERAM Closest to Average Result at -0.03 Nm^3/m^2h
  - 2012 Plate Test – CERAM 4^{th} Closest to Average at -1.0 Nm^3/m^2h
- Routine Benchmarking With Other Industry Leading Laboratories

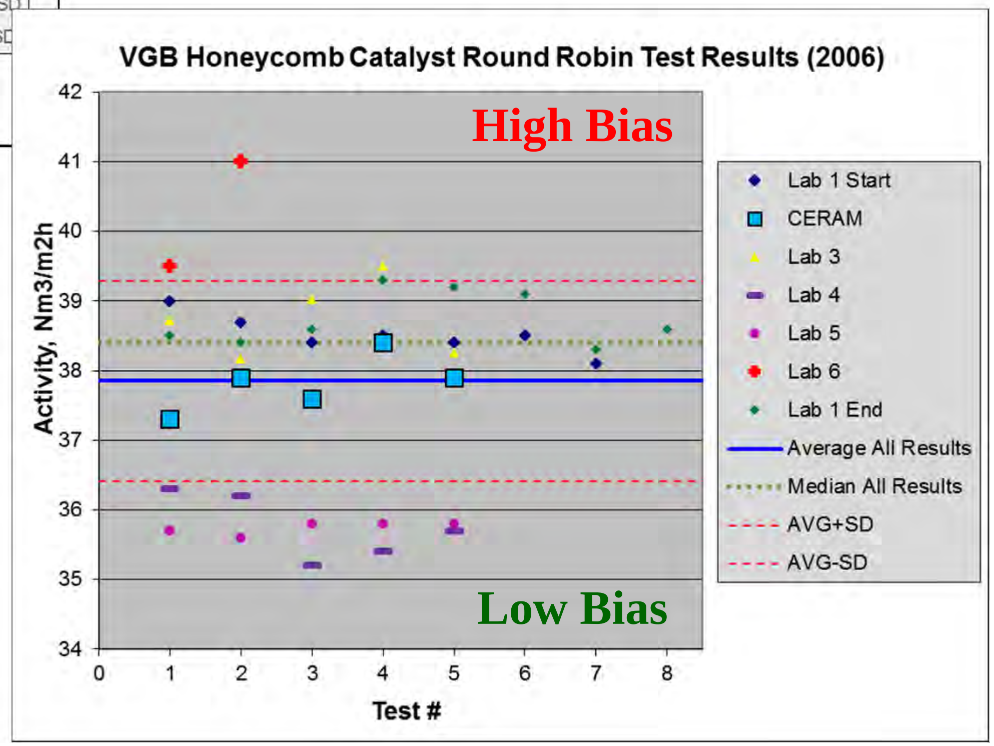


VGB Round Robin* Test Results

CERAM's Laboratory Has Confirmed Accuracy for Testing Honeycomb and Plate Catalyst

- **Low Bias** = <u>Premature Catalyst Replacement</u> (increased catalyst cost)
- **High Bias** = <u>Late Catalyst Replacement</u> (increased NH_3 use and operating risk)

Laboratory Bias Exceeding 2 K Problematic for Catalyst Management



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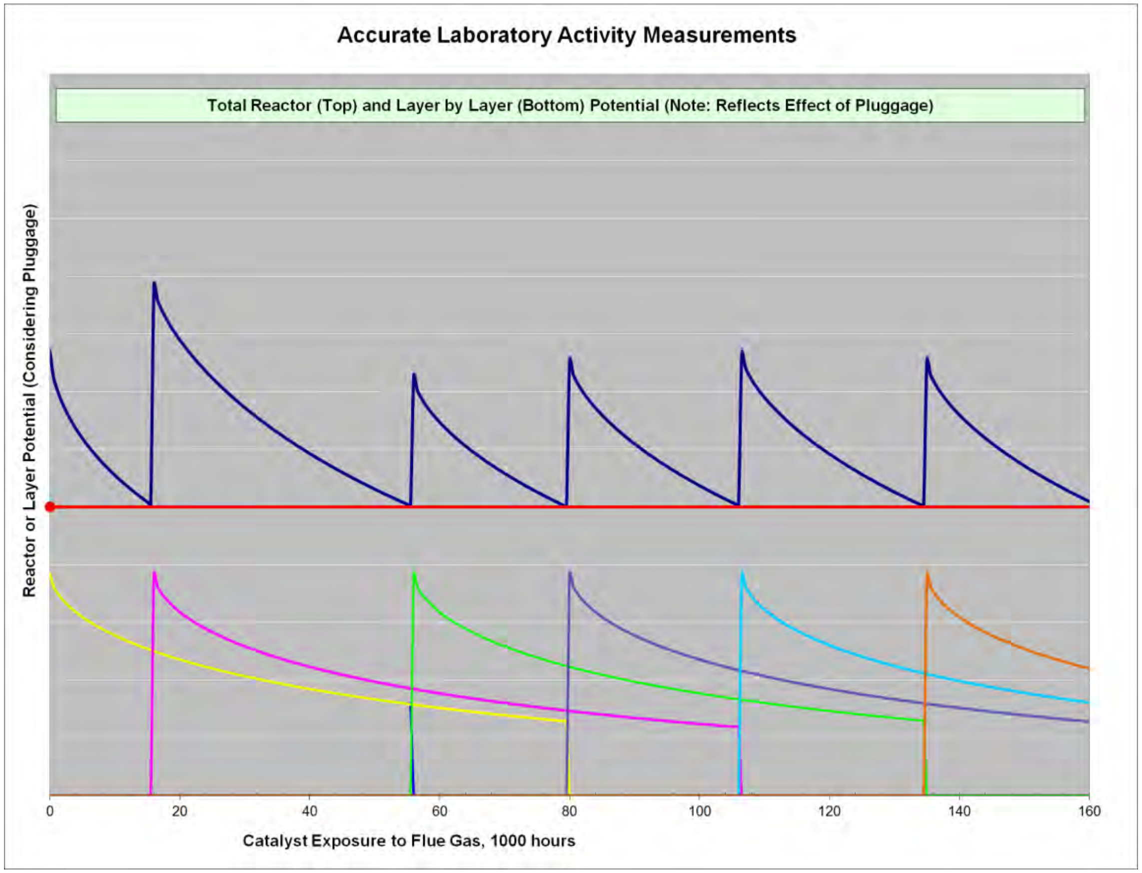
*VGB Round Robin: Element With Unknown Activity Circulated to Participating SCR Catalyst Test Laboratories

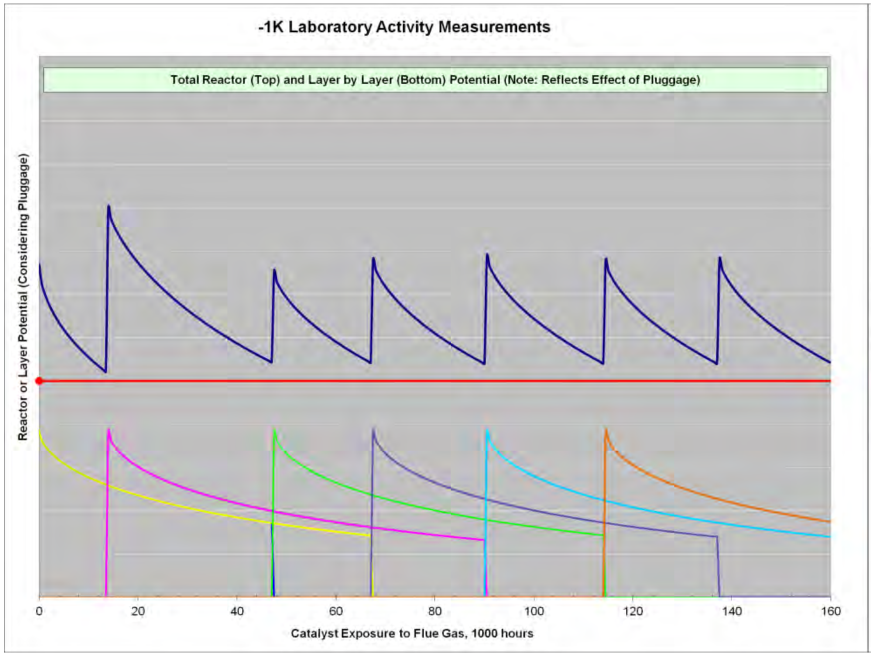
Implications of Biased K Measurements

- Example 500 MW Unit With 2+1 Reactor
- 80% NOx Reduction / 2 ppm NH_3 Slip / 16,000 Hour Life
- Assumed Unbiased Measurement:
  - $11M in Catalyst Costs Over 20 Years
- 5 Catalyst Events



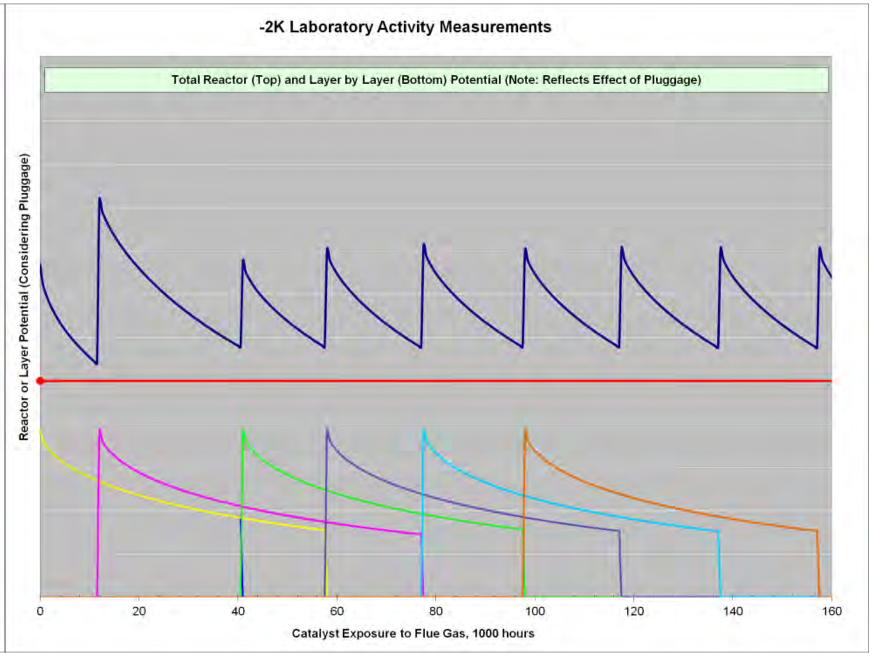
Low Bias Lab Activity Result:
Wasted Activity and Increased Catalyst Costs

Minus 1 K Bias



- $1.5 M (14%) more catalyst
- 6 Events (+1 to Unbiased)

Minus 2 K Bias



- $3.6 M (33%) more catalyst
- 8 Events (+3 to Unbiased)

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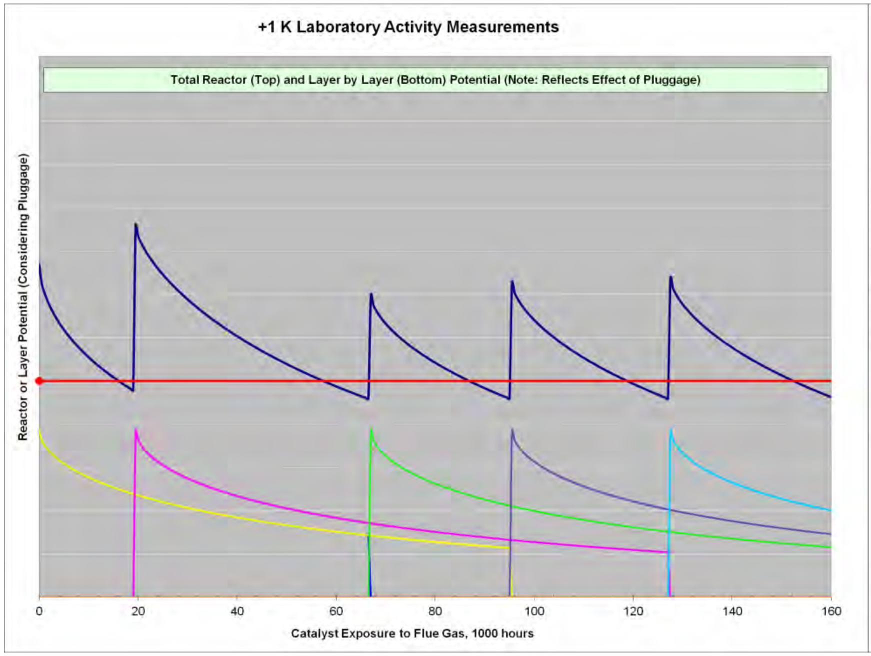
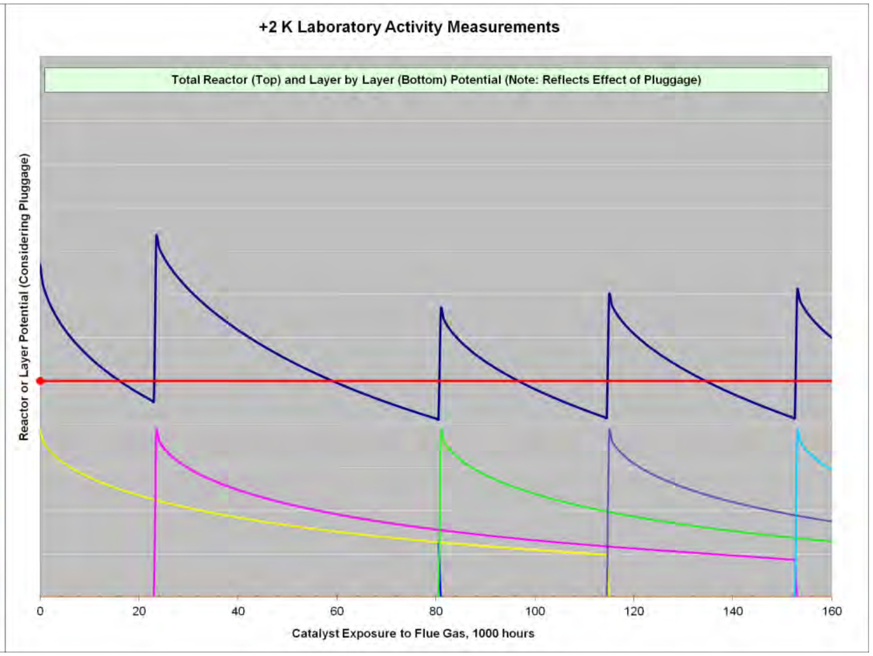
High Bias Lab Activity Result: Deficient Performance

Plus 1 K Bias



- 3.5 ppm NH_3 slip
- Surprise Catalyst Needs (+$/m^3)

Plus 2 K Bias



- 6 ppm NH_3 slip
- Surprise Catalyst Needs (+$/m^3)

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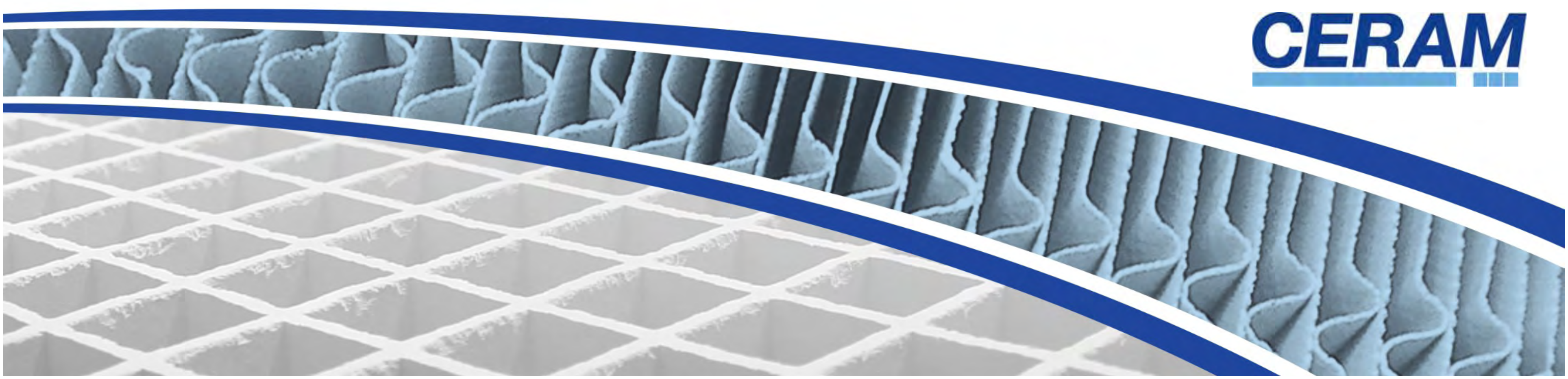
Traditional Catalyst Management

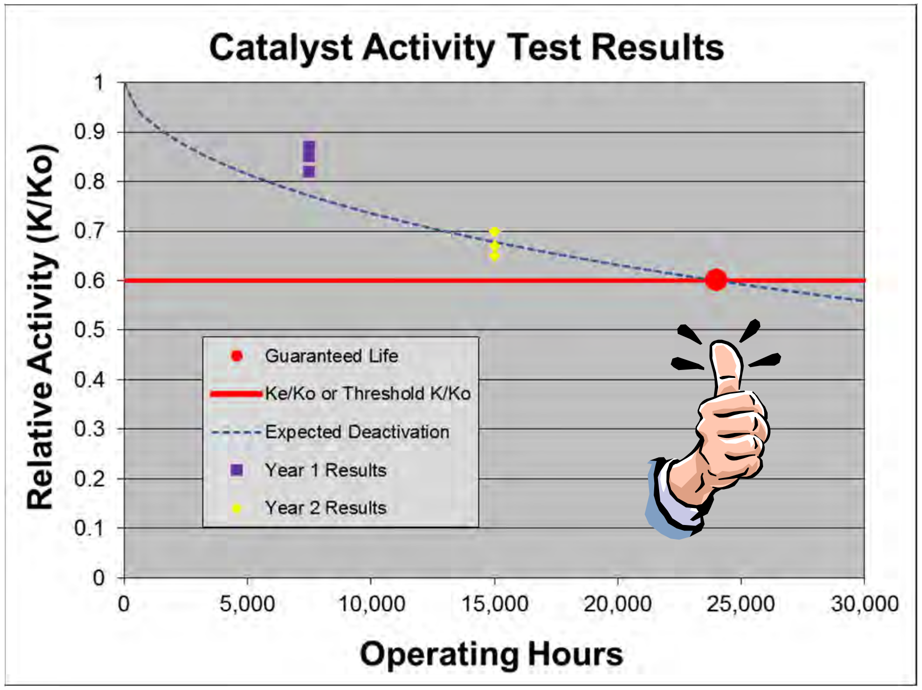


Traditional Catalyst Management Approach

- Test Elements Removed From Reactor and Sent to Laboratory
- Laboratory Tests Determine if K/Ko is Above Original Sizing Basis Ke/Ko
  - Example Below Says All Performance is Good, But Time to Procure Catalyst – Is It Really?
  - Are Laboratory Results Representative of Operating Catalyst?
  - What Has Changed Since Original Design?
    - Boiler Operations (T, NOx, O_2), Fuels, Gas Flow Rates, Pluggage, DeNOx Objectives, SO_2:SO_3 Conversion Rate Objectives, Hg Oxidation Objectives ….

This Approach:

- Neglects Catalyst Mechanical Condition
- Neglects DeNOx Demand Different from Original Design Basis
- Neglects Catalyst Operating Condition



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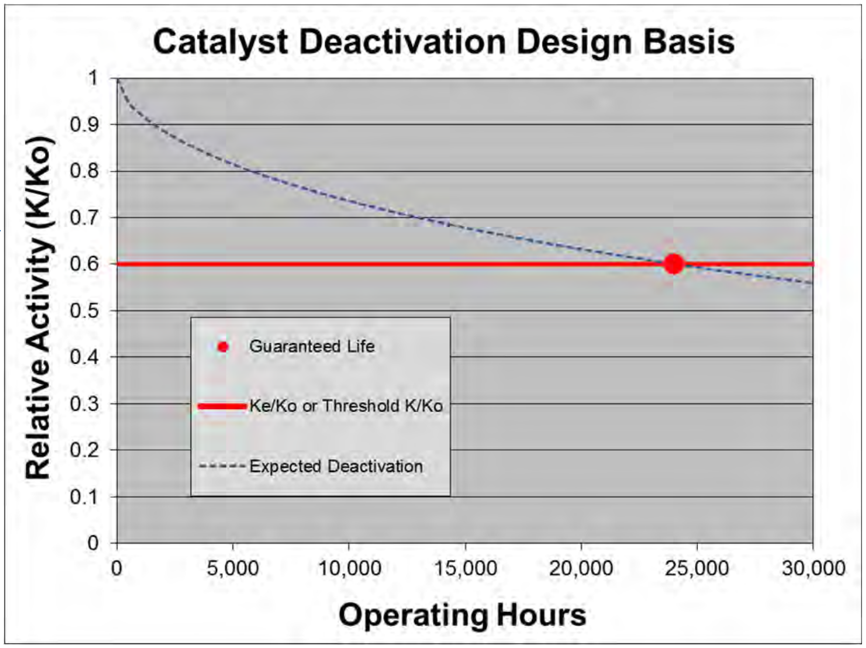
Traditional Catalyst Management

- Dependent on Original Catalyst Design
- Catalyst Designed to Project Specific Envelope
  - Flue Gas Conditions (Flow, Inlet NOx, T, O_2, H_2O, etc.)
  - Fuel Quality
  - NOx Removal/Outlet NOx, Ammonia Slip, and Conversion Rate
- Ke/Ko Based on Design Envelope
  - Subsequently Used as Catalyst Management Basis
- <u>Assumes</u> Design Envelope = Reality

Design Envelope 700 MW PRB:
Inlet/Outlet NOx: 0.35/0.08 lb/MBtu
Gas T = 745 F   Oxygen = 3.1%
Flow = 3.9 MACFM
Catalyst Pluggage ≤ 5%



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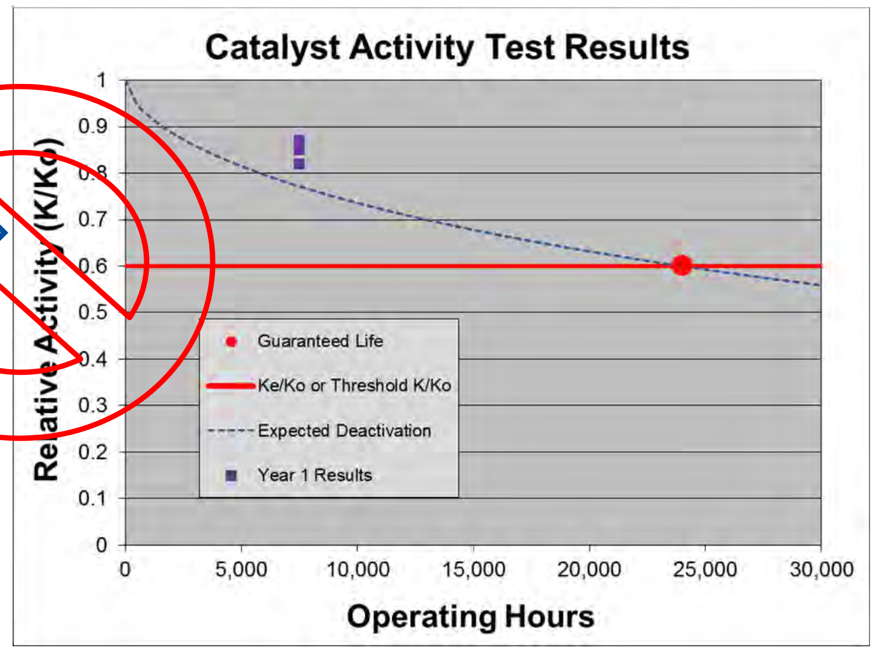
Pitfall of Traditional Catalyst Management

- Catalyst Performance Dependent on Many Factors
- Ke/Ko Basis Typically Not Representative of Actual Operations
- Actual Operations Can Be Quite Different Than Design Envelope
  - Experience Below Illustrates Differences That Can Occur
  - New Catalyst Layer Installation Delayed Two Years/16,000 Hours
- Accurate Catalyst Management Planning Assured With Reactor Potential Based Approach

Actual Operations 700 MW PRB :
Inlet/Outlet NOx: **0.23/0.06** lb/MBtu
Gas T = **672 F** Oxygen = **2.0%**
Flow = **3.5** MACFM
Catalyst Pluggage ≥ **10%**

Design Envelope 700 MW PRB:
Inlet/Outlet NOx: 0.35/0.08 lb/MBtu
Gas T = 745 F Oxygen = 3.1%
Flow = 3.9 MACFM
Catalyst Pluggage ≤ 5%



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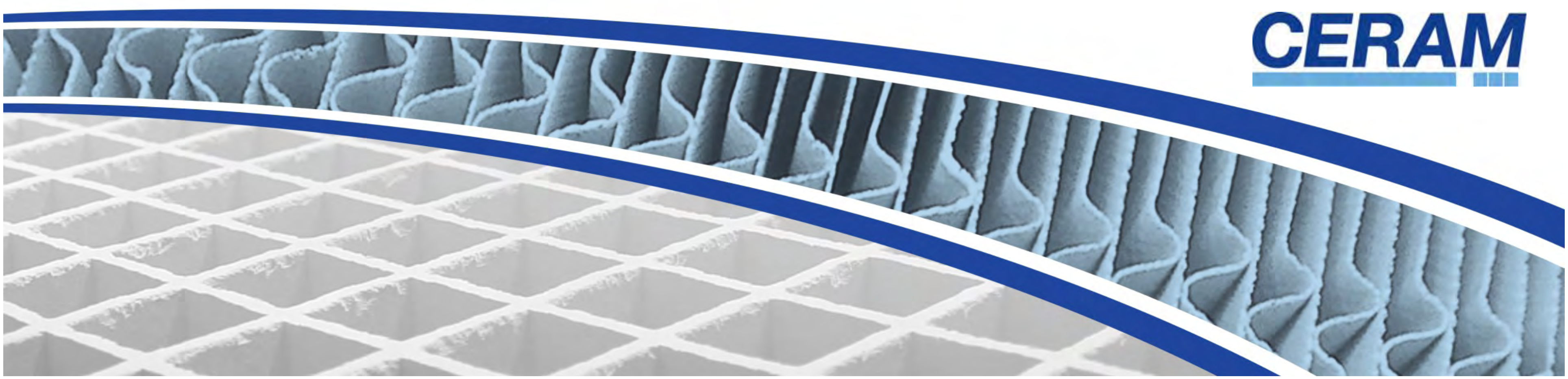
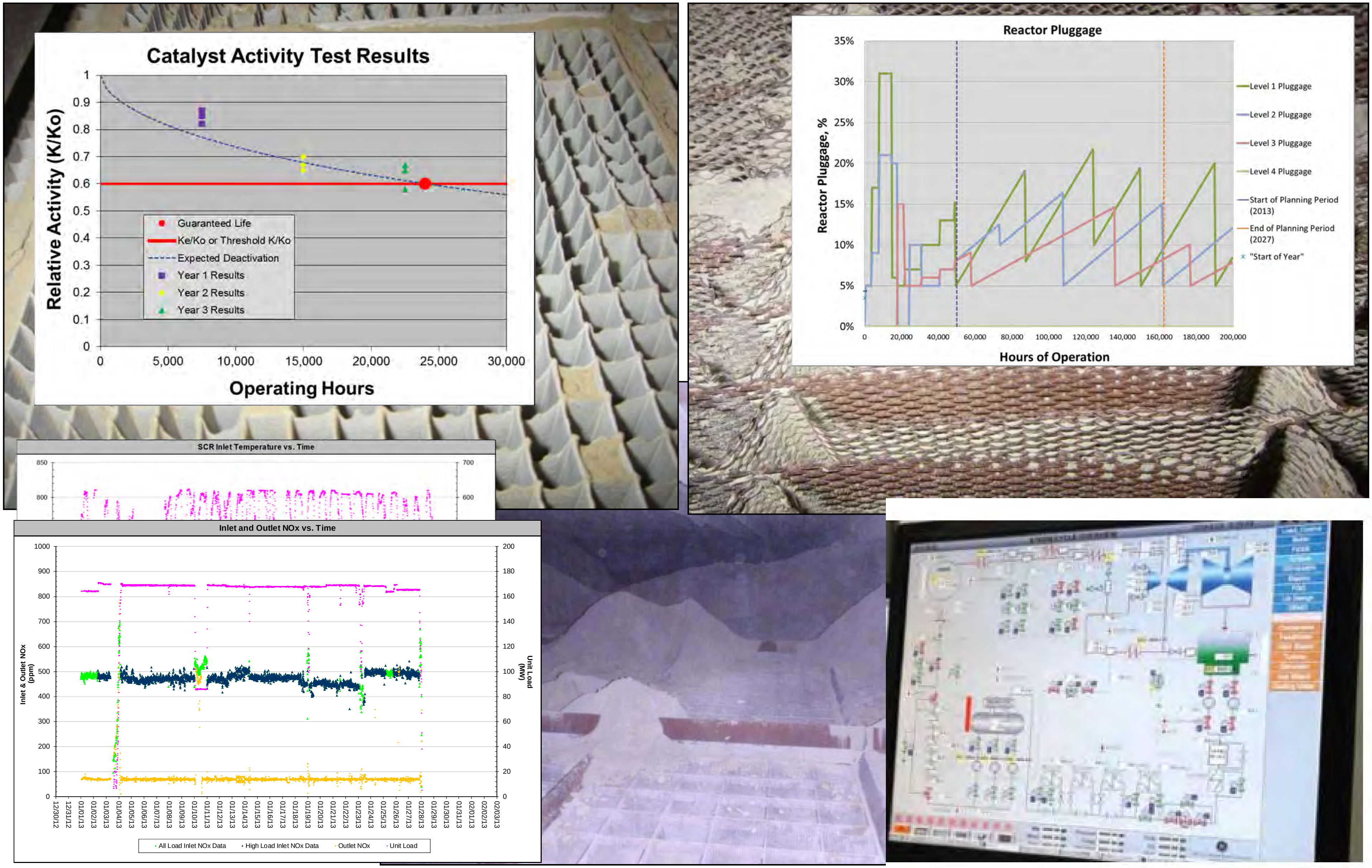
CATLife® Enhanced Catalyst Management Planning



All Aspects Affecting Catalyst Must Be Considered to Assure Accurate Planning



Operating Reactor Potential

$$P_o = \sum K_l / Av_l$$

P_o = Operating Reactor Potential

K_l = Operating Catalyst Activity (layer based), Nm^3/m^2h
(based on maximum operating load conditions and limiting fuel gas conditions, e.g., T, O_2, H_2O, etc.)

Av_l = Area Velocity (layer based), Nm/h
(normal gas flow, Nm^3/h divided by total catalyst surface area in service, m^2)

The Magnitude of Reactor Potential Determines the Amount of SCR System Performance Possible (DeNOx & Ammonia Slip Control)

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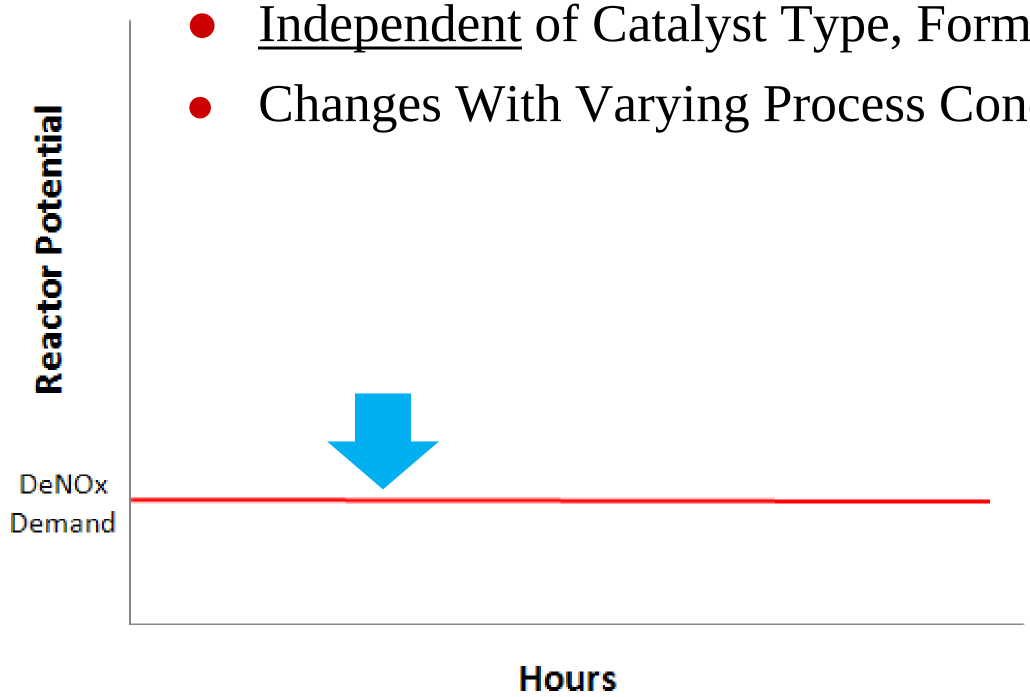
DeNOx Demand

- DeNOx Demand (P_{req}) = The Reactor Potential Required to Meet NOx Removal and Ammonia Slip Requirements
- Calculated Based on NO_X Removal Requirements, NH_3 Slip, and SCR Reactor Distributions (velocity, NH_3/NOx, temperature)
- <u>Independent</u> of Catalyst Type, Formulation or Manufacturer
- Changes With Varying Process Conditions and Requirements



$$P_{req} = K_{req} / Av$$

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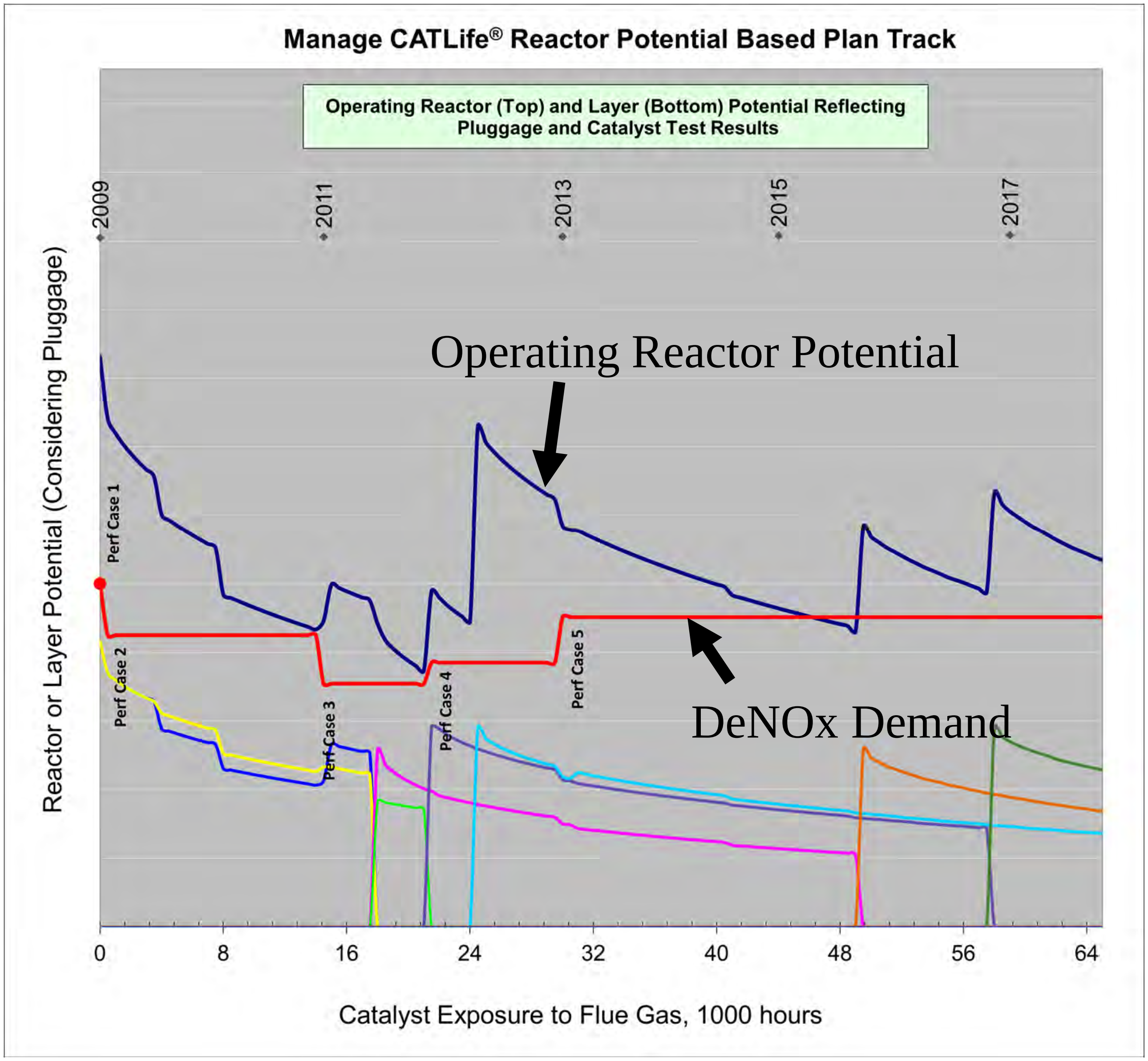
CATLife® Method – Assessment of DeNOx Demand and Operating Reactor Potential



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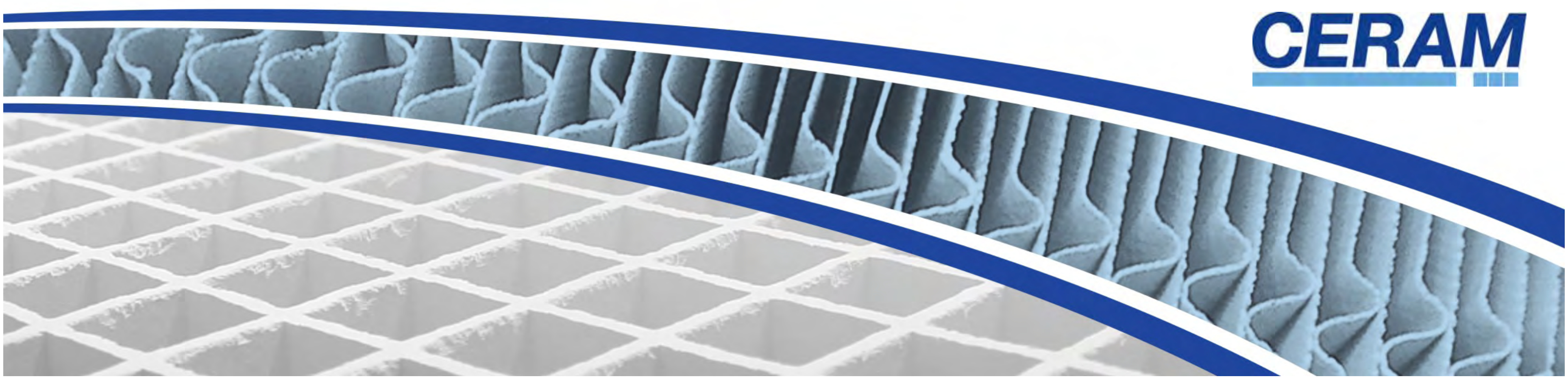
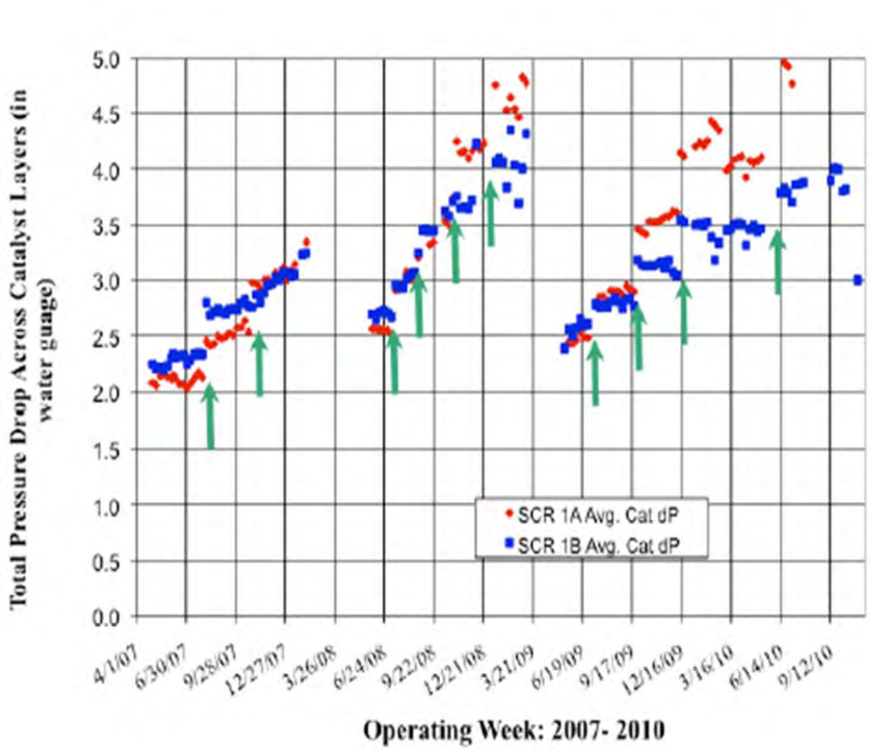
Recent Experience: Midwest Utility 810 MW Unit Burning PRB



Case Example: Midwest Utility

- 810 MW (Gross) Cyclone
- 100% PRB or 85/15 blend of PRB and local high sulfur coal
- SCR began commercial operation in 2007
  - 3+1 Reactor (7.1 mm pitch honeycomb)
  - 45% pluggage after one year
- Catalyst replaced in 2009 due to pluggage, DP, and erosion
  - 8.2 mm pitch honeycomb
- In 2011 after 11,500 hours heavy pluggage continues
  - Add new CERAM L1, rejuv./ vacuum L2 & vacuum L3



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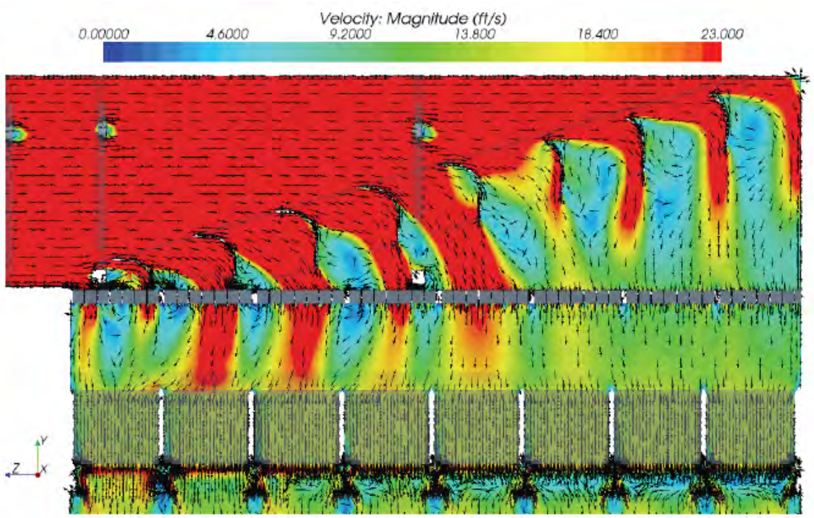
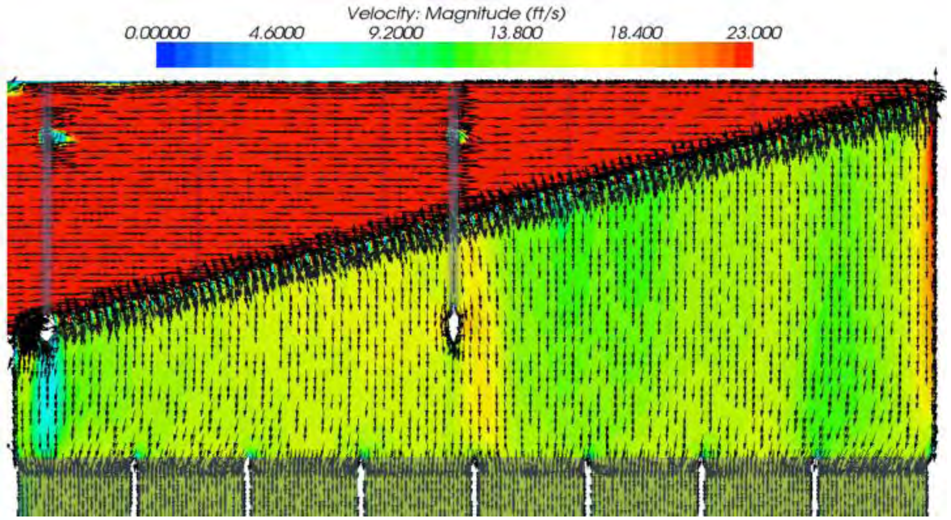
Major Modifications Made in 2012

- Another full catalyst replacement occurs
  - 3 layers of regenerated catalyst installed (L1 empty)
    - Johnson Matthey 5.7 mm plate in L2
    - Cormetech 8.2 mm honeycomb in L3
    - CERAM 8.2 mm honeycomb in L4
- New cyclone burners
  - Potential improvement in phosphorus poisoning
- Reactor hood redesigned
  - Fuel Tech GSG replaces turning vanes
  - Egg crate and supports removed
  - External reinforcement added
  - Goal of achieving 20% pluggage
- Install tented seals and support beam ash guards

Before and After CFD

Original Turning Vanes | **Fuel Tech GSG**





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CERAM CATLife® Services

- CERAM begins CATLife® services in 2012
  - Catalyst testing
  - AIG tuning
  - Operating data assessments
  - Ammonia slip testing
  - Manage CATLife® modeling
- Begin gathering data
  - Start with operating data analysis

Design vs. Operating DeNOx Demand

Performance Cases	**Case 1**	**Case 2**
Performance Basis Description	**Original Design 1/0.08 lb/MBtu NOx, 2 ppm Slip @700 F**	**Operating Data 0.65/0.08 lb/MBtu NOx, 5 ppm Slip @730 F**
NOx In, lb/MBtu	1	0.65
NOx Out, lb/MBtu	0.08	0.08
NOx Removal, %	92%	88%
Ammonia Slip, ppmvd@3% O2	2.0	5.0
DeNOx Temperature Basis ,F	700	730
SCR Oxidation Temp Basis, F	700	730
Fuel Burn Rate, MBtu/hr	8,100	8,100
Econ Outlet Gas Flow, acfm	4,000,000	4,123,493
Oxygen, % wet	2.1	2.1
Moisture, %	14.0	12.9
Min Ammonia Inj. Temperature, F	607	603
Ammonia Flow Rate, lb/h	2,902	1,813
Relative DeNOx Demand	**1.0**	**0.77**

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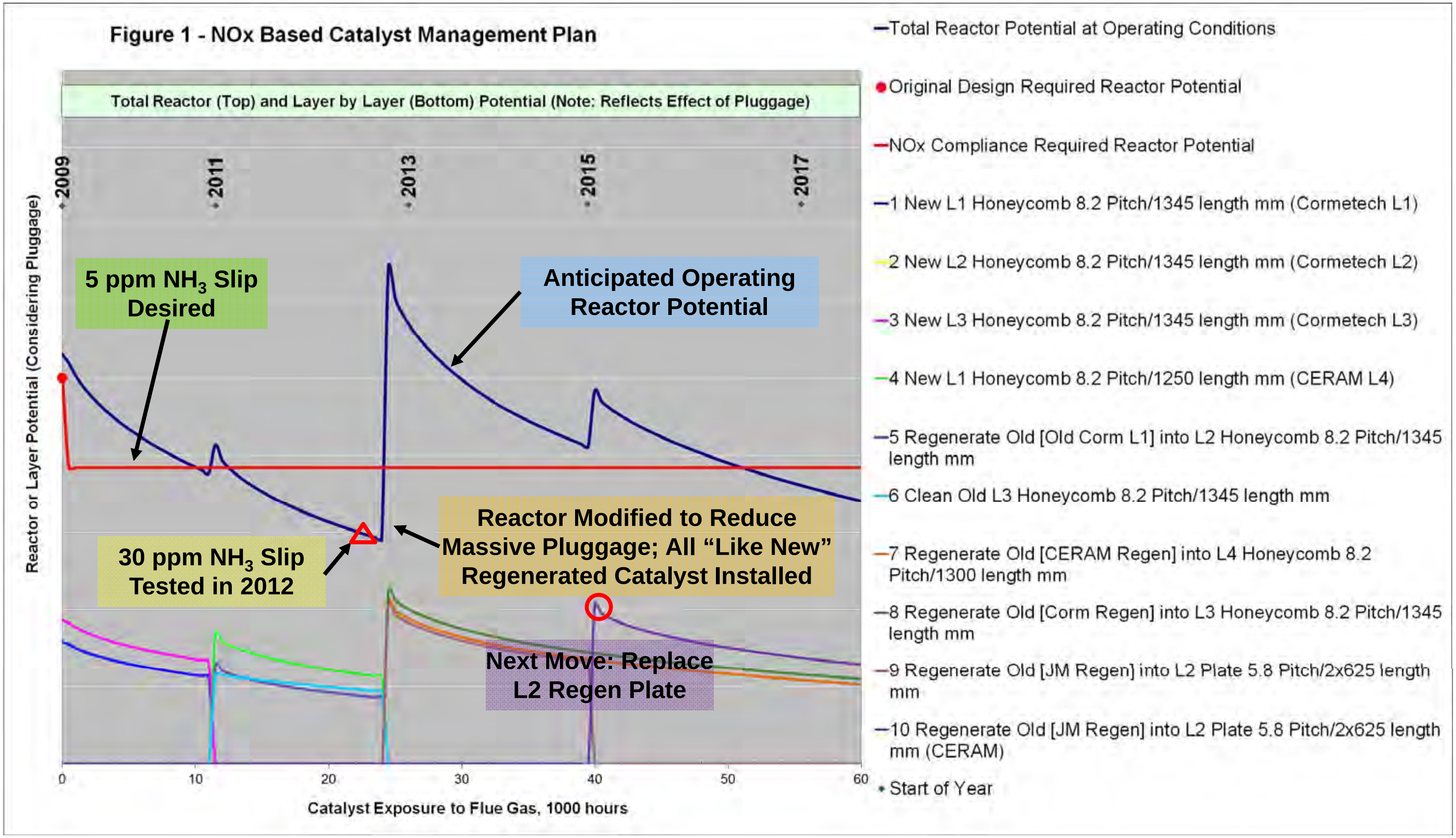
Anticipated Operating Reactor Potential and Original Plan (2013-2015)



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Dry Ice Blasting

- Performed in December 2013
- Approximately 45% of modules cleaned
- Reduced average pluggage from 29% to 9%

NH_3 Slip Testing

- May 2014 (11,000 hours of operation on regen catalyst)
  - <3 ppm slip expected
  - 18 ppm slip measured
- November 2014 (15,000 hours of operation on regen catalyst)
  - 22 ppm slip measured at slightly reduced load
  - 28 ppm slip extrapolated to full load

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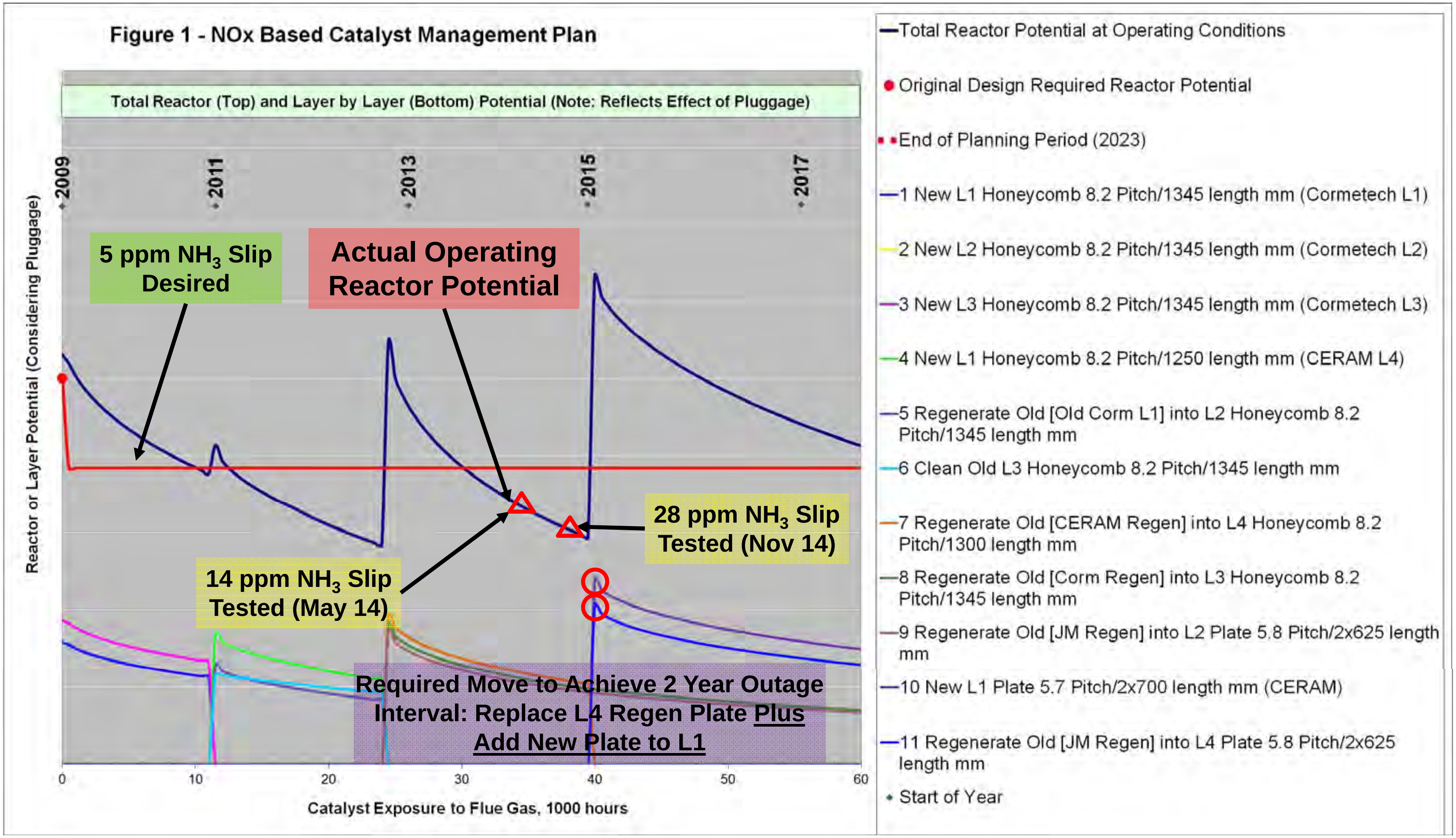
Actual Operating Reactor Potential Established With Ammonia Slip Tests and Required Plan to Achieve 2017 Outage Objective



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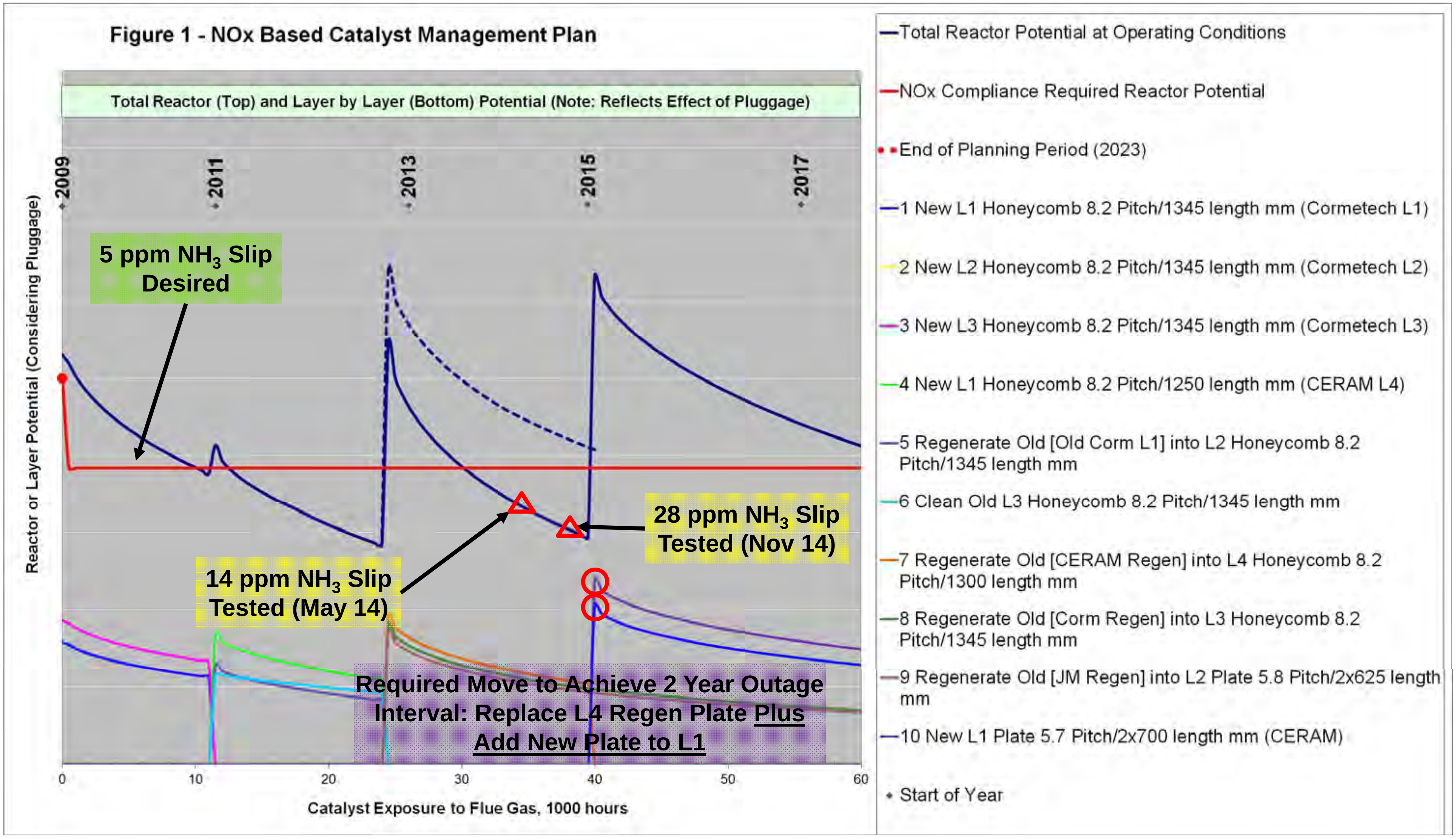
Anticipated vs. Actual Operating Reactor Potential
Why don't they agree???



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Catalyst Test History Does Not Substantiate Operating Reactor Potential Shortfall

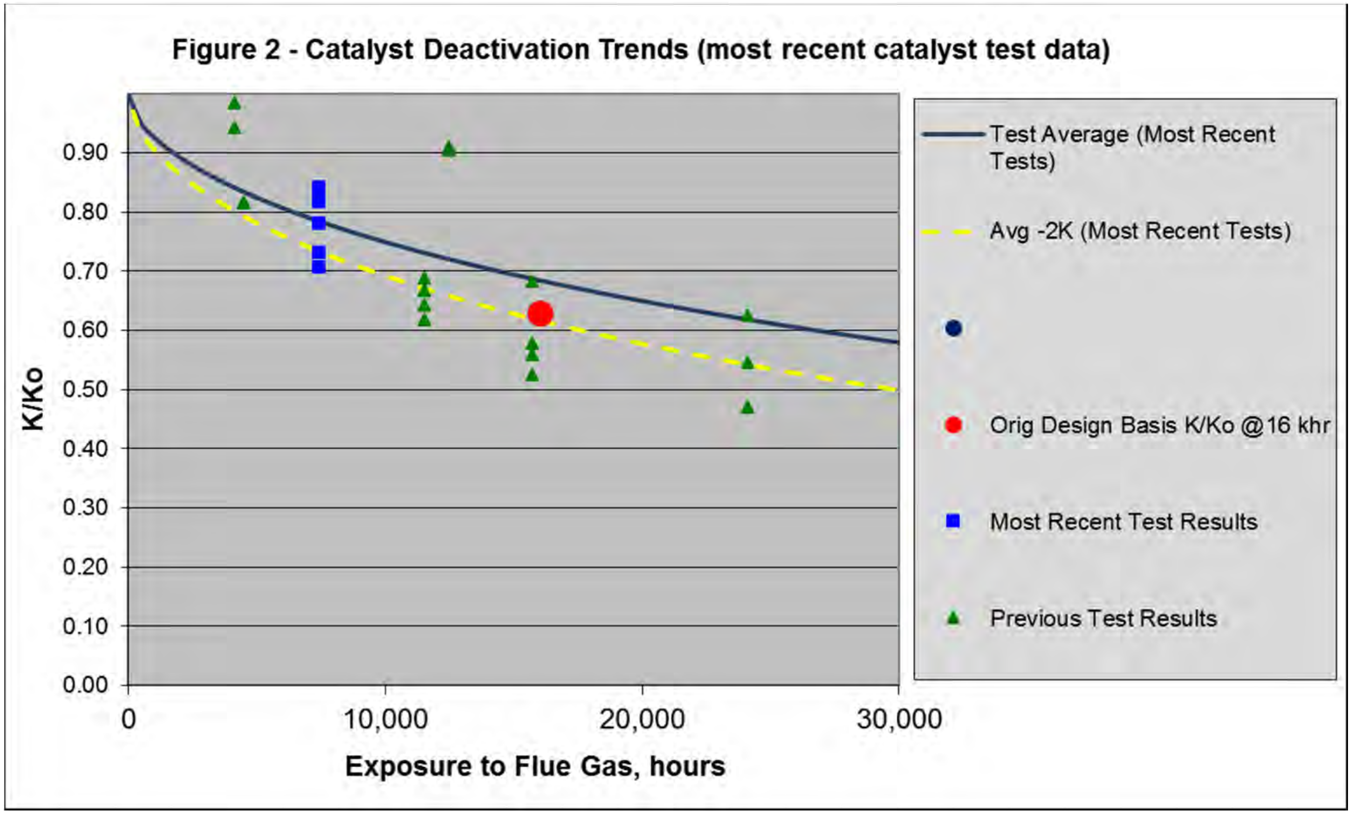

Figure 2 - Catalyst Deactivation Trends (most recent catalyst test data)

Catalyst Test Results Summary	Most Recent Catalyst Tests (6 tests & 0.074 St Dev)				All Catalyst Tests (27 tests & 0.12 St Dev)		
	Most Recent K/Ko	Average K/Ko @ 16khr	Avg -1K Based K/Ko @ 16khr	Avg -2K Based K/Ko @ 16khr	Average K/Ko @ 16khr	Avg -1K Based K/Ko @ 16khr	Avg -2K Based K/Ko @ 16khr
Reactor Average		**0.686**	0.652	0.619	**0.670**	0.638	0.606
Level 1		#DIV/0!			0.785	0.749	0.713
Level 2	0.823 (7400 hr)	0.737	0.703	0.670	0.642	0.612	0.582
Level 3	0.758 (7400 hr)	0.648	0.614	0.580	0.607	0.577	0.547
Level 4	0.776 (7400 hr)	0.674	0.639	0.606	0.674	0.639	0.606

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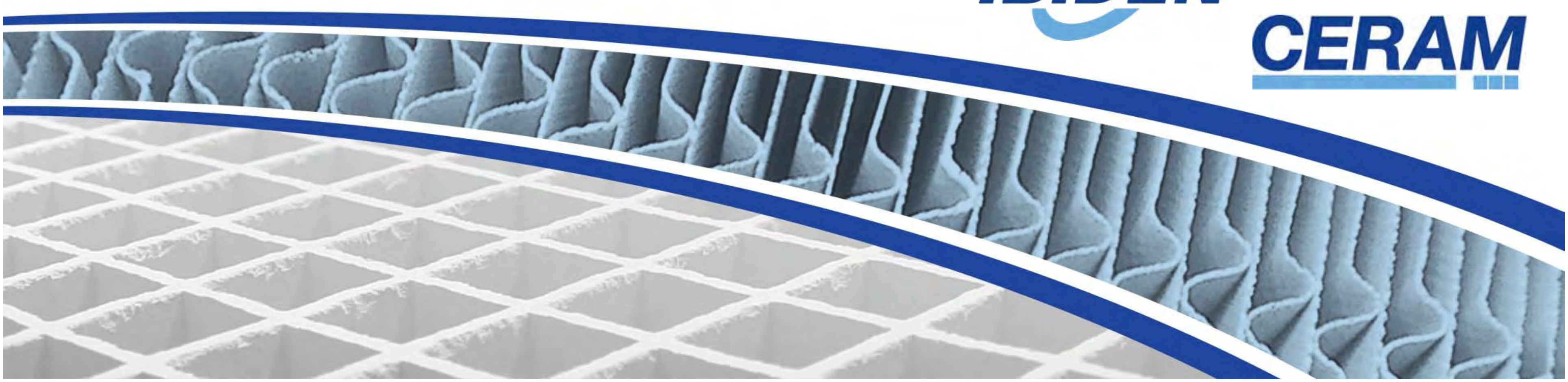
Reactor Inspection Findings



Pluggage Quantified

- Layer 2: 5.7 mm Pitch Plate
- 33% Plugged

2	2	2	2	2	2	2	20	100	40	5	2	2	2	2	2
2	2	2	2	2	2	2	50	100	30	5	2	2	2	2	2
2	2	2	2	10	2	25	100	100	60	5	2	2	2	2	2
2	2	2	2	33	50	100	100	100	100	66	2	2	2	2	2
2	2	2	2	10	90	100	100	100	100	80	2	2	2	2	2
2	2	2	2	12	100	100	100	100	100	100	2	2	2	2	2
2	2	2	2	33	100	100	100	100	100	100	2	2	2	2	2
2	2	2	2	50	100	100	100	100	100	100	2	2	2	2	2
2	2	2	2	50	100	100	100	100	100	80	2	2	2	2	2
2	2	2	2	90	100	100	100	100	100	80	2	2	2	2	2
2	2	2	2	33	100	100	100	90	100	40	2	2	2	2	2
2	2	2	2	13	100	100	100	95	85	50	15	20	10	10	10
2	2	2	2	50	100	100	100	80	60	90	10	5	5	20	20

Pluggage Quantified

- Layer 3: 8.2 mm Pitch Honeycomb
- 48% Plugged

33	33	35	15	25	55	45	45
5	5	5	30	15	20	45	25
5	10	10	33	33	40	70	50
10	10	5	25	40	55	90	60
50	20	33	30	60	65	100	100
20	30	35	35	40	25	100	100
25	55	40	50	33	33	60	100
15	60	60	50	25	45	50	100
25	60	70	70	50	85	100	100
15	50	75	33	45	80	100	100
15	35	55	40	45	70	100	100
20	35	30	30	40	100	100	100
33	35	45	45	40	100	100	100

50	40	65	40	40	40	30	20
70	35	55	45	20	5	10	5
80	35	40	40	30	25	15	5
100	85	20	10	30	10	20	5
100	100	35	50	70	50	35	10
100	100	25	15	35	25	35	10
100	100	55	25	40	20	25	40
100	100	85	35	12	35	35	25
100	100	60	75	65	75	40	60
65	100	40	70	40	35	25	40
80	70	35	25	50	15	20	35
80	90	45	35	35	35	10	10
70	65	55	65	50	65	90	33

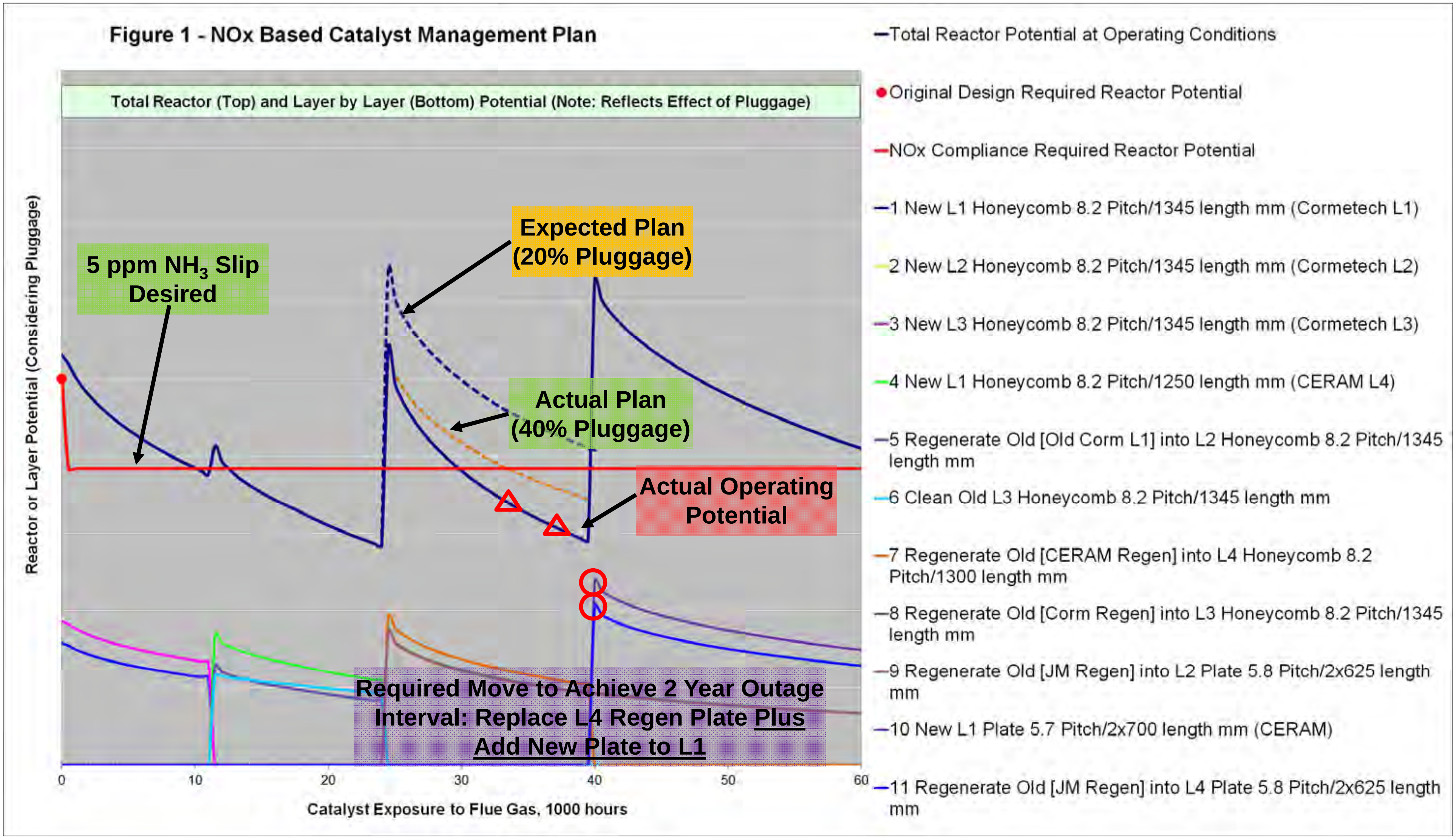
Pluggage Quantified

- Layer 4: 8.2 mm Pitch Honeycomb
- 41% Plugged

5	15	10	5	10	10	25	20
5	20	20	10	10	15	25	10
25	30	30	10	30	40	70	20
30	15	30	15	55	30	40	30
50	50	50	40	50	90	100	100
45	30	25	25	40	85	100	100
25	20	25	30	50	60	100	100
25	30	33	25	90	60	100	100
45	40	50	70	80	90	100	100
35	10	30	20	60	50	80	100
30	25	40	35	70	15	100	100
25	20	45	35	25	60	100	100
20	30	10	20	30	60	90	100

10	20	5	5	20	10	10	15
20	20	5	10	5	10	10	5
60	25	20	15	25	20	25	10
80	35	80	15	15	20	15	25
90	50	70	55	60	60	50	25
100	33	55	10	35	35	25	30
90	33	65	30	45	20	10	25
80	40	65	15	30	30	25	45
75	25	100	25	40	45	45	60
80	50	60	35	35	25	20	40
60	70	50	35	30	33	25	40
90	60	50	25	15	15	30	30
60	55	45	45	15	20	25	25

Actual Pluggage Rates Do Not Account for Operating Reactor Potential Shortfall



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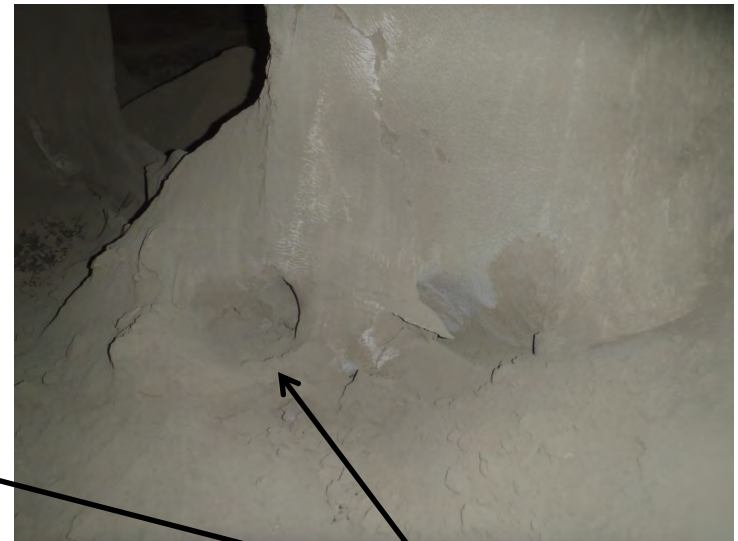
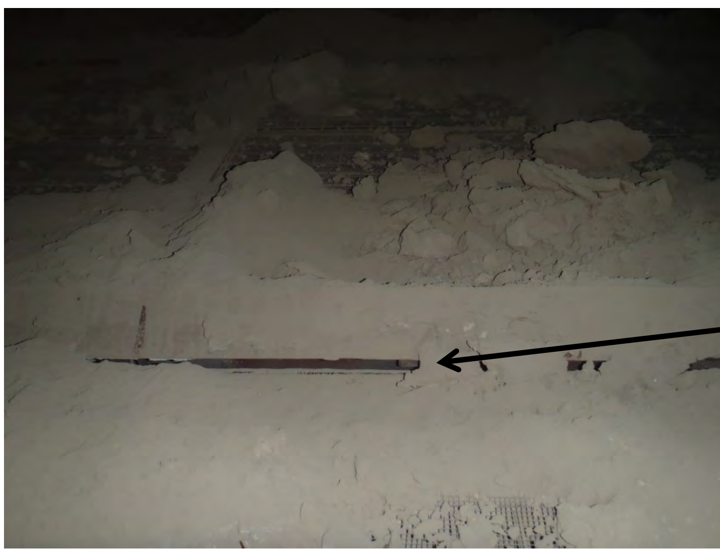
Module Seal Damage Causing Bypass





Flue gas tunneling through ash piles

Module seal gap

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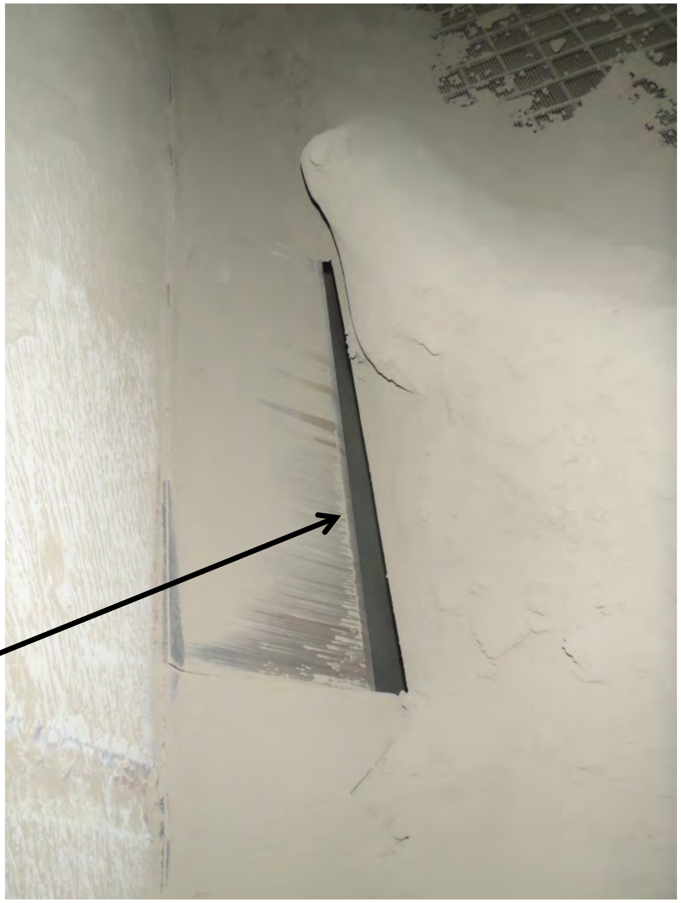
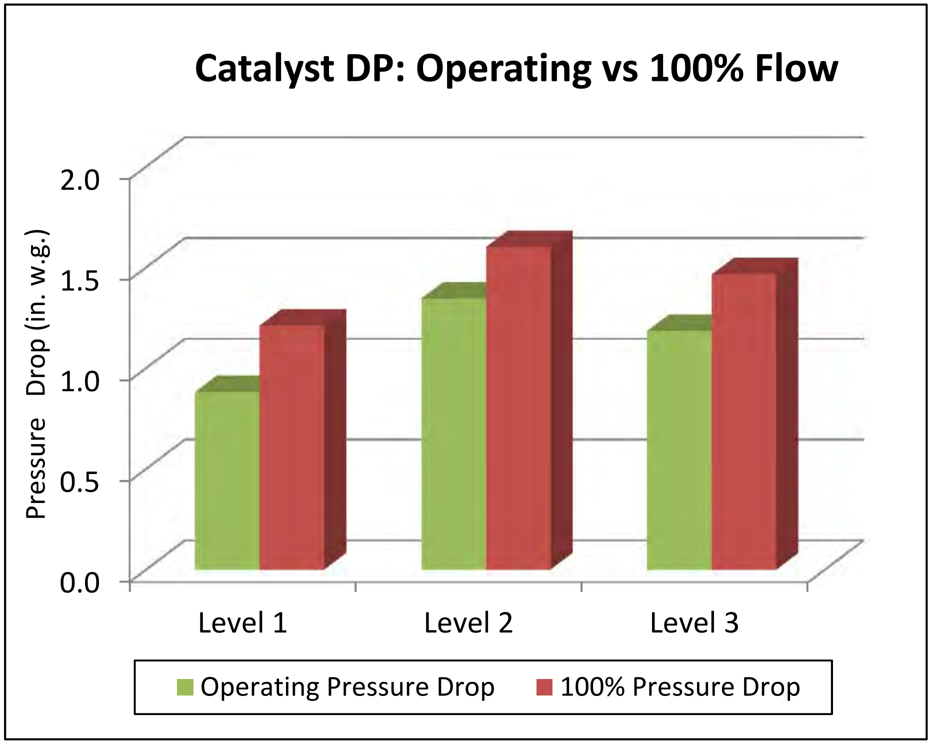
Wall Seal Damage Causing Bypass

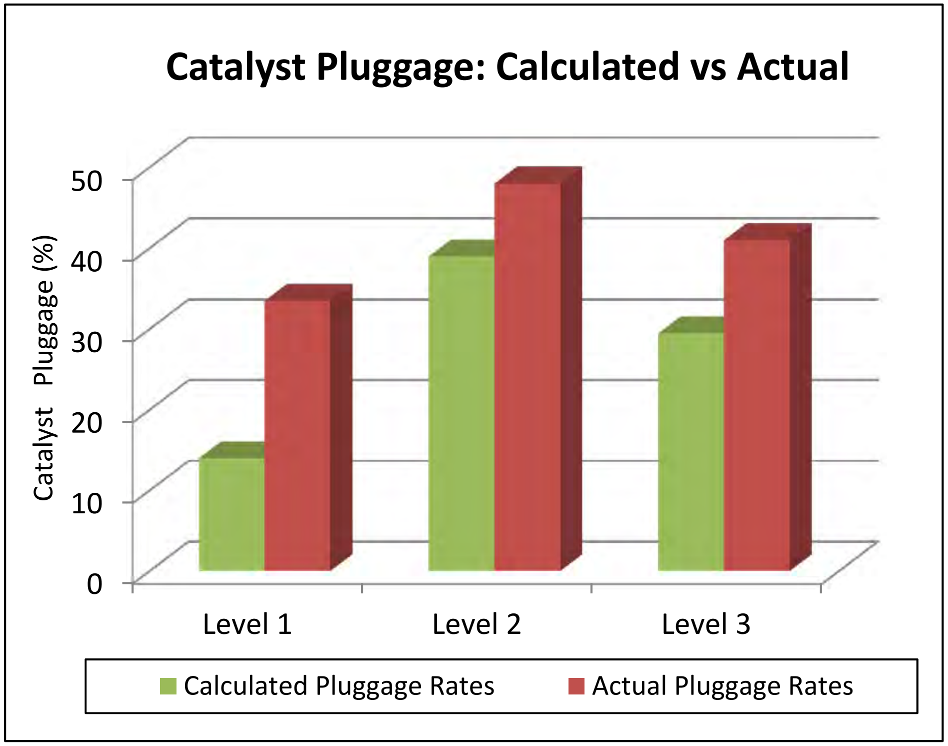


Wall seal damage

Pluggage and Seal Leakage Analysis

- Average operating DP indicated approx. 27% pluggage
- Inspection observed approx. 41% pluggage
- Operating DP lower than expected based on actual pluggage





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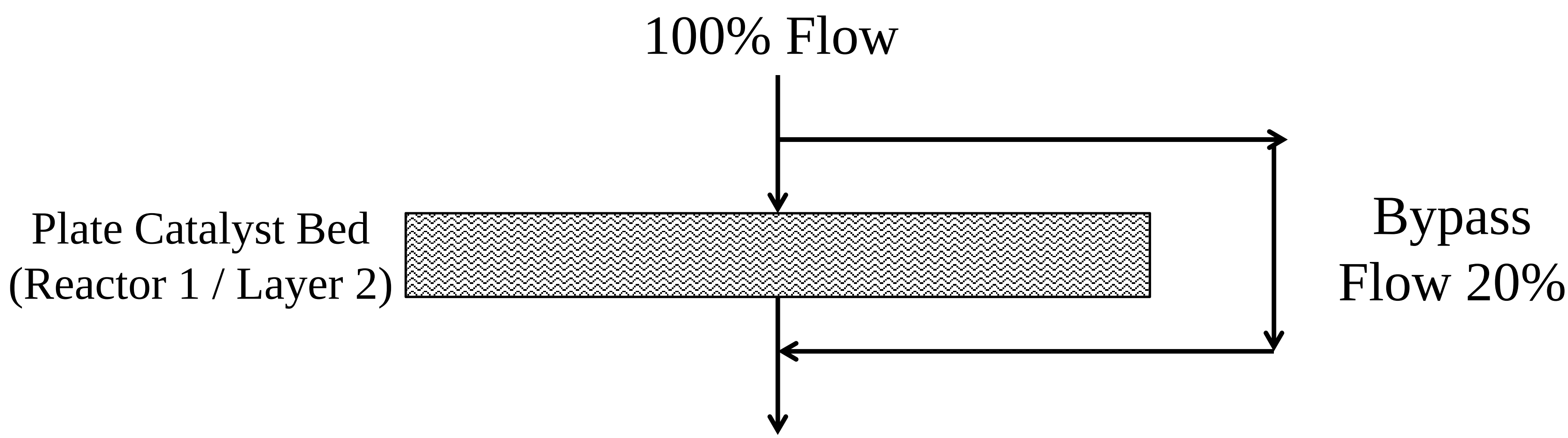
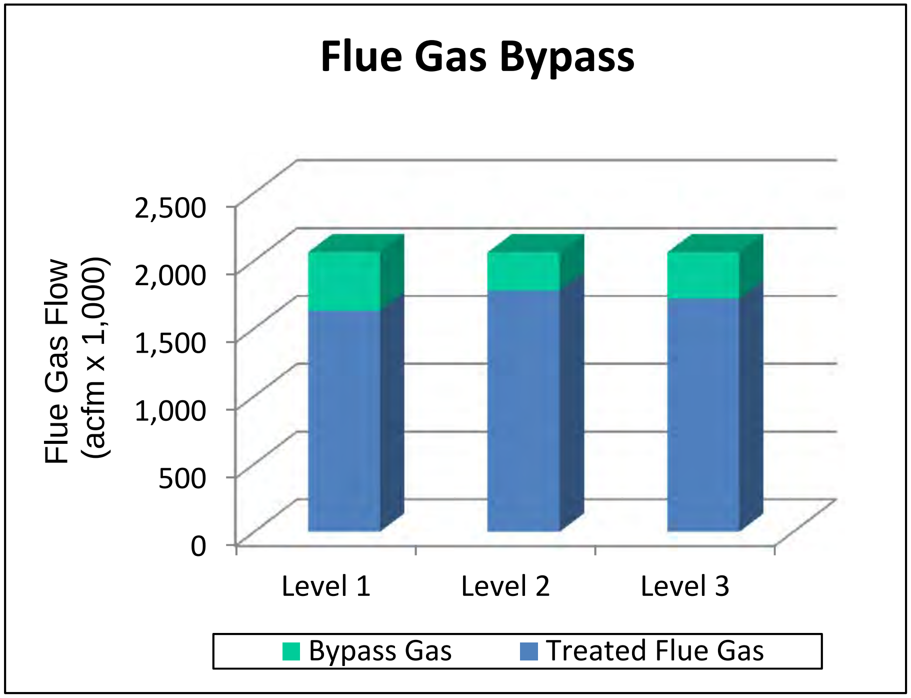
Operating Reactor DP without and with Bypass



- Operating DP of 0.91 in wg → 16% Pluggage with 100% Flow
- Actual pluggage from inspection is 35% → less flow through catalyst
- Calculated flue gas bypassing seals to correlate 35% pluggage to operating DP
  - 20% bypass calculated for this layer
- Repeat process for all reactor layers

Flue Gas Bypass

- Flue gas bypass ranges from approx. 10 – 22% per layer
- Untreated flue gas bypassing the catalyst
- Significant increase to the ammonia slip concentration



Reactor	Catalyst Levels	Catalyst Type	Percentage Bypass (%)
A	Level 2	Plate	20%
	Level 3	Honeycomb	17%
	Level 4	Honeycomb	19%
B	Level 2	Plate	22%
	Level 3	Honeycomb	10%
	Level 4	Honeycomb	14%

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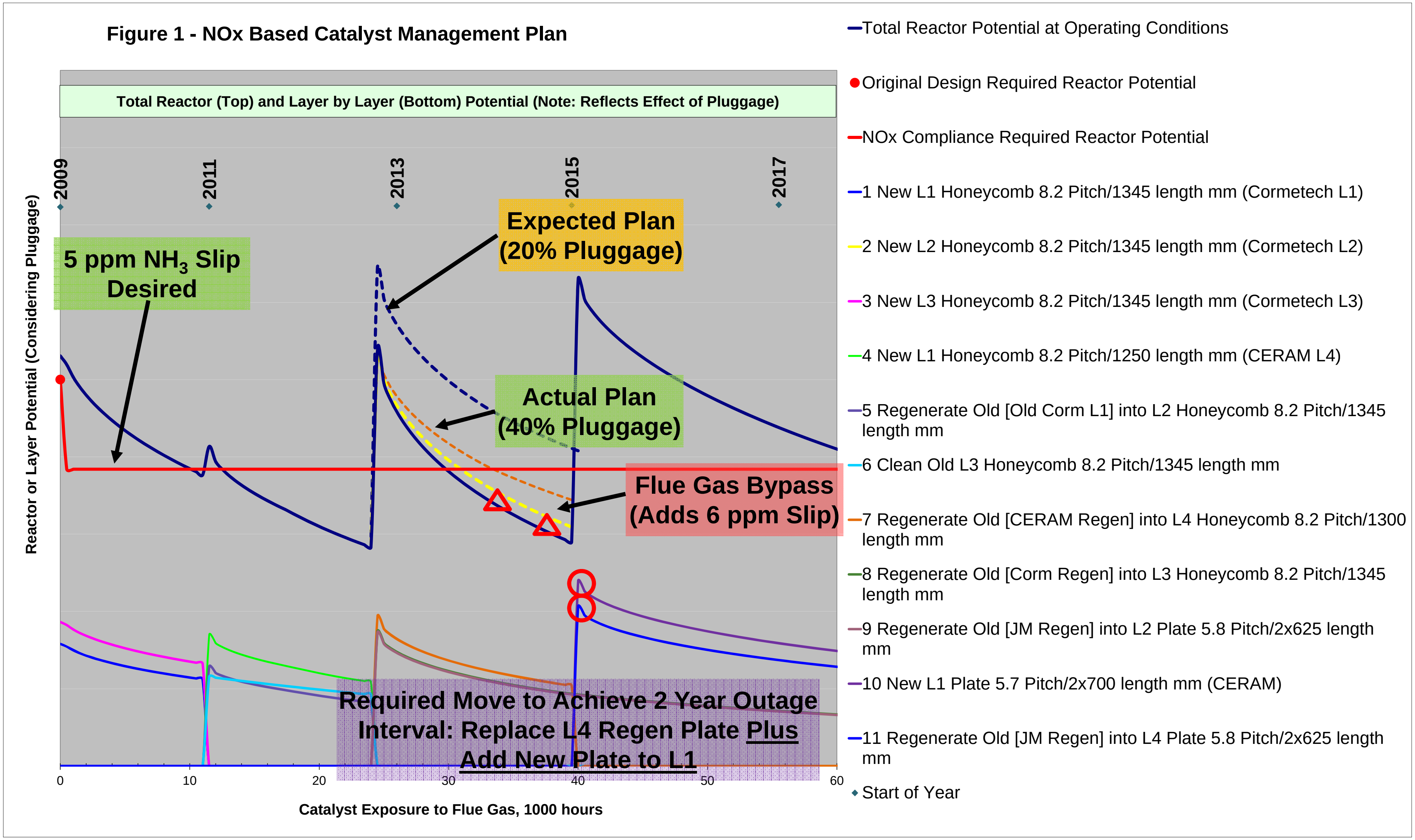
Catalyst Seal Damage Accounts for Increased Slip



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Catalyst Activity Measurement Affected by Mechanical Integrity

- In the Laboratory Plate Spacing Can be Nearly Ideal (Maximizing Activity)
- In the Reactor Plate Spacing Can Only be Assured by Maximizing Geometric Uniformity Design
  - Plate Thickness
  - # of Spacers
- Deficient Geometric Uniformity Can Reduce Operating Activity by 4 to 8 Nm^3/m^2h (10 to 20%)

Plate Prepared for Laboratory Testing

Competitor Plate in Reactor

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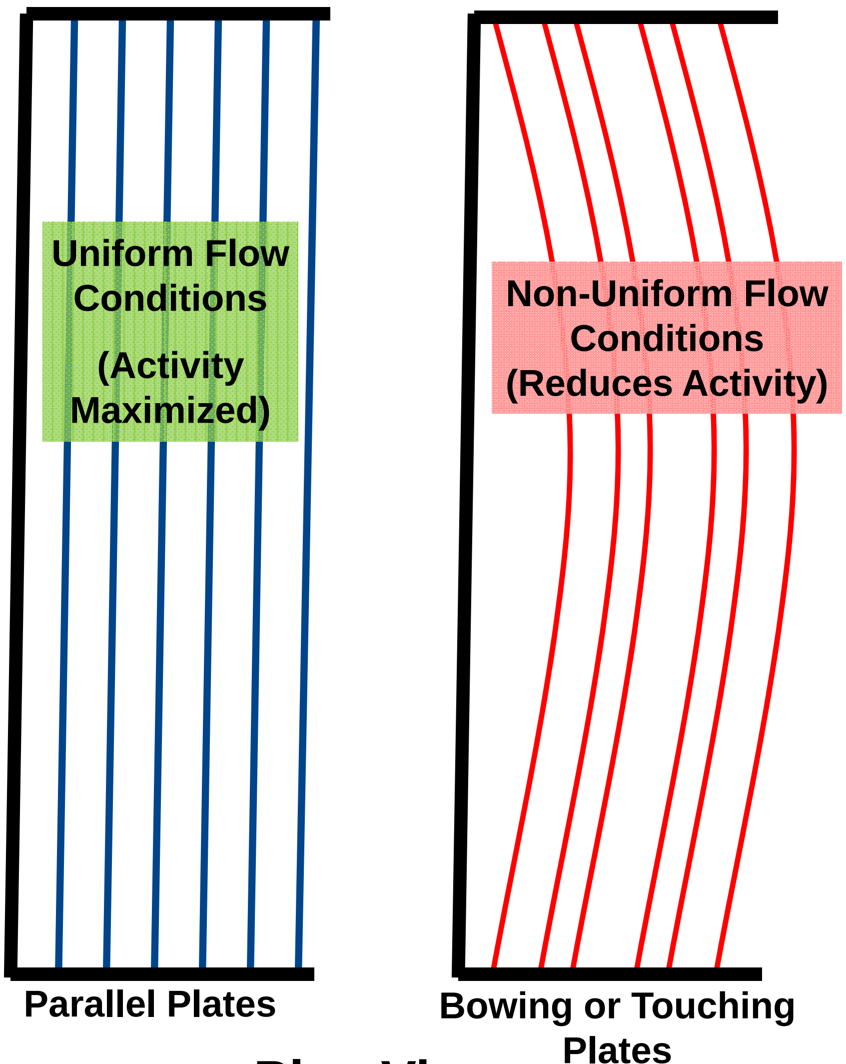
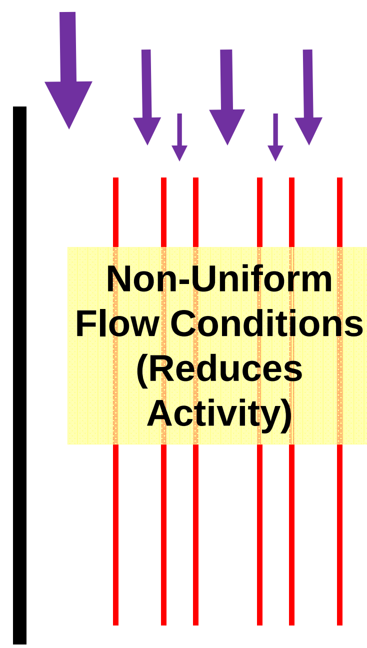
Operating Reactor Potential Affected by Catalyst Mechanical Condition



Plan View

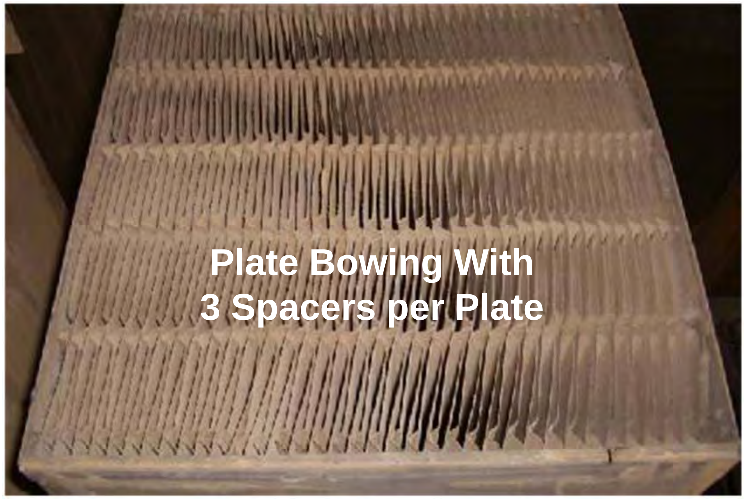
- Plate Bowing or Touching Reduces Operating Reactor Potential
- Varying Flow Widths and Touching Plates Lead to Non-Uniform Flow
- Non-Uniform Flow Reduces Operating Activity (Reactor Potential)



Elevation View With Bowing or Touching Plates

Geometric Uniformity Important to Maximize In-Situ Activity and to Minimize Pluggage

Plate Catalyst Geometric Uniformity Recommendations	
Plate Thickness	≥0.75 mm (Substrate + Catalyst)
Spacers	4 Per Plate With Proper Spacing



- Adequate Plate Thickness and Spacers Maintain Desired Geometry
- Plate Bowing Occurs From Thinner Material, Longer Length, Fewer Spacers, & Regen
- Touching Plates Increase Pluggage Risk
- Touching Causes Flow Disruption Increasing Turbulence and Reducing Activity
- Plate Samples for Lab Tests are Optimized to Assure Geometric Uniformity (Nearly Ideal Spacing) - Configured to Maximize Measured Catalyst Activity
- Deficient Plate Mechanical Design Can Reduce Operating Activity by 10 to 20%
  - Specification Needed to Assure Operating Activity Result

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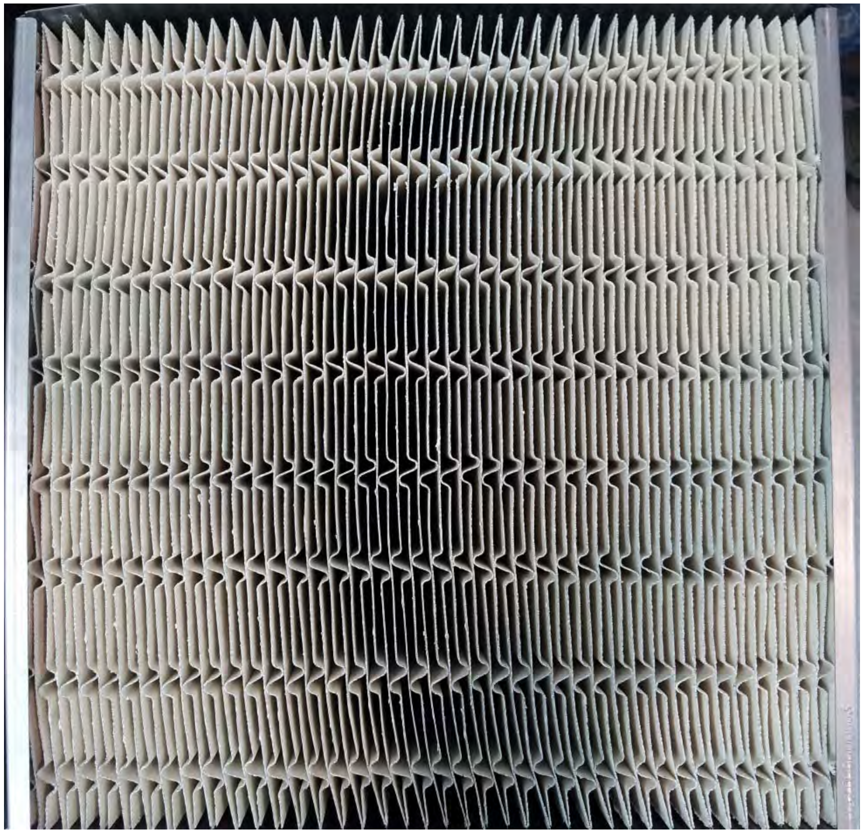
Which Catalyst Will Have a Better Operating Reactor Potential?



CERAM Plate Catalyst (4 Spacers/Plate)

Competitor Plate Catalyst from Different Unit for Illustration (3 Spacers/Plate)

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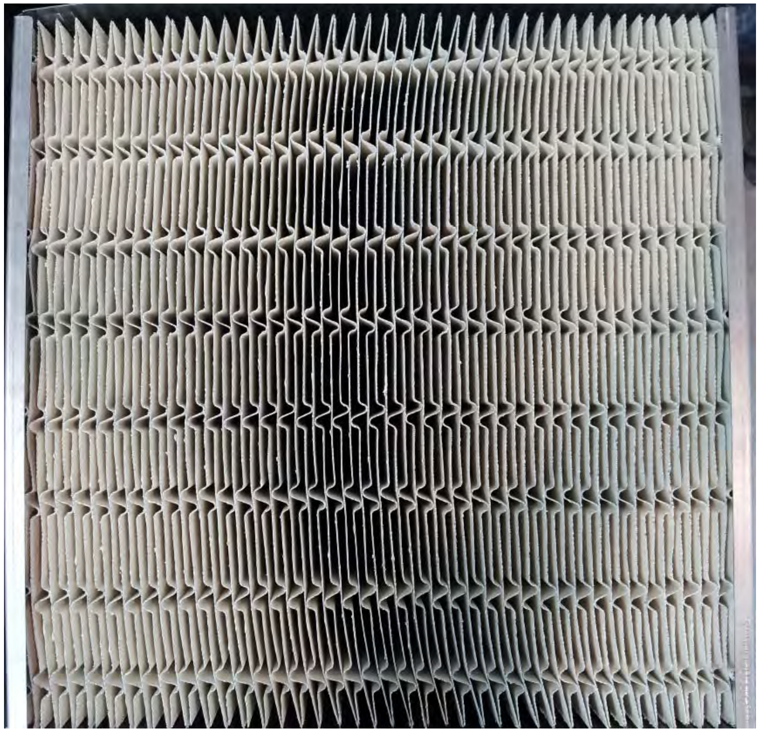
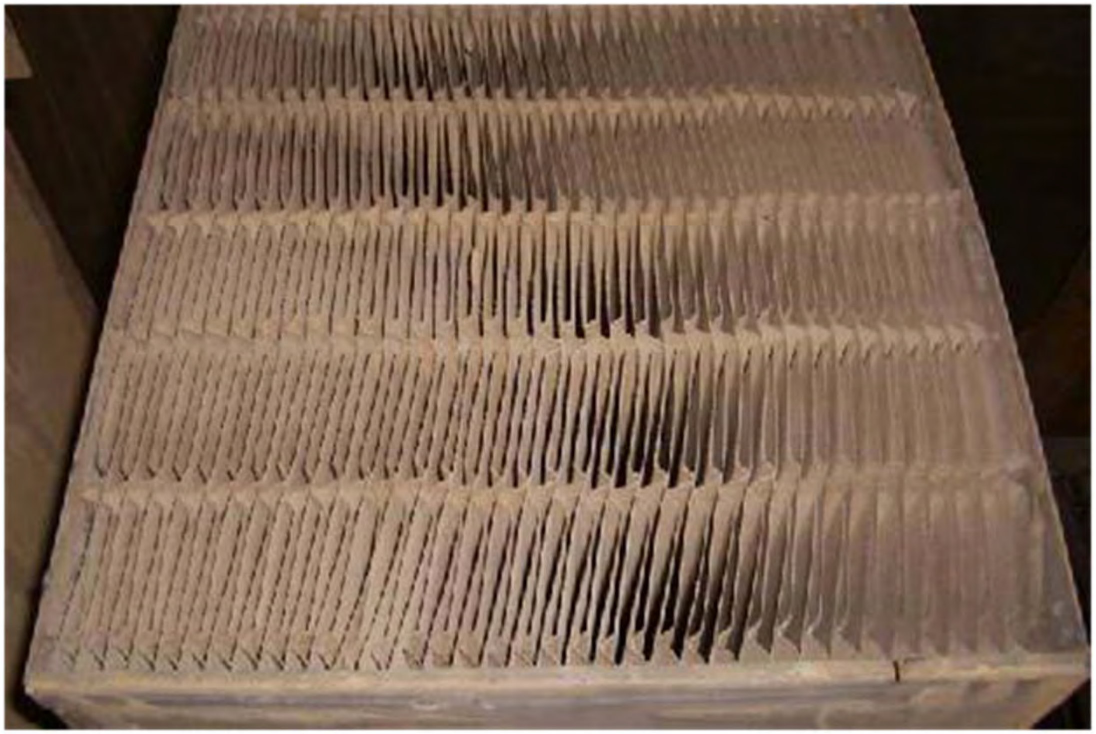
Which Catalyst Will Have a Better Operating Reactor Potential?



CERAM Plate Catalyst (4 Spacers/Plate)



Competitor Plate Catalyst from Different Unit for Illustration (3 Spacers/Plate)

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Presentation Summary

- Consider Accuracy/Bias of Catalyst Test Lab/Results
  - Benchmarking Necessary to Minimize Bias
  - Perform Sensitivity Analysis to Better Assess Recommendations
- Consider Operating DeNOx Demand and Reactor Potential
  - Impacts of Operating Conditions (Temp, O_2, Flow, etc.)
- Does Field Performance Correlate to Laboratory Test Results?
  - Consider Pluggage, Mechanical Condition, Seal Leakage, NH_3 Slip test results
- Geometric Uniformity Critical to Assure Plate Catalyst Operating Reactor Potential
  - Up to10 to 20% impact
- Catalyst Testing Accuracy/Bias Considerations Important for New Catalyst (Ko Guarantee) and Aged Catalyst Testing

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Thank You!

Questions?

John Cochran & Noel Rosha
IBIDEN CERAM Environmental, Inc.
john.cochran@ceram-usa.com
noel.rosha@ceram-usa.com
+1 913-239-9896