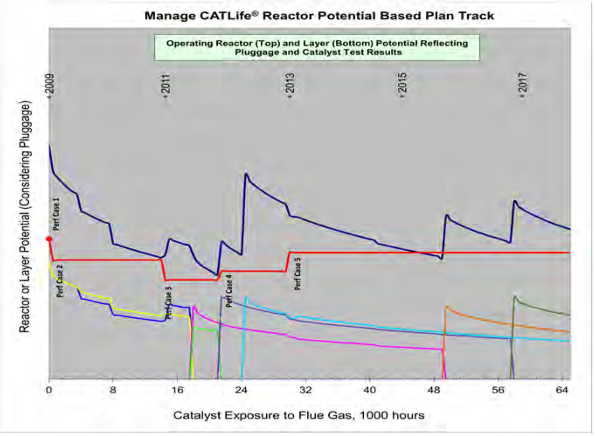
REINHOLD ENVIRONMENTAL Ltd.

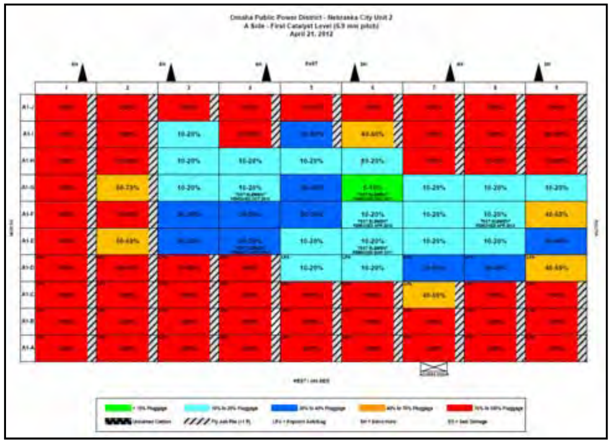
2016 NOx-Combustion-CCR Round Table Presentation

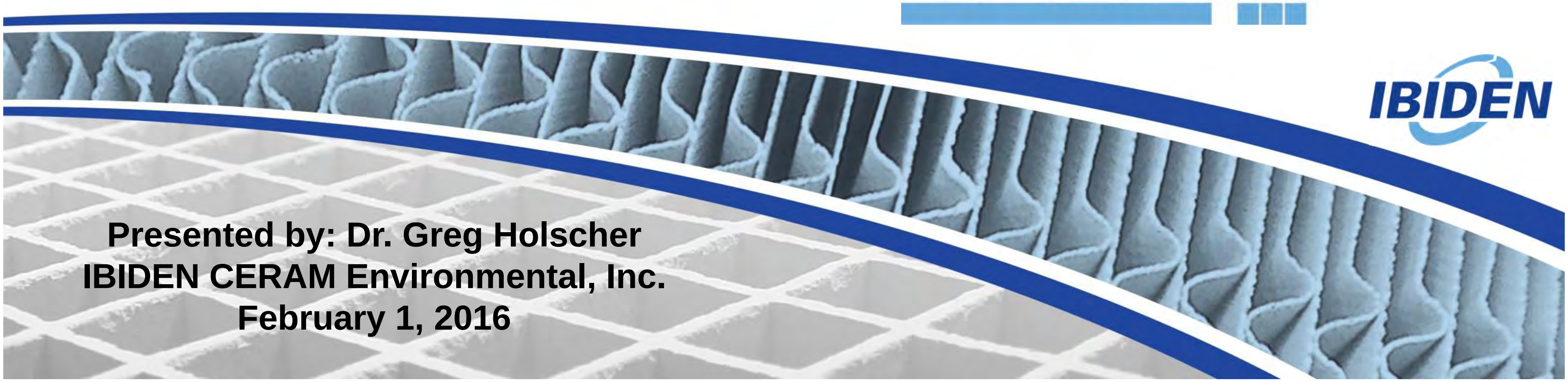
February 1 & 2, 2016, in Orlando, FL / Hosted by OUC

Reinhold Environmental 2016 NOx-Combustion Round Table

Catalyst Design: What Potential Does Your SCR System Have?

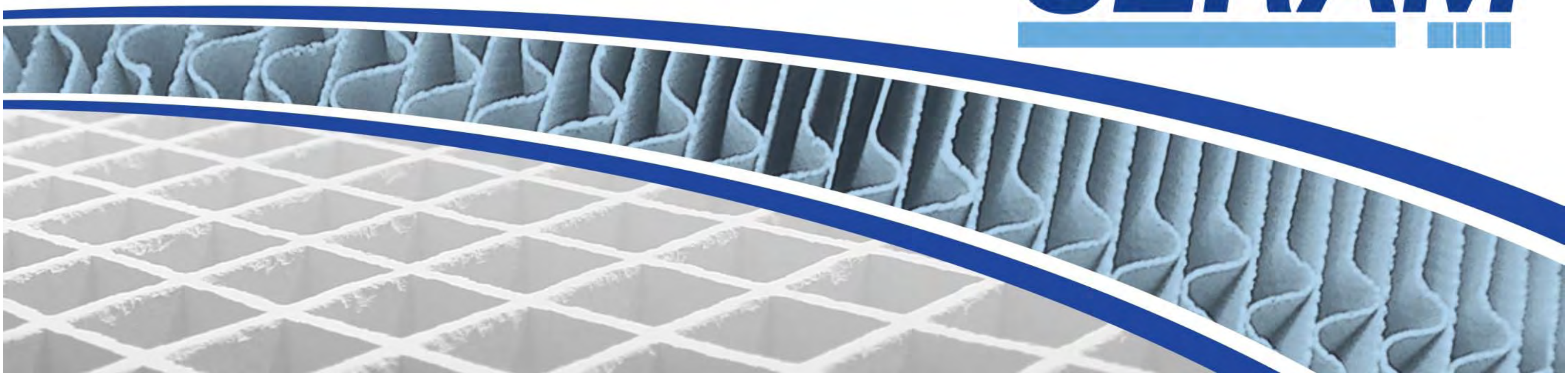






Presented by: Dr. Greg Holscher
IBIDEN CERAM Environmental, Inc.
February 1, 2016

DeNOx Demand and Reactor Potential



Reactor Potential

$$P = K/A\nu$$

P = Reactor Potential

K = Catalyst Activity, Nm^3/m^2h or Nm/h

$A\nu$ = Area Velocity, Nm/h
(normal gas flow, Nm^3/h divided by total installed catalyst surface area, m^2)

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

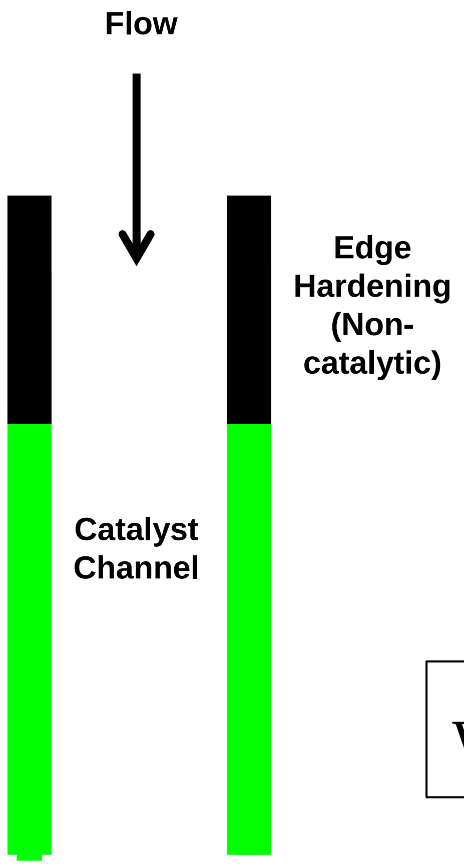
Area Velocity (Av)

$$\boxed{Av = Q_{fg} / A_{cat} = Q_{fg} / \left(V_{rcat} \times SSA\right)}$$

Where: Q_{fg} = flue gas flow rate, Nm^3/h
A_{cat} = catalyst geometric surface area, m^2
V_{rcat} = reactive catalyst volume available, m^3
SSA = catalyst specific surface area, m^2/m^3

Volume Calculation

Considering Edge Hardening



$$\boxed{V_{rcat} = V_{cat} \times \frac{\left(l_{cat} - l_{eh}\right)}{l_{cat}}}$$

Where: *Vcat* = total catalyst volume, m^3
lcat = catalyst element total length, m
leh = length of edge hardening applied to each catalyst element, m

When no edge hardening is used: $\boldsymbol{V_{rcat} = V_{cat}}$

Activity Required
Including Distribution and Pluggage Factors

$$\boxed{K_{req} = \overline{K} \times DF_{total} \times \left(1 + PF/100\right)}$$

Where: K_{req} = activity required including distribution factor & pluggage

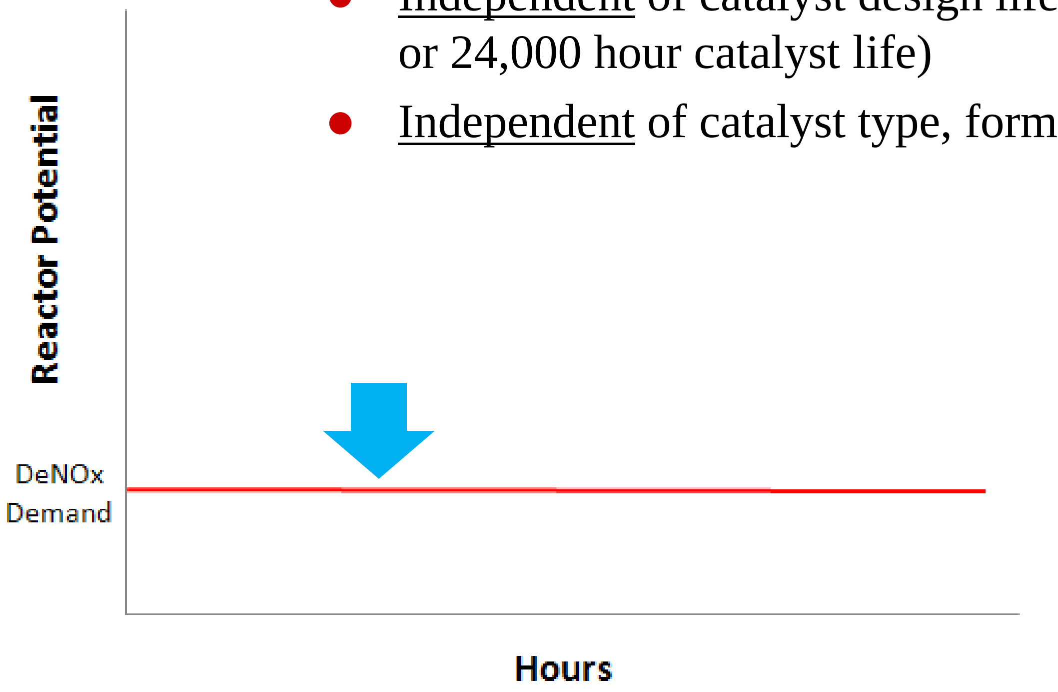
$\overline{K}$ = theoretical activity required

DF_{total} = total distribution factor (NH_3:NOx, velocity and temperature)

PF = pluggage factor, %

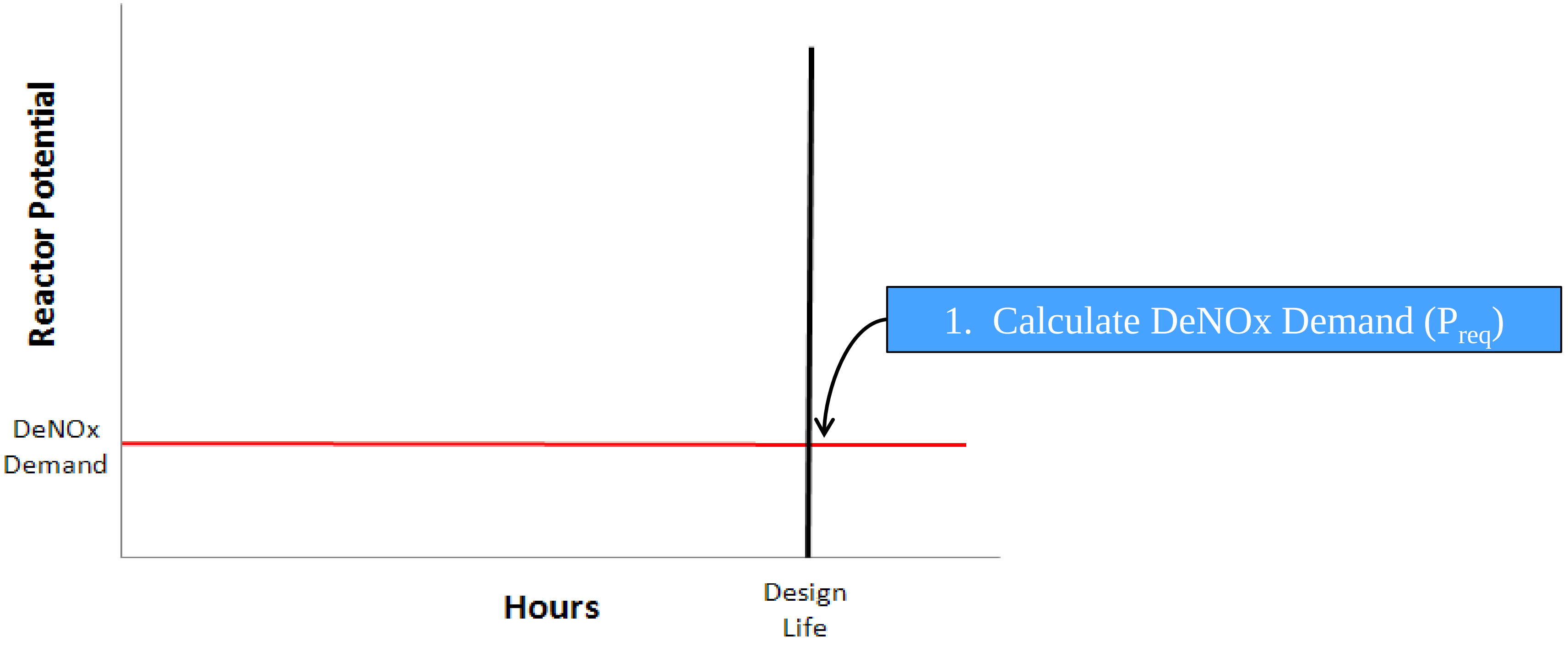
DeNOx Demand

- DeNOx Demand (P_{req}) = The reactor potential required to meet NOx removal and ammonia slip requirements
- Calculated based on NOx removal requirements, NH_3 slip, and SCR reactor pluggage and distributions (velocity, NH_3/NOx, temperature)
- <u>Independent</u> of catalyst design life (i.e. same value for 16,000 or 24,000 hour catalyst life)
- <u>Independent</u> of catalyst type, formulation or manufacturer



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

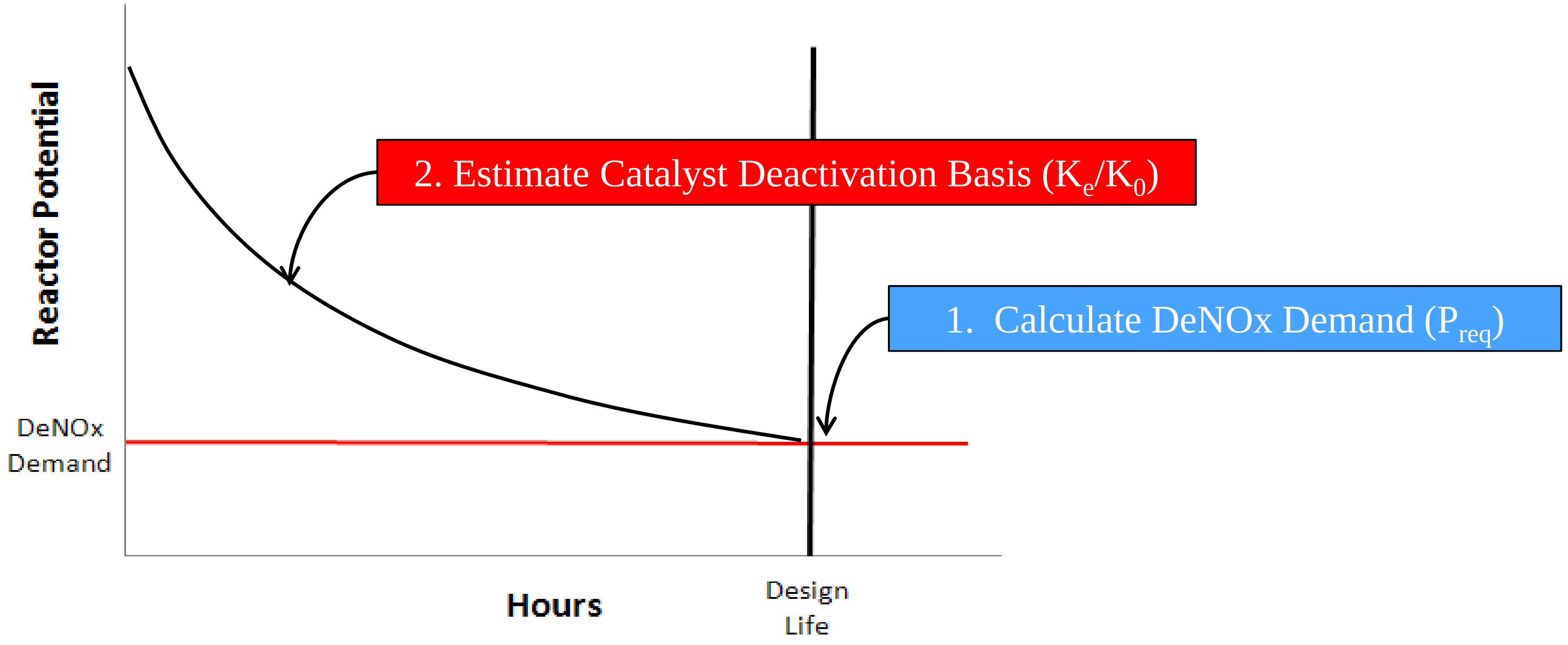
Catalyst Design Process



1. Calculate DeNOx Demand (P_{req})

1. Calculate DeNOx demand (P_{req}) required (function of NOx removal, NH_3 slip required, distribution requirements and design pluggage) – **SAME FOR ALL CATALYSTS**

Catalyst Design Process



2. Estimate Catalyst Deactivation Basis (K_e/K_0)

1. Calculate DeNOx Demand (P_{req})

1. Calculate DeNOx demand (P_{req}) required (function of NOx removal, NH_3 slip required, distribution requirements and design pluggage) – **SAME VALUE FOR ALL CATALYSTS**
2. Estimate catalyst deactivation basis (K_e/K_0) based on fuel quality, combustion practices, unit duty, and design life – **ESTIMATED BY CATALYST SUPPLIER BASED ON EXPERIENCE OR STRATEGY**

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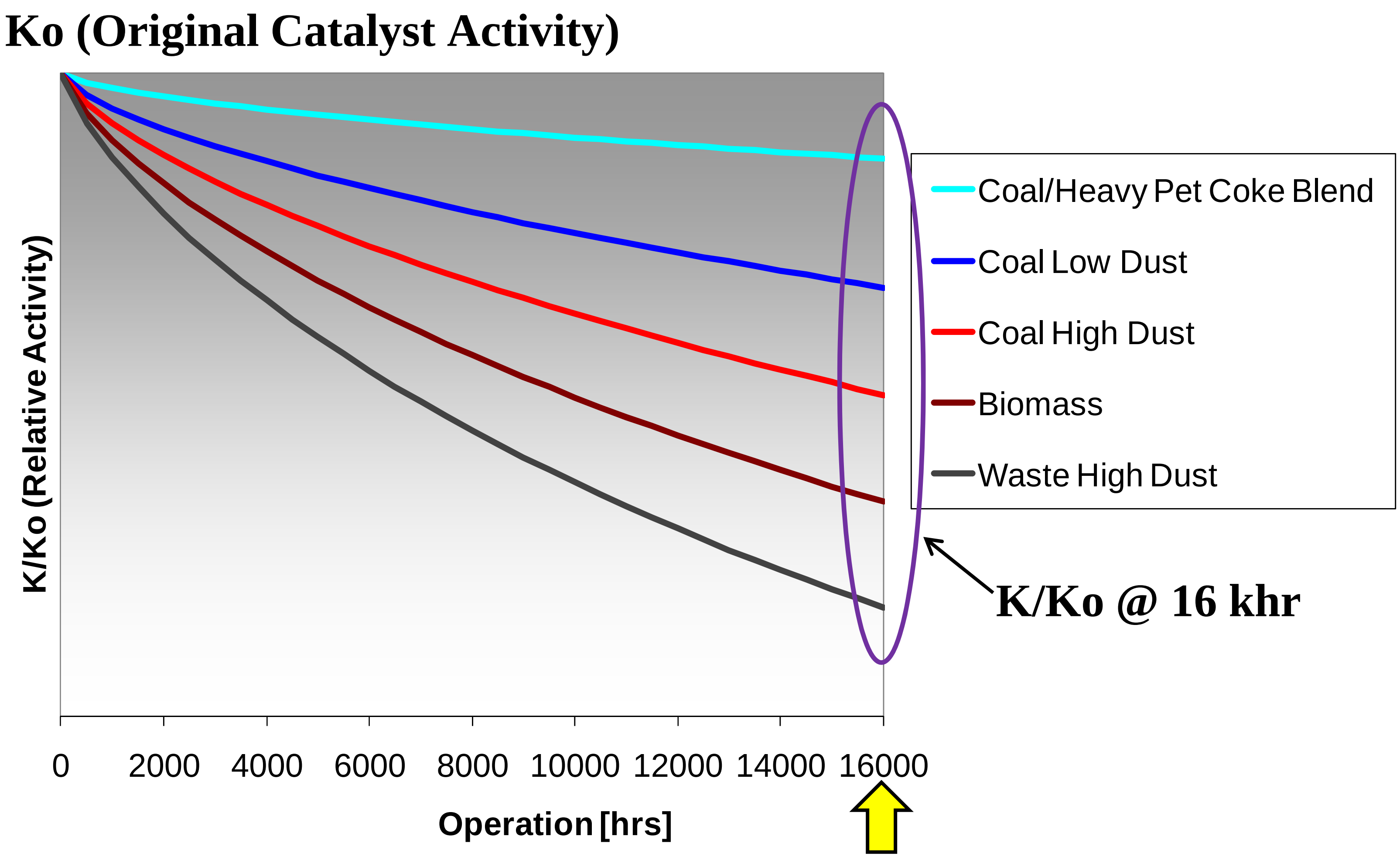
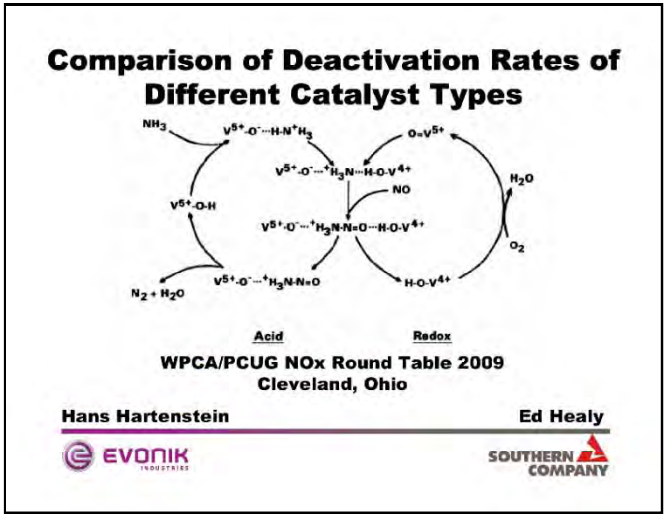
Catalyst Deactivates With Time of Exposure to Flue Gas



Catalyst Design (at hour=0) Must Anticipate Deactivation to End of Guarantee Period (e.g., 16,000 hours) to Size Catalyst Properly

Catalyst Deactivation

- Supplier Claims of “Poison Resistant” Catalysts are NOT Supported by Industry Experience
- Vanadia–Titania Type Catalysts Deactivate **<u>Independent</u>** of….
  - Catalyst Type and Geometry
  - Catalyst Composition
- 25+ Years of Experience With Testing Catalyst From All Suppliers Confirms Conclusion
  - Experience Confirmed by Major Utilities and IPPs: Southern Company, AEP, Steag, E.ON
  - Reference Also Paper Presented by the Southern Company and Evonik (now Steag) at the 2009 Reinhold Round Table
- Deactivation Resistance <u>ONLY</u> Comes From Providing Adequate Reactor Potential



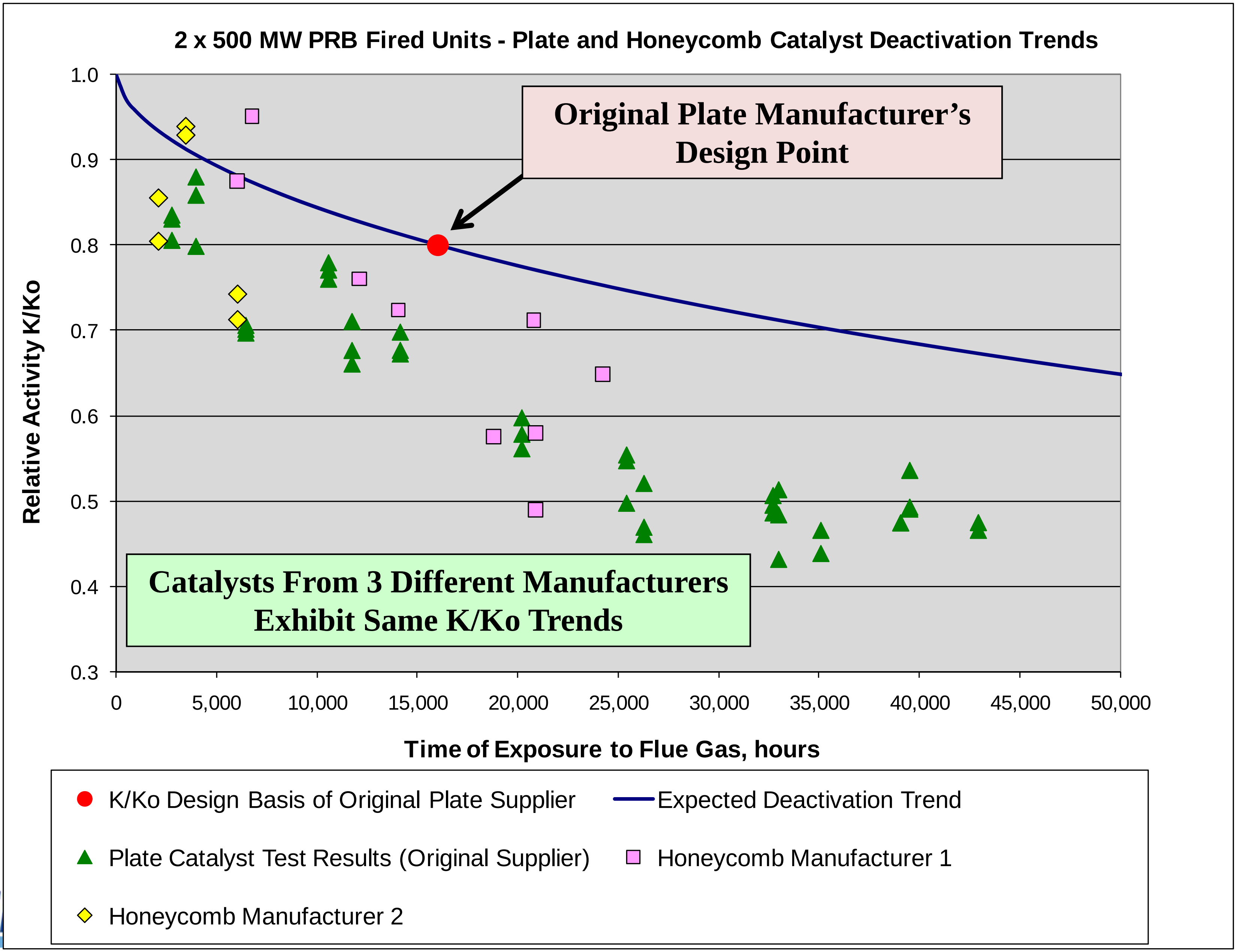
Comparison of Deactivation Rates of Different Catalyst Types

WPCA/PCUG NOx Round Table 2009
Cleveland, Ohio

Hans Hartenstein **Ed Healy**

<u>Web Address for Paper:</u>
<u>http://www.reinholdenvironmental.com/public/47bc6d6a7e8f479388a20d66579738f8/Hans%20Hartenstein%20presentation%20Deactivation%202009.pdf</u>

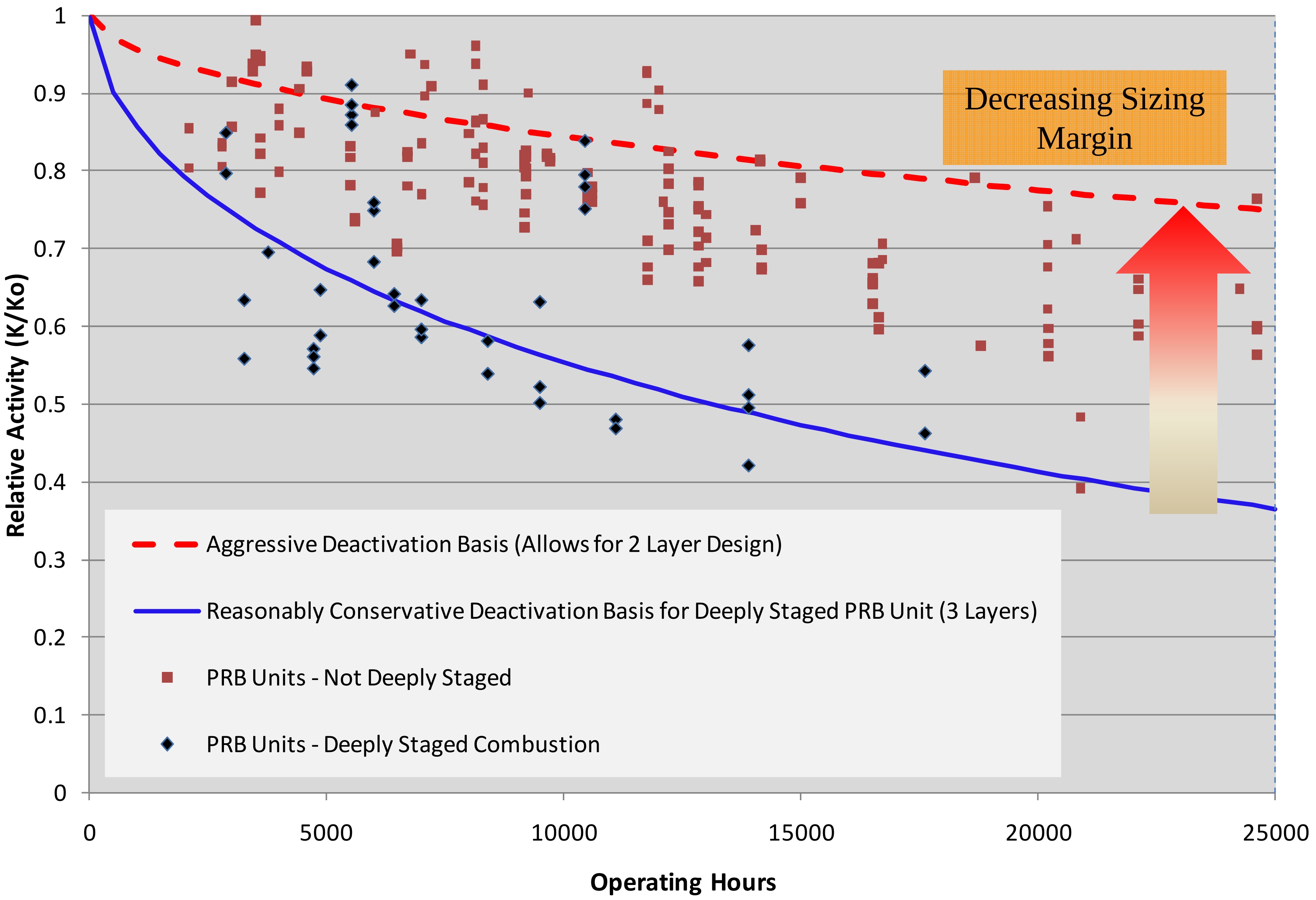
Plate and Honeycomb Deactivation Trends - PRB Units



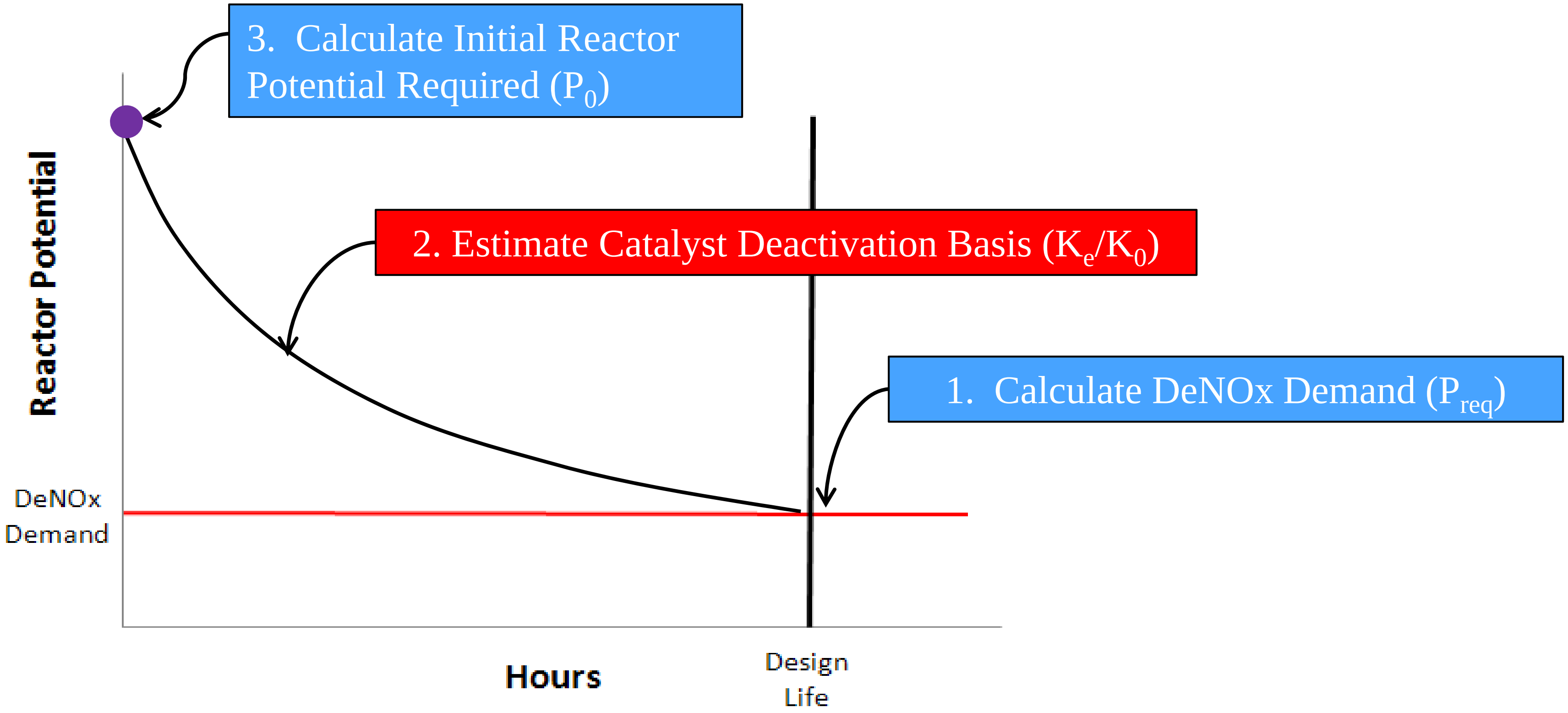
Original Plate Manufacturer's Design Point

Catalysts From 3 Different Manufacturers Exhibit Same K/Ko Trends

Example Catalyst Design Deactivation Rate Assumptions



Catalyst Design Process



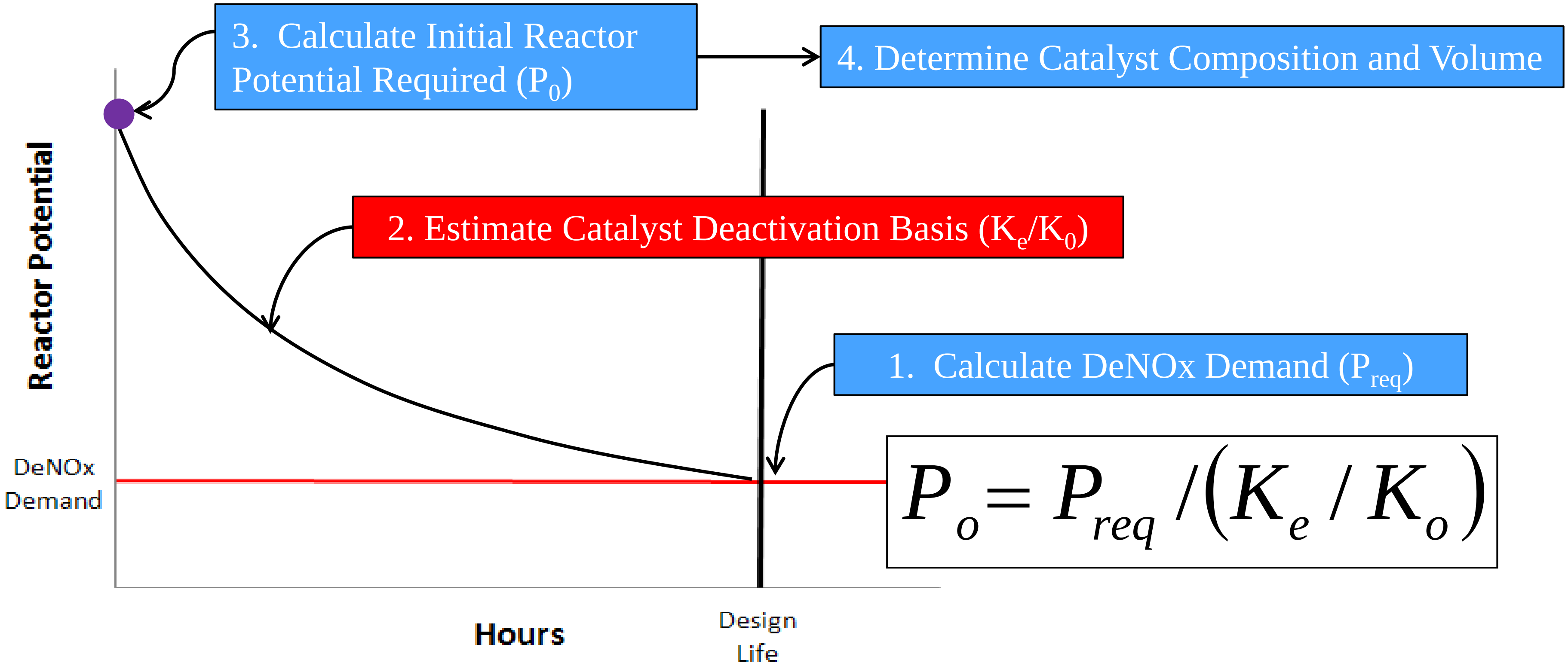
3. Calculate Initial Reactor Potential Required (P_0)

2. Estimate Catalyst Deactivation Basis (K_e/K_0)

1. Calculate DeNOx Demand (P_{req})

1. Calculate DeNOx demand (P_{req}) required (function of NOx removal, NH_3 slip required, distribution requirements and design pluggage) – **SAME VALUE FOR ALL CATALYSTS**
2. Estimate catalyst deactivation basis (K_e/K_0) based on fuel quality, combustion practices, unit duty, and design life – **ESTIMATED BY CATALYST SUPPLIER BASED ON EXPERIENCE OR STRATEGY**
3. Calculate initial reactor potential required [$P_0 = P_{req}/(K_e/K_0)$]

Catalyst Design Process



3. Calculate Initial Reactor Potential Required (P_0)

4. Determine Catalyst Composition and Volume

2. Estimate Catalyst Deactivation Basis (K_e/K_0)

1. Calculate DeNOx Demand (P_{req})

$$P_o = P_{req} / \left(K_e / K_o \right)$$

1. Calculate DeNOx demand (P_{req}) required (function of NOx removal, NH_3 slip required, distribution requirements and design pluggage) – **SAME VALUE FOR ALL CATALYST SUPPLIERS**
2. Estimate catalyst deactivation rate (K_e/K_0) based on fuel quality, combustion practices, unit duty, and design life – **ESTIMATED BY CATALYST SUPPLIER BASED ON EXPERIENCE OR STRATEGY**
3. Calculate initial reactor potential required [$P_0 = P_{req}/(K_e/K_0)$]
4. Catalyst volume determined based on P_0, operating conditions, SO2:3 conversion rate requirement, and catalyst geometry

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Why is Estimating Catalyst Deactivation So Important

- If Deactivation is Underestimated
  - Catalyst is Undersized
  - Incapable of Meeting NOx Removal and Ammonia Slip Performance at Some Point During the Guarantee Period
  - Deficient Performance is Either Tolerated or an Early Outage (Unscheduled) is Required for Catalyst Addition
  - Catalyst Management Costs are Underestimated
- Understanding and Managing Reactor Potential Critical to Minimize Risk
- Examples Help to Illustrate Risk

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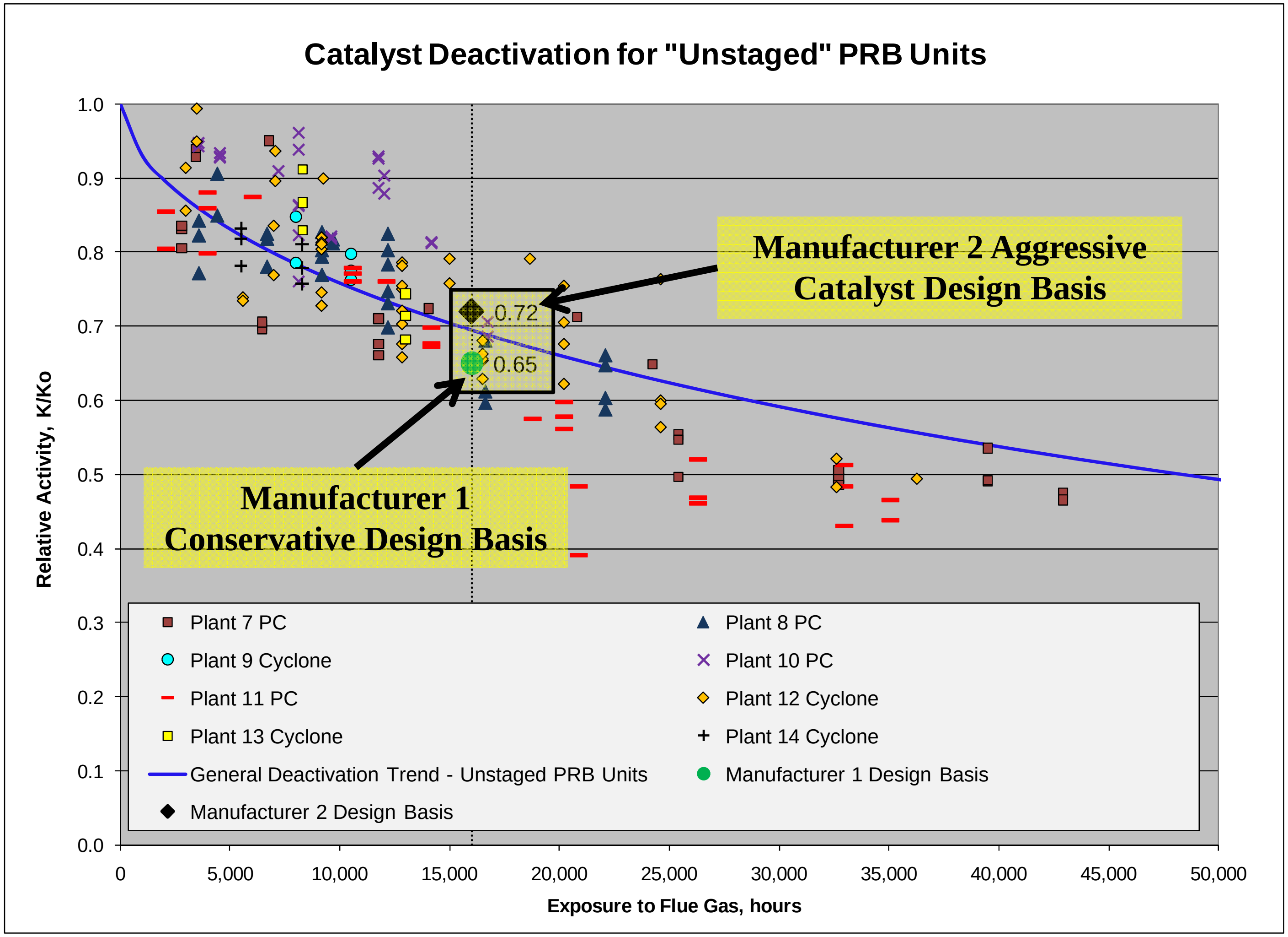
“Unstaged” PRB Unit Catalyst Design Basis



- Manufacturer 1 Designs Catalyst for K/Ko = 0.65 (Conservative) Requires 3 Layers
- Manufacturer 2 Designs Catalyst for K/Ko = 0.72 (Aggressive) Allows 2 Layers

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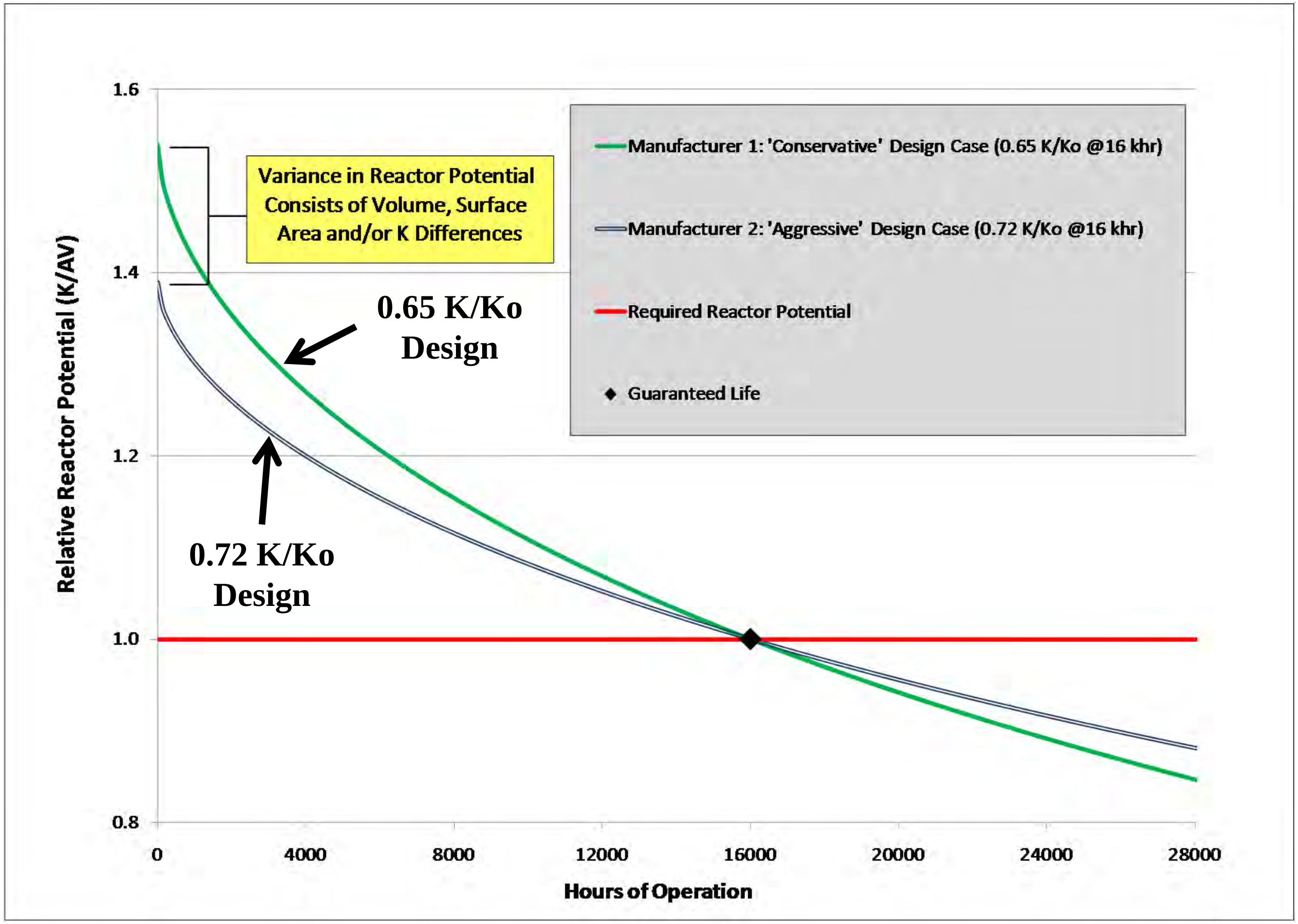
“Unstaged” Catalyst Design Comparison of Two Catalyst Manufacturer Designs



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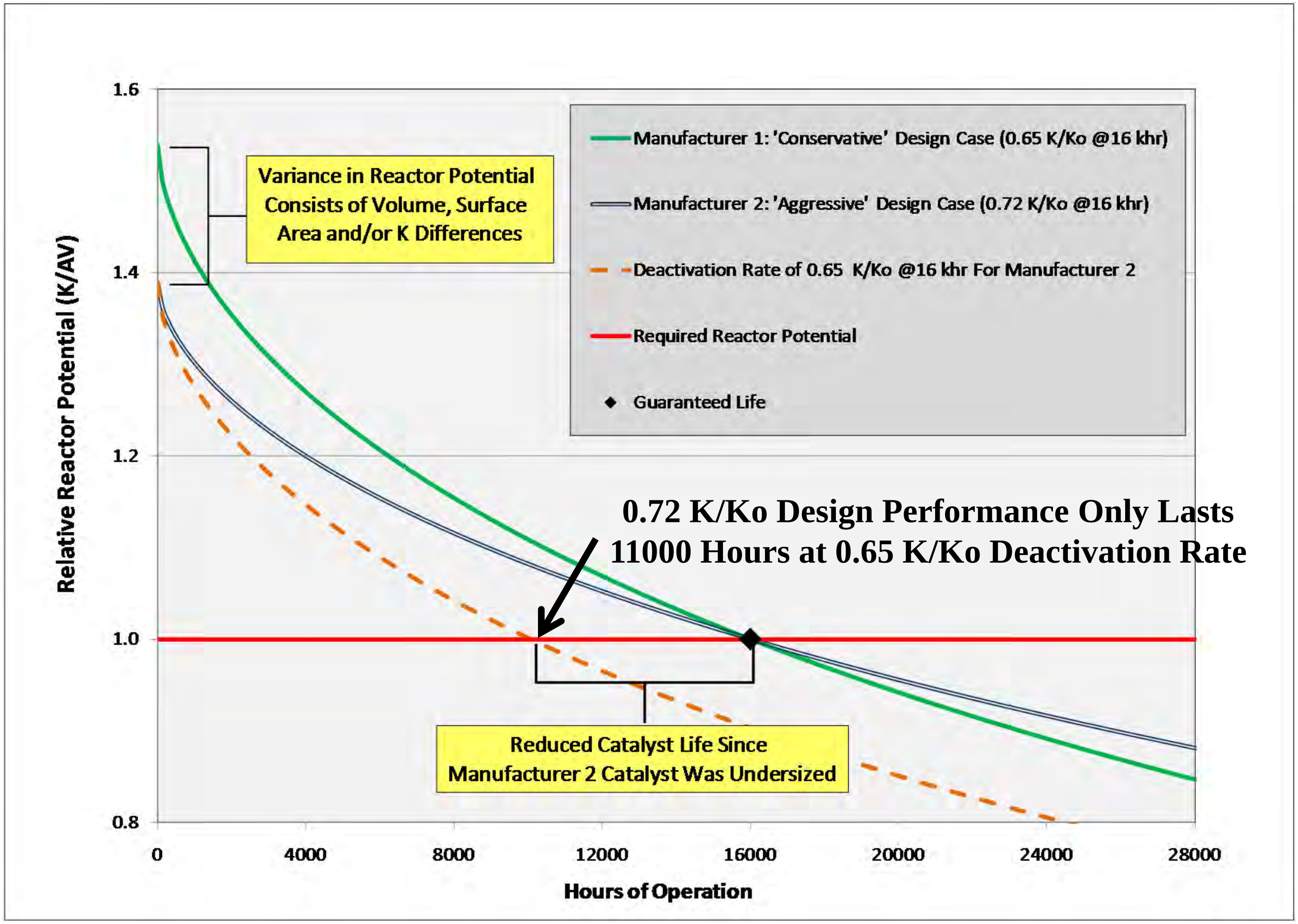
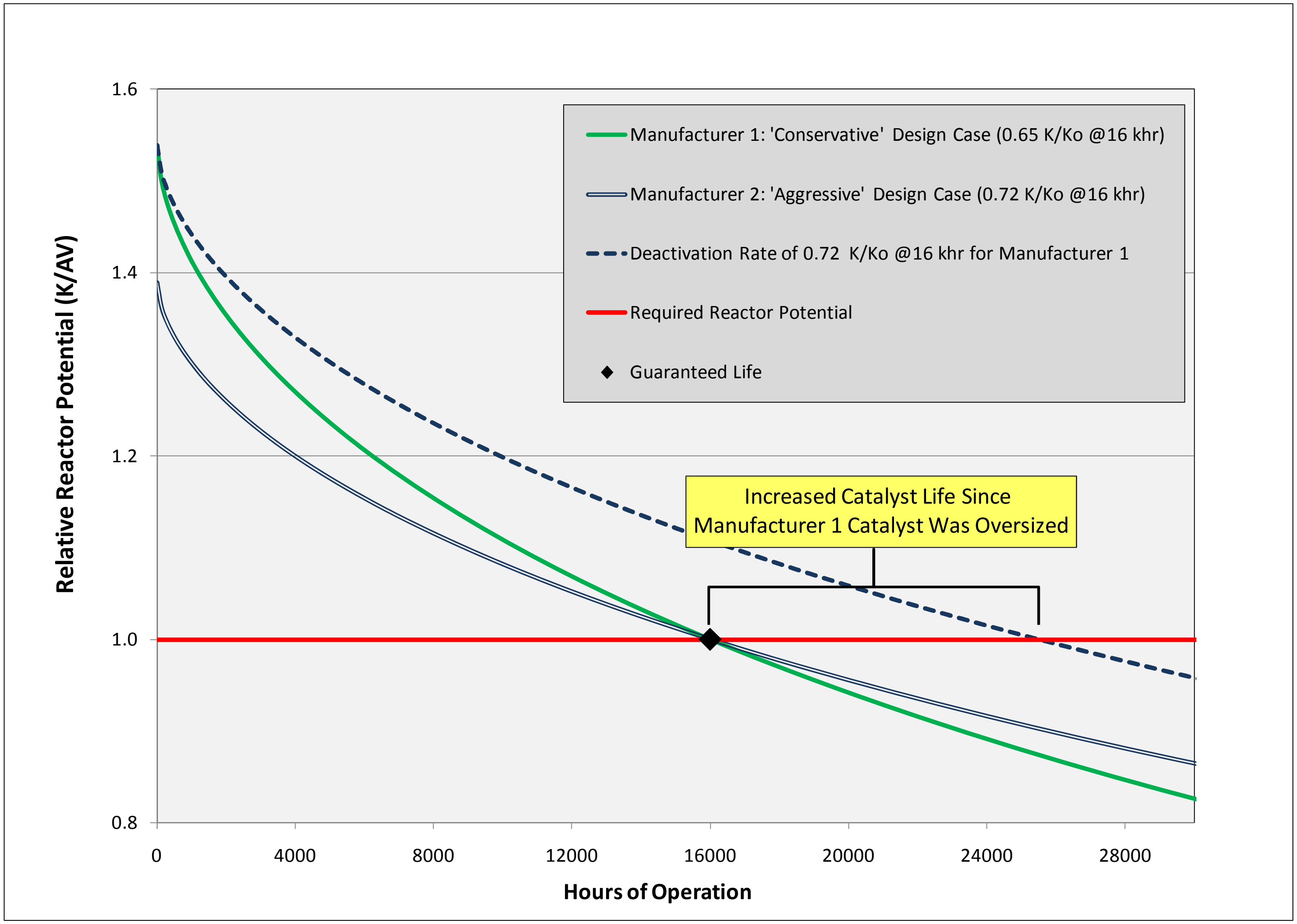
“Unstaged” Catalyst Design Comparison – Case 1 High Deactivation



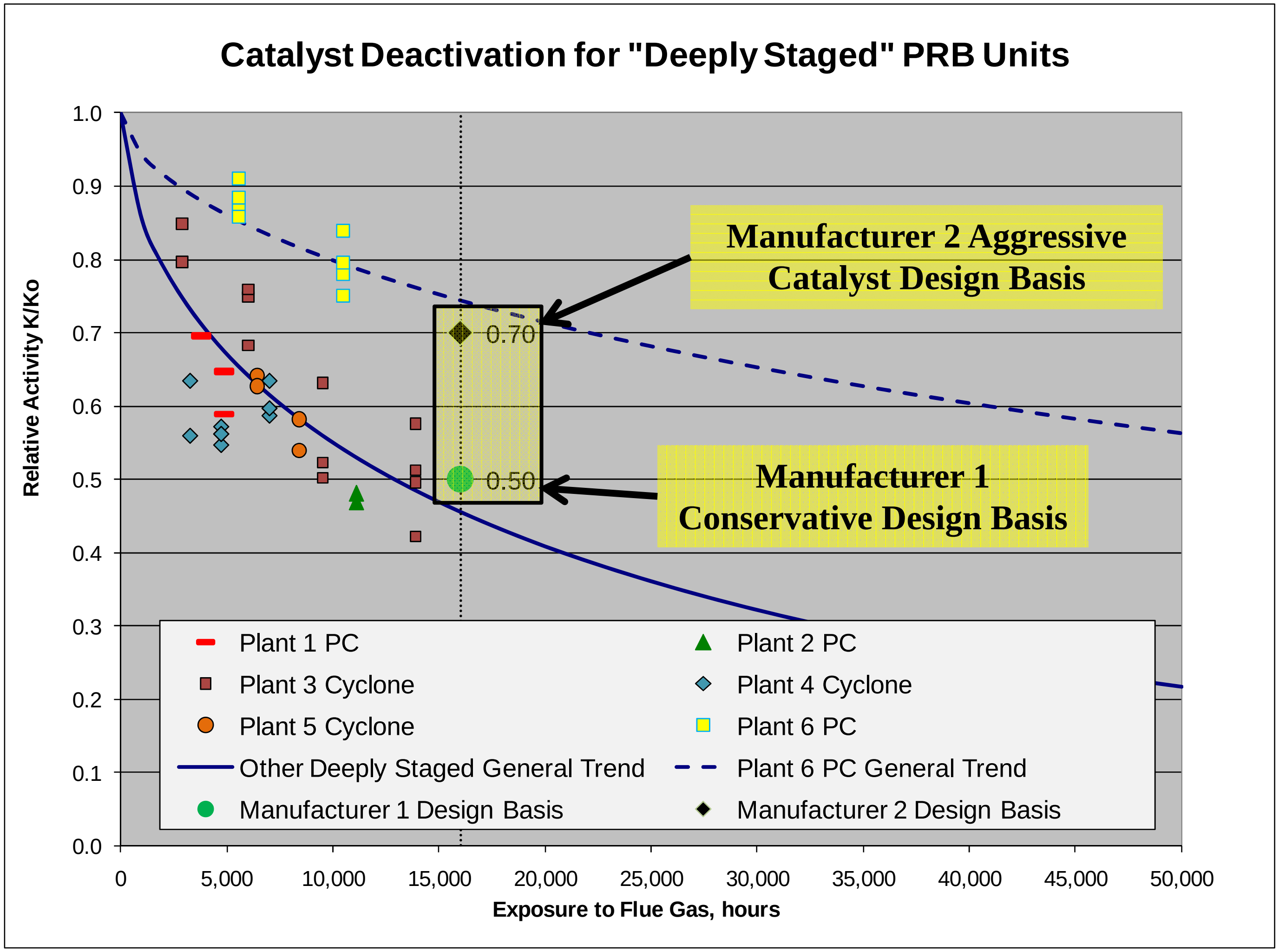
- A Catalyst Designed for a Deactivation Rate K/Ko =0.72 @16khr Will Require a Catalyst Addition at Approximately 11,000 Hours if a Deactivation Rate K/Ko = 0.65 Occurs (see dashed line above)

“Unstaged” Catalyst Design Comparison – Case 2 Low Deactivation



- A Catalyst Designed for a Deactivation Rate K/Ko = 0.65 @16khr Will Not Require a Catalyst Addition Until Approximately 26,000 Hours if a Deactivation Rate K/Ko = 0.72 Occurs (see dashed line above)

“Deeply Staged” PRB Unit Catalyst Design Basis



- Manufacturer 1 Designs Catalyst for K/Ko = 0.50 (Conservative) Requires 3 Layers
- Manufacturer 2 Designs Catalyst for K/Ko = 0.70 (Aggressive) Allowing 2 Layers

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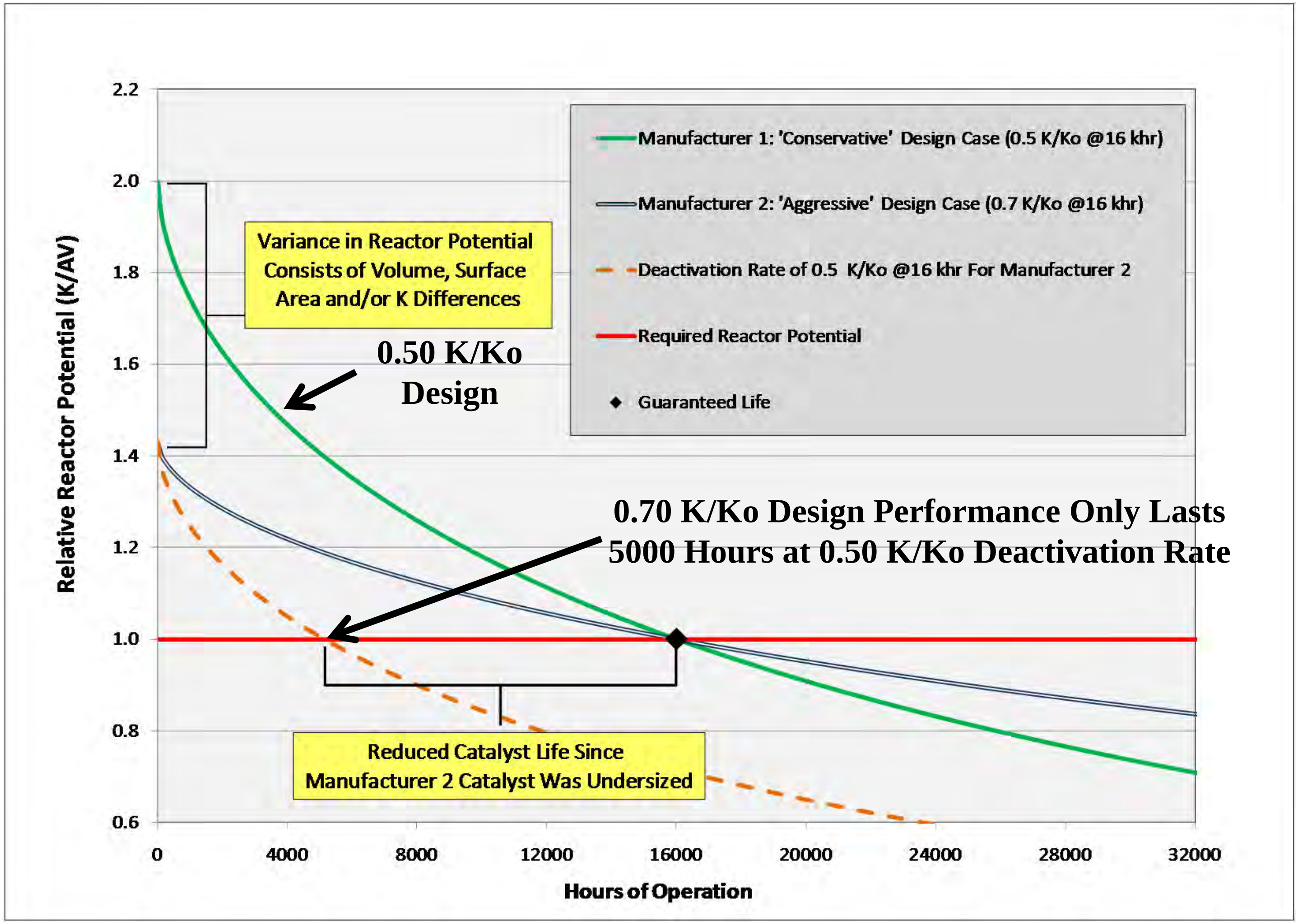
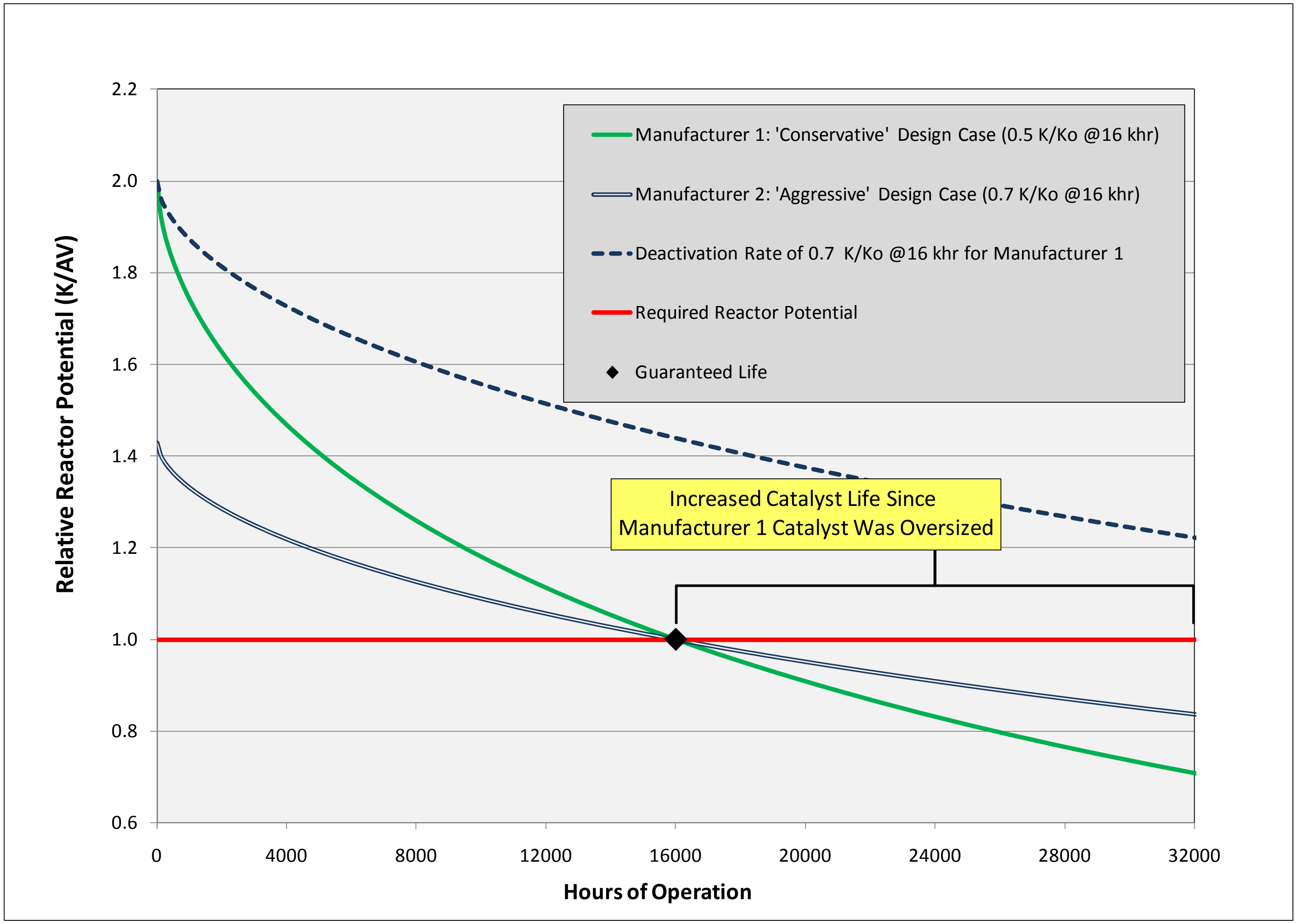
“Deeply Staged” Catalyst Design Comparison – Case 1 High Deactivation



- A Catalyst Designed for a Deactivation Rate K/Ko = 0.70 @16khr Will Require a Catalyst Addition at Approximately 5000 Hours if a Deactivation Rate K/Ko = 0.50 Occurs (see dashed line above)

"Deeply Staged" Catalyst Design Comparison – Case 2 Low Deactivation



- A Catalyst Designed for a Deactivation Rate K/Ko = 0.50 @16khr Will Not Require a Catalyst Addition Until More Than 32,000 Hours if a Deactivation Rate K/Ko = 0.70 Occurs (see dashed line above)

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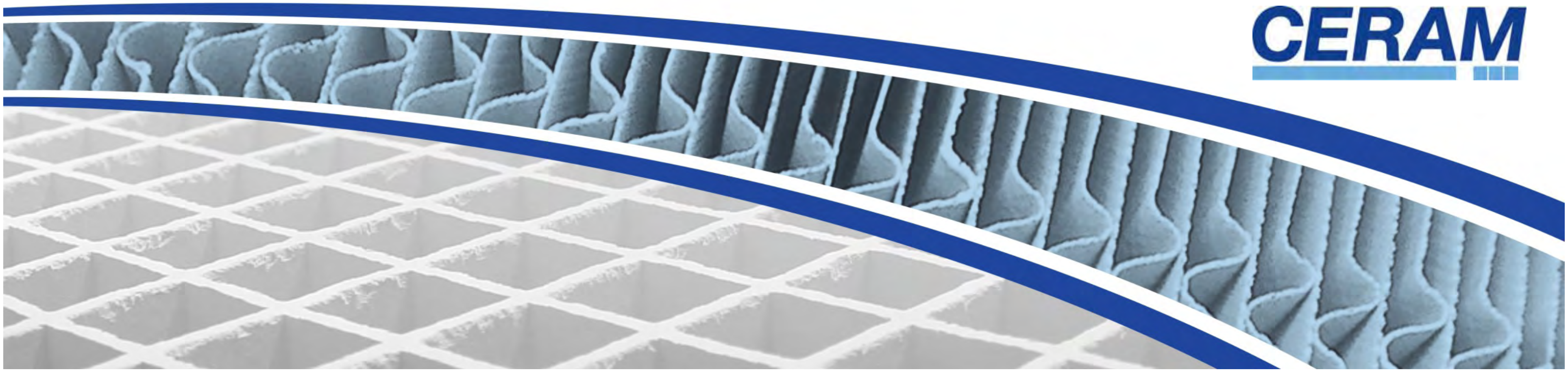
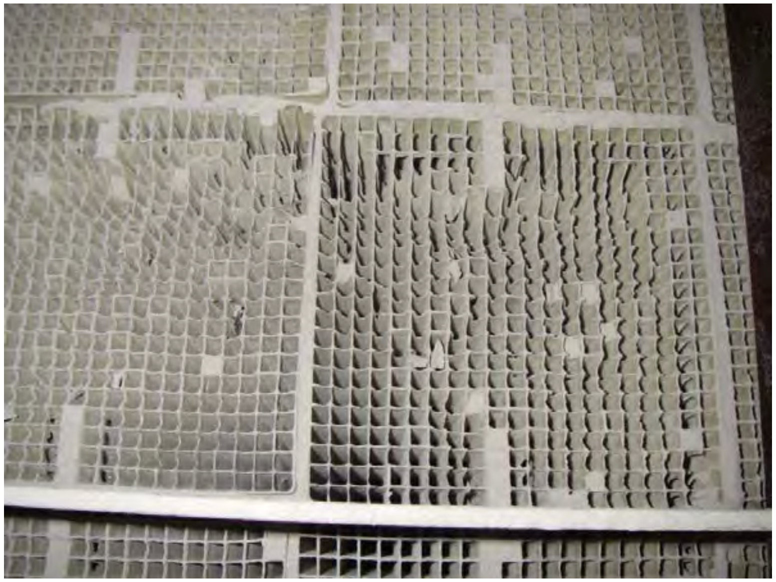
Why is Mechanical Design Important to Reactor Potential?



Erosion Can Affect Any Catalyst Type

- Erosion Risk Varies as Ratio of Flow to 3rd or 4th Power
- Exposed Plate Stainless Steel Provides No Activity and Available for SO_2 to SO_3 Conversion
- Managed by Limiting Face Velocity
  - 4.5 to 5.5 m/s Generally
  - 5.0 to 5.5 m/s for PRB
  - 4.8 to 5.0 m/s for High Ash Content With High Silica
  - Assure Good Flow Distribution
  - Minimize Catalyst Pluggage



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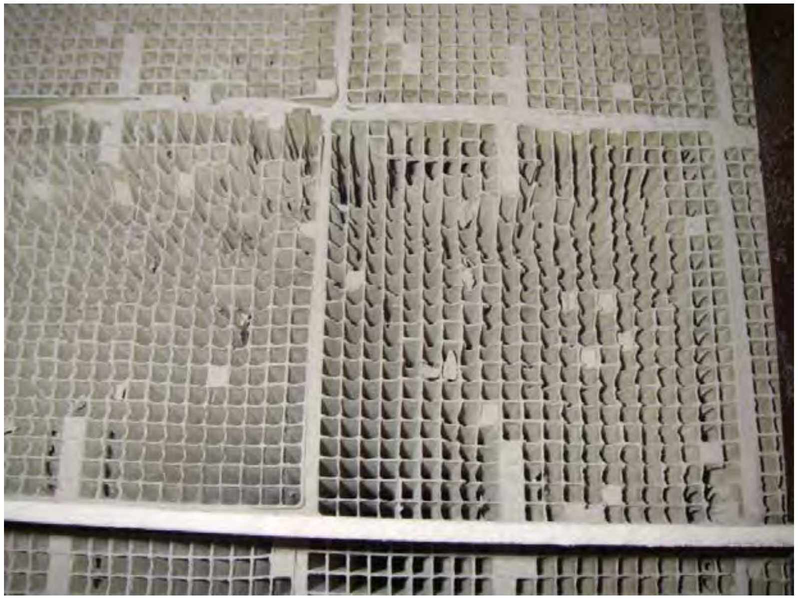
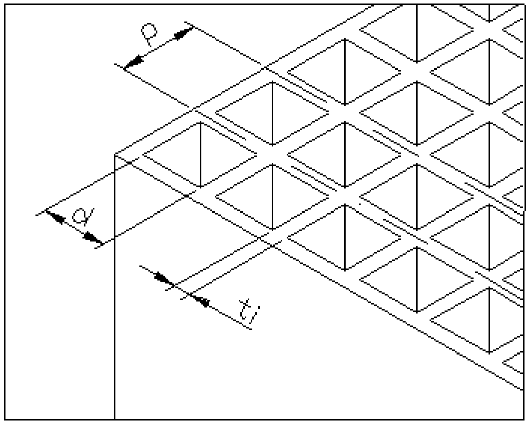
Catalyst Wall Thickness

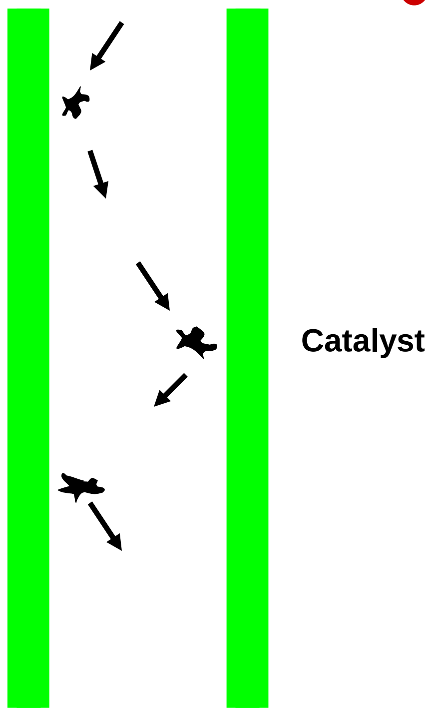
Erosion Has Two Areas of Attack:

- Catalyst Leading Edge
- Catalyst Walls



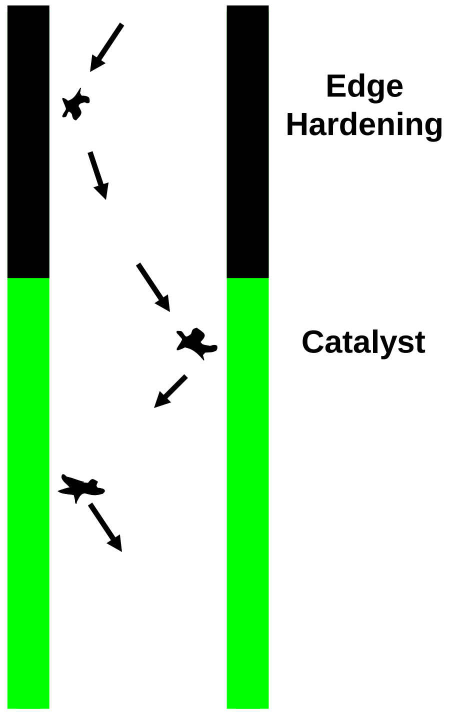


Catalyst Wall Erosion



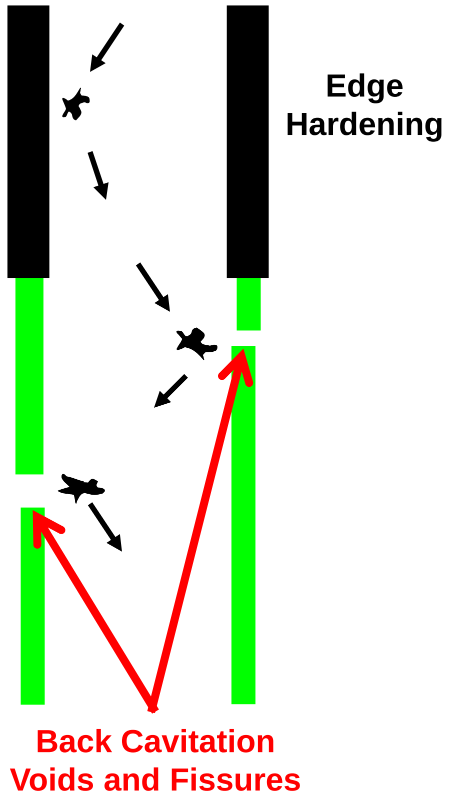
- Mechanism:
  - Gas Flow Transitions From Turbulent to Laminar Within Catalyst
  - Dust Particles (Irregularly Shaped) Do Not Follow Laminar Gas Flow Pattern
  - Particles Tend to Tumble and Impact Wall Over Entire Element Length
  - Erosion Uniform Top to Bottom

Catalyst Wall Erosion



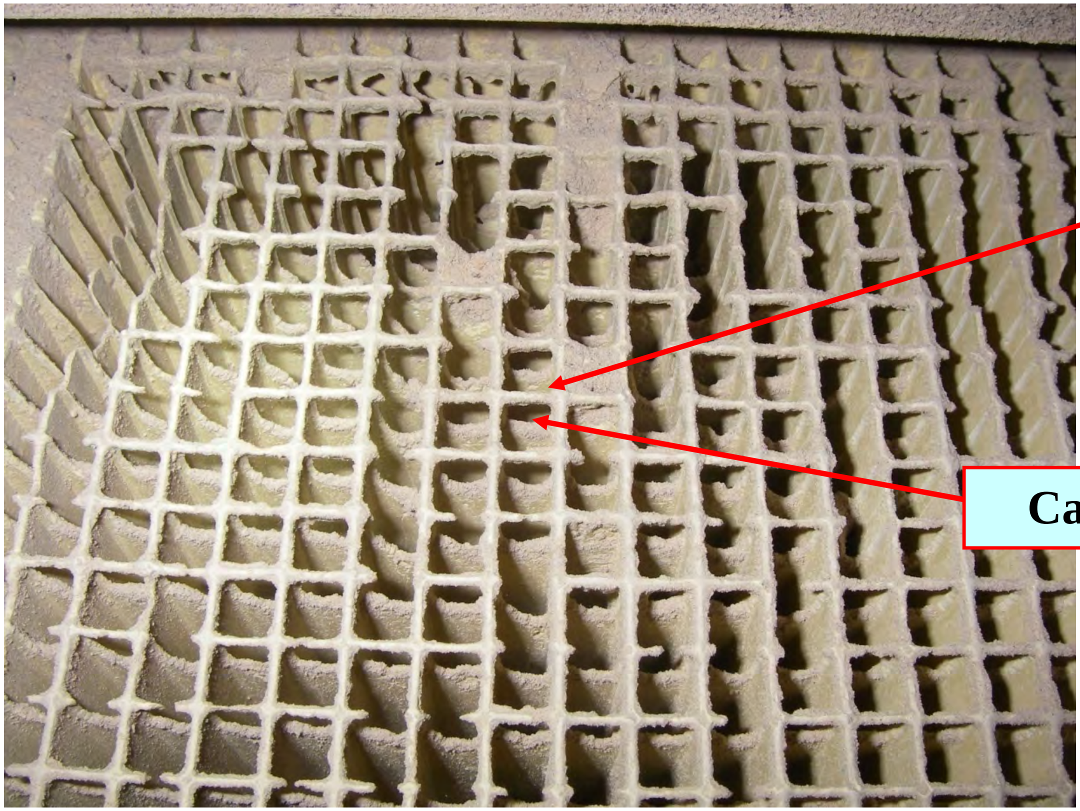
- Edge Hardening is a Applied to Catalyst Surface
- Chemically Inactive Substance That Resists Erosion
- Edge Hardened Material is Not Catalytic and is Unavailable for NOx Removal

Catalyst Wall Erosion



- Ultimately Catalyst Walls Can Break Down Behind Edge Hardening Due to Wall Thinning
- Thin Wall Catalyst Will Have Earlier Incidence of Mechanical Failure
- Mechanical Failure Will Lead to Increasing Pluggage Rates and Increasing Pressure Drop
- Use of “Higher Hardness” Materials Reduces Catalyst Activity
- Edge Hardening Does Not Increase Catalyst Mechanical Life
- Adequate Wall Thickness Provides Sufficient Mechanical Life

Edge Hardened Catalyst Erosion
@ 14,000 Hours – Back Cavitation and Wall Thinning



Edge Hardened Leading Edge

Cavitation Void

Continued Operation Will Ultimately Result in Complete Structural Failure

Catalyst Manufactured by North American Supplier (NOT CERAM)

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Ferritic (Type 400) Stainless Steel Substrate Has Deficient Mechanical Strength for Regeneration

Corrosion Loss From Plate Trailing Edge

Brittle Material Breaks Out With Thumb Pressure

Hand Torn Pieces from Element Pulled Up on Right

- Historically Plate Catalyst Used Type 300 (Austenitic) Stainless Steel
  - Excellent Mechanical Life Including Multiple Regenerations
- If Unspecified, Suppliers Will Utilize Type 400 (Ferritic) Stainless Steel to Minimize Cost (~+10% of Total Cost to Use Type 300)
- Type 400 Stainless Steel is Subject to Corrosion Each Time the Flue Gas Goes Through the Acid Dew Point

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Photos taken of catalyst delivered for regeneration to one of the predominant suppliers of this service.

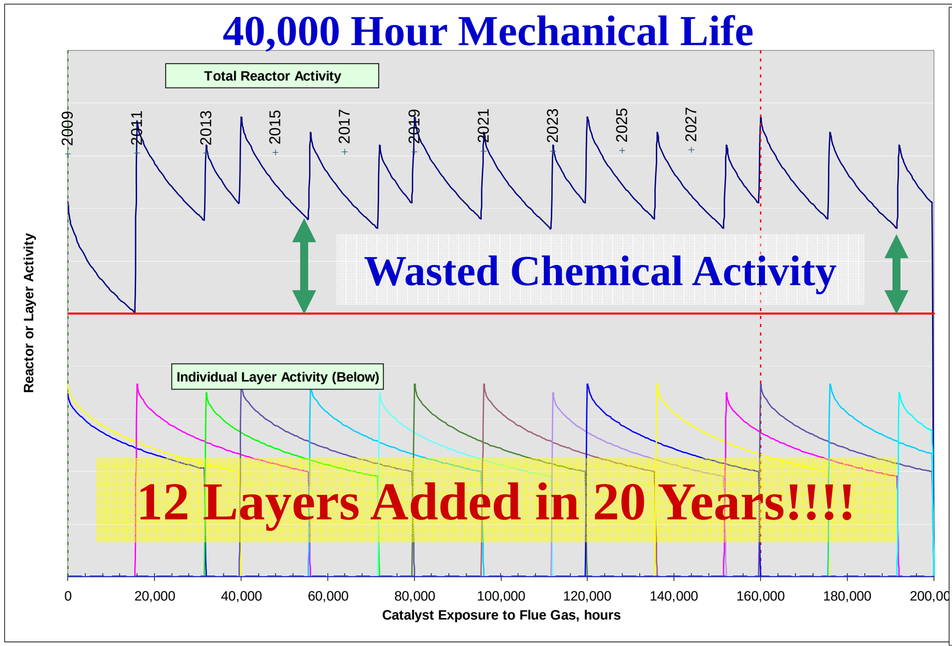
Catalyst Mechanical Recommendations to Enhance Mechanical and Reduce Pluggage

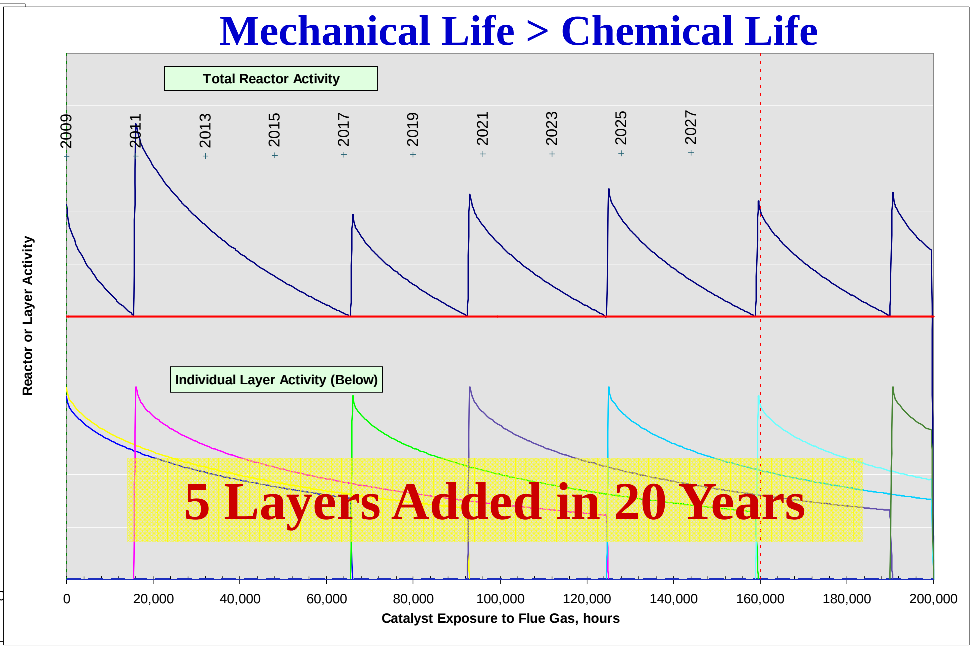
Honeycomb Catalyst Wall Thickness Recommendations			
		>80,000 to 100,000 Mechanical Life and Multiple Regenerations	
Pitch	**Cells**	**Inner Wall**	**Outer Wall**
mm	x by x	mm	mm
6.7	22	0.8 to 0.9	1.3
7.1	21	0.8 to 0.9	1.4
7.4	20	0.8 to 0.9	1.4
8.2	18	0.9 to 1.0	1.7

- Recommendations:
  - Honeycomb Catalyst: Maximum Length of 1300 mm and Wall Thicknesses Highlighted Above
  - Plate Catalyst: Minimum Wall Thickness of 0.75 mm, Maximum Length of 700 mm, Austenitic Steel Substrate, and Including 4 Spacers
- CERAM Can Produce Thin Wall Catalyst
  - Not in Best Interest of Client For Washing/Regeneration and Long Mechanical Life
- CERAM Offers a 60,000 Hour Mechanical Warranty Including Two Catalyst Washes or Regenerations
- Coal High Dust References Regenerated 4 to 5 Times

Life Cycle Considerations Related to Catalyst Mechanical Quality

- "Economic" Plate Catalyst Has <u>Severely</u> Constrained Mechanical Life for Deficient SS Material Choice (e.g. SS430) and/or Thin Wall (<0.7 mm) Construction
- "One Way" Catalyst Difficult and Expensive to Regenerate or Clean - Expected Mechanical Life = 20,000 to 40,000 Hours (Increasing Catalyst Replacements)
- Increased Number of Outages Needed to Replace Mechanically Deficient Catalyst
- Significantly Increased Life Cycle Cost


40,000 Hour Mechanical Life


Mechanical Life > Chemical Life

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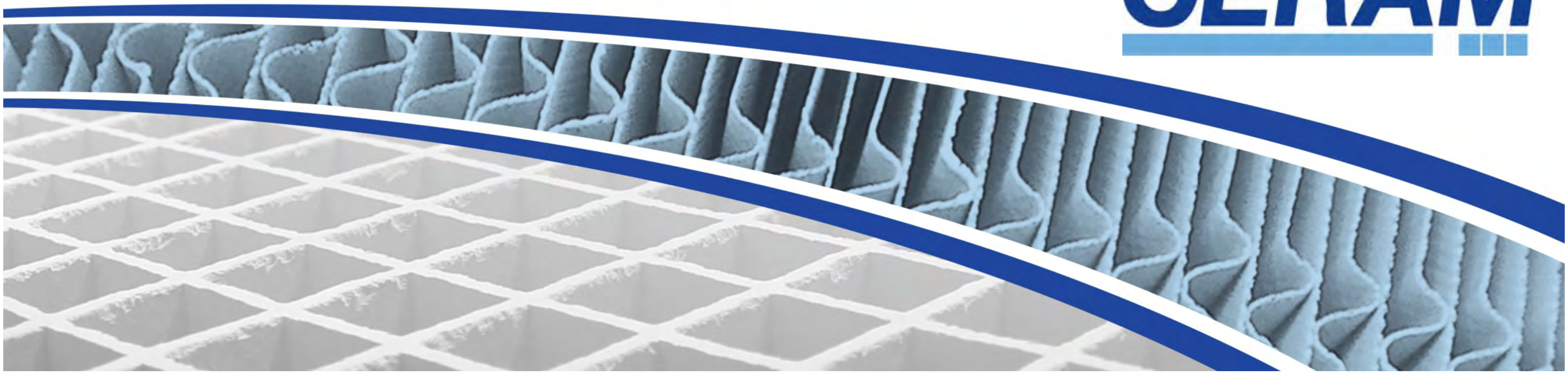
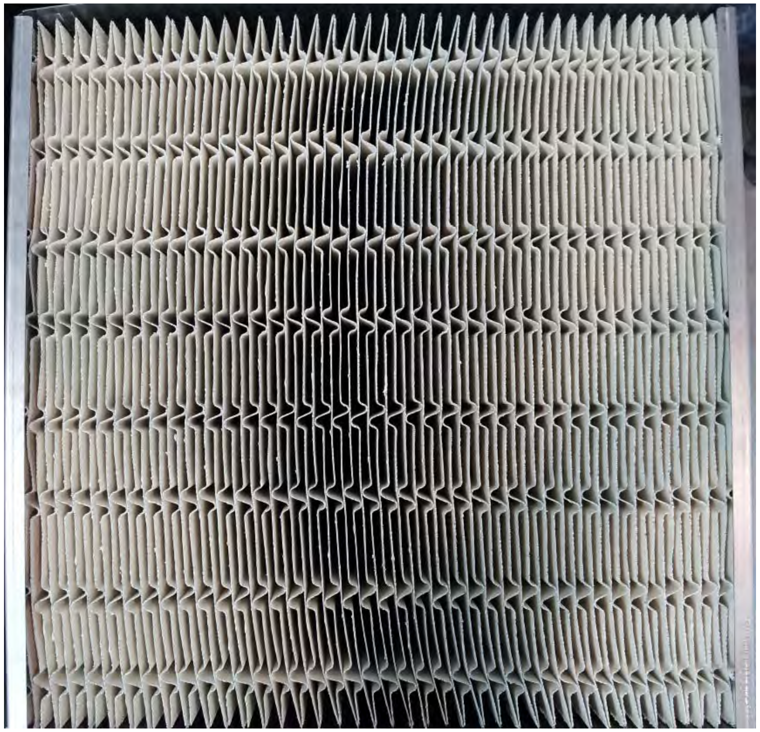
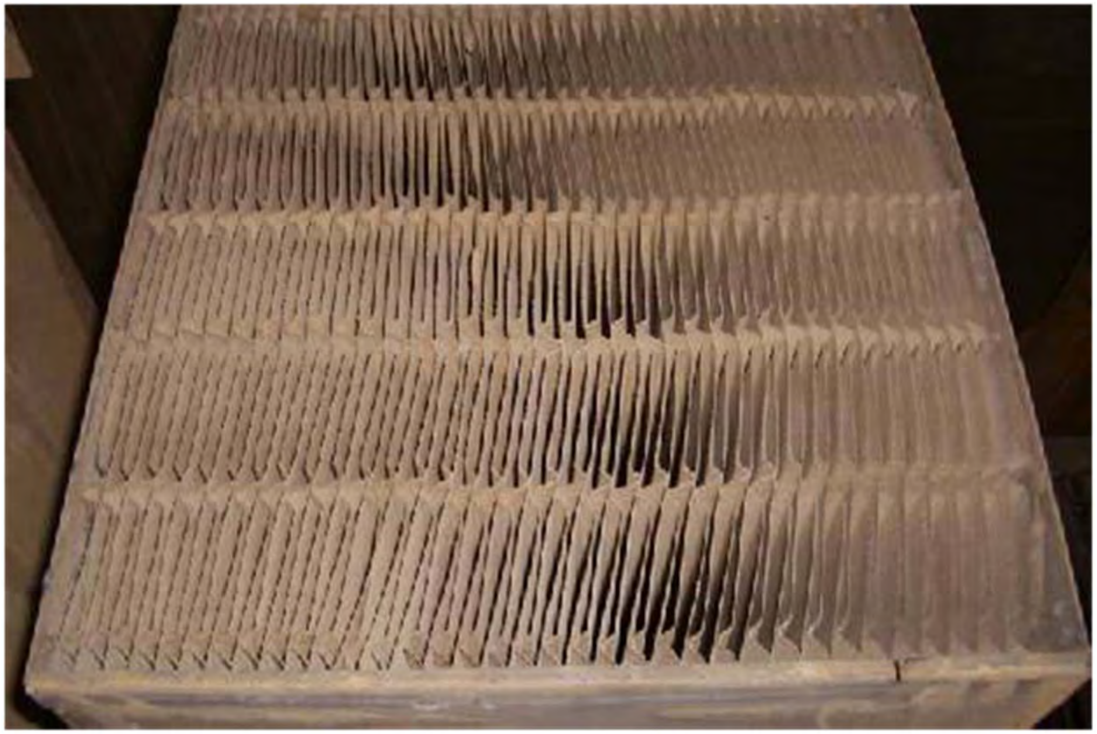
Assuring Operating Reactor Potential



Which Catalyst Will Have a Better Operating Reactor Potential?



CERAM Plate Catalyst
(4 Spacers/Plate +Uniform Spacing)



Competitor Plate Catalyst
(3 Spacers/Plate)

Deficient Plate Mechanical Design (Poor Geometric Uniformity) Can Reduce Operating Activity K by 10 to 20%

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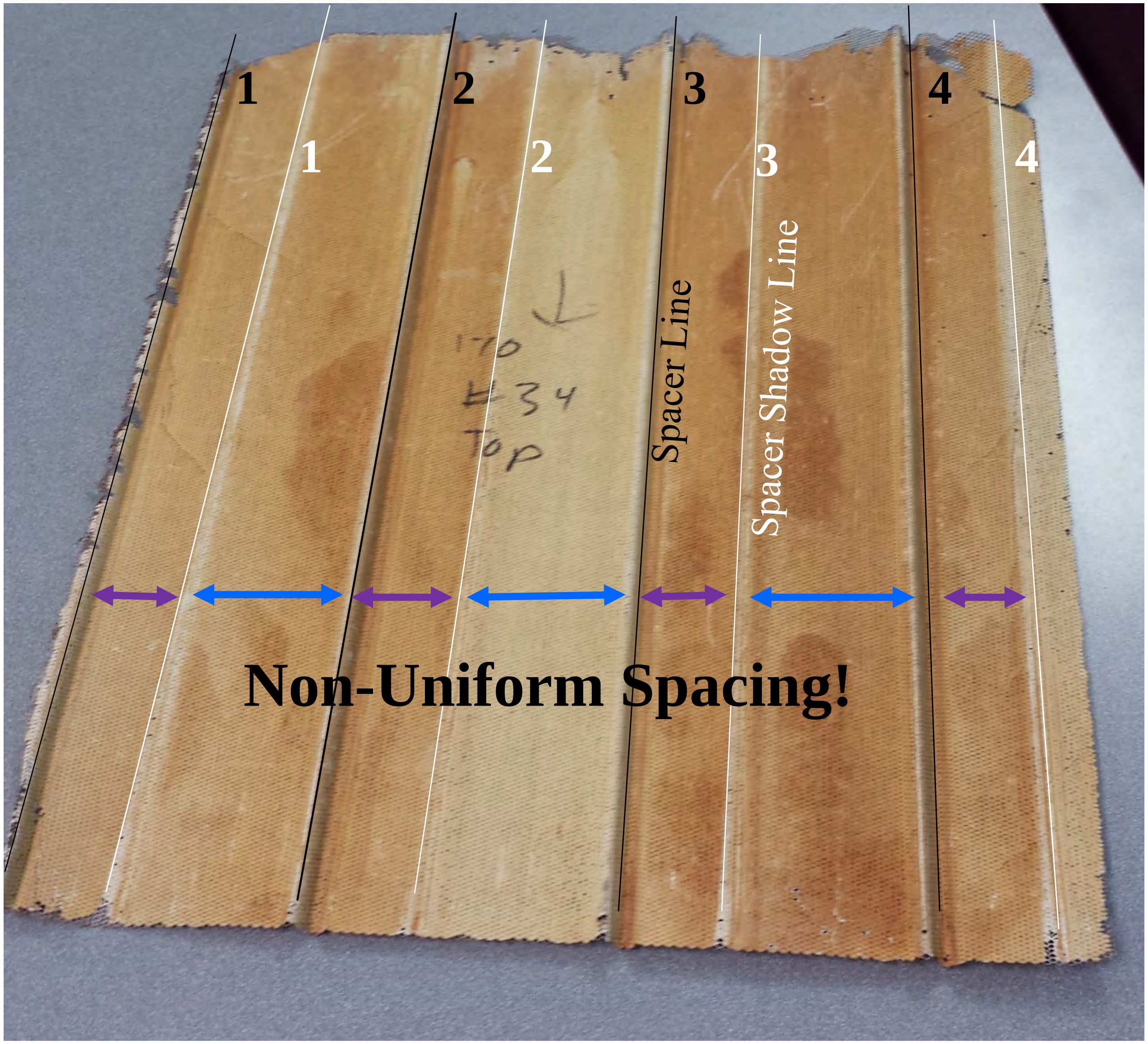
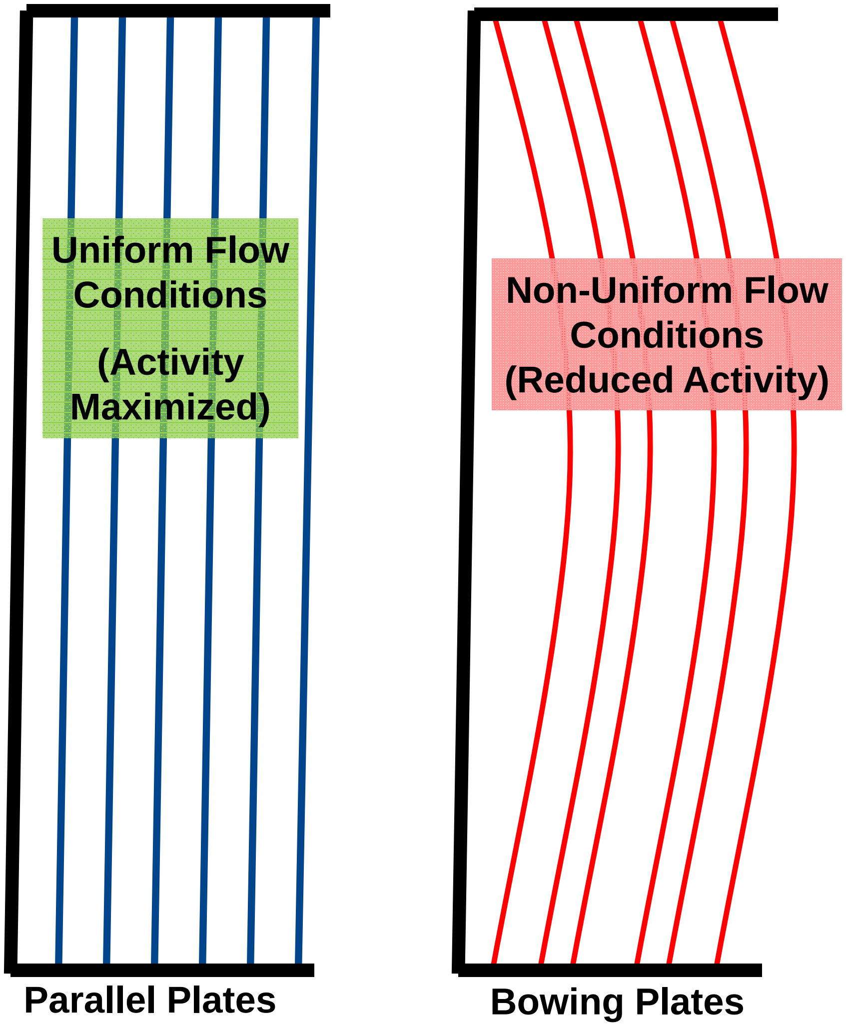
Competitor 4 Spacer Plate With Poor Geometric Uniformity

Opposing Plate Leaves a Spacer Shadow Line Illustrating Spacer Locations



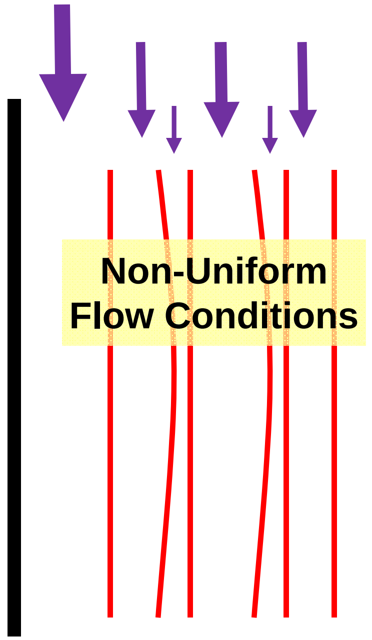
Non-Uniform Spacing!

Operating Reactor Potential Affected by Catalyst Mechanical Condition



Plan View

- Plate Bowing 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 W/ Bowing Plates

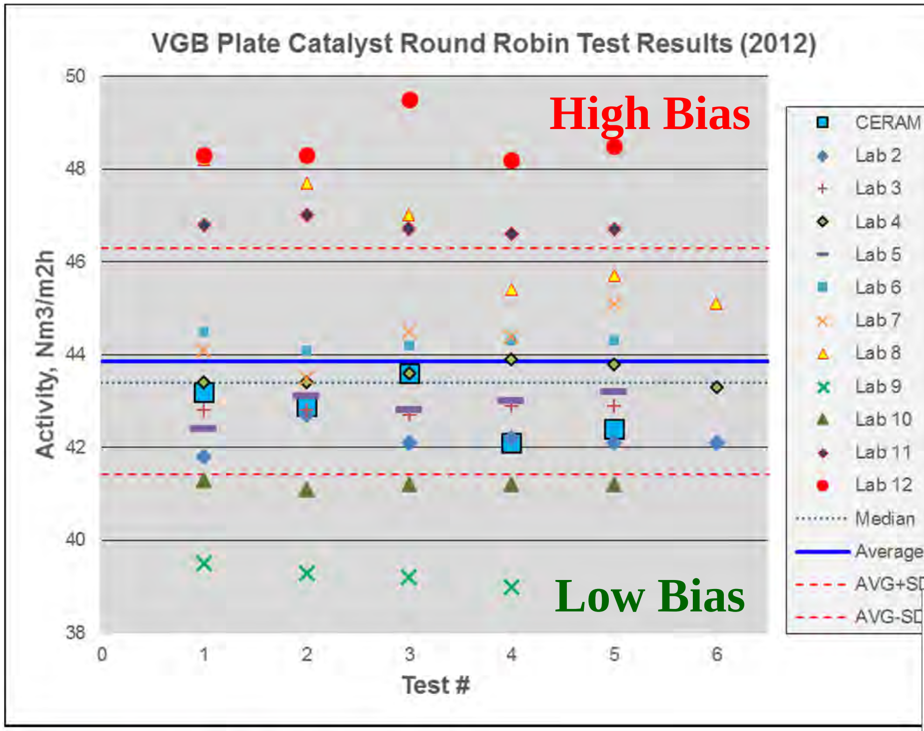
What About Catalyst Testing?
Most Important Factor: Accuracy

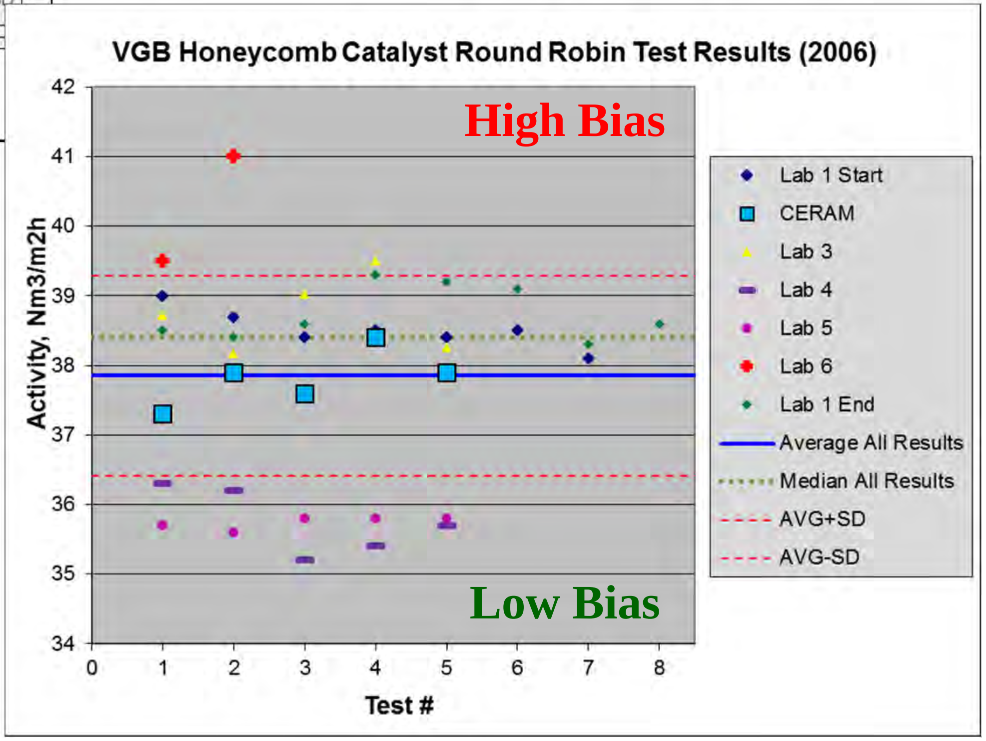
- There is No Direct Measurement of Activity
- Must Accurately Measure and Control….
  - NOx Reduction
  - NH_3 Molar Ratio
  - Gas Flow
  - Sample Geometry
  - Recreate Flue Gas Conditions

- 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?

VGB Round Robin* Test Results

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





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

Laboratory Bias Exceeding 2 K Problematic for Catalyst Management

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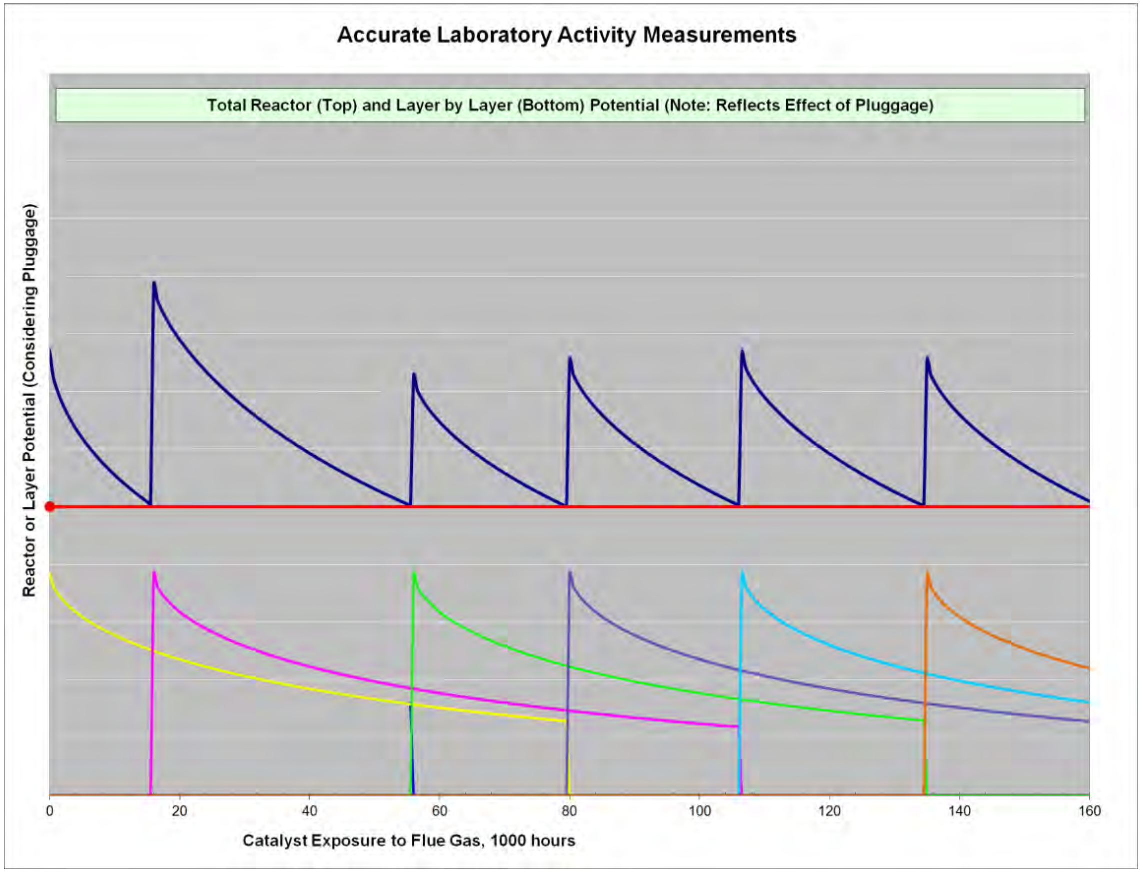
*VGB Round Robin: Element With Unknown Activity
Circulated to Participating SCR Catalyst Test Laboratories

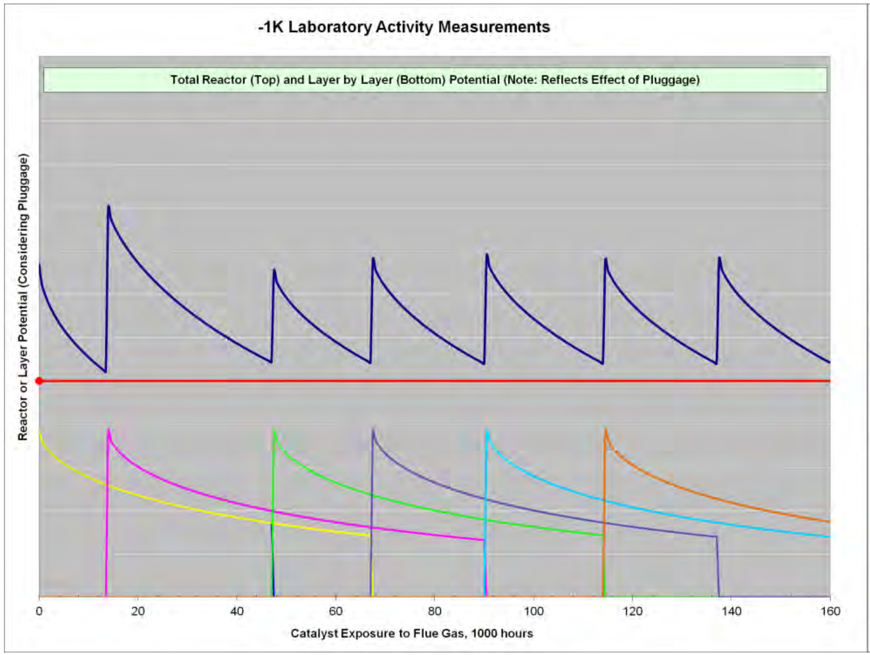
Implications of Biased K Measurements

- 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



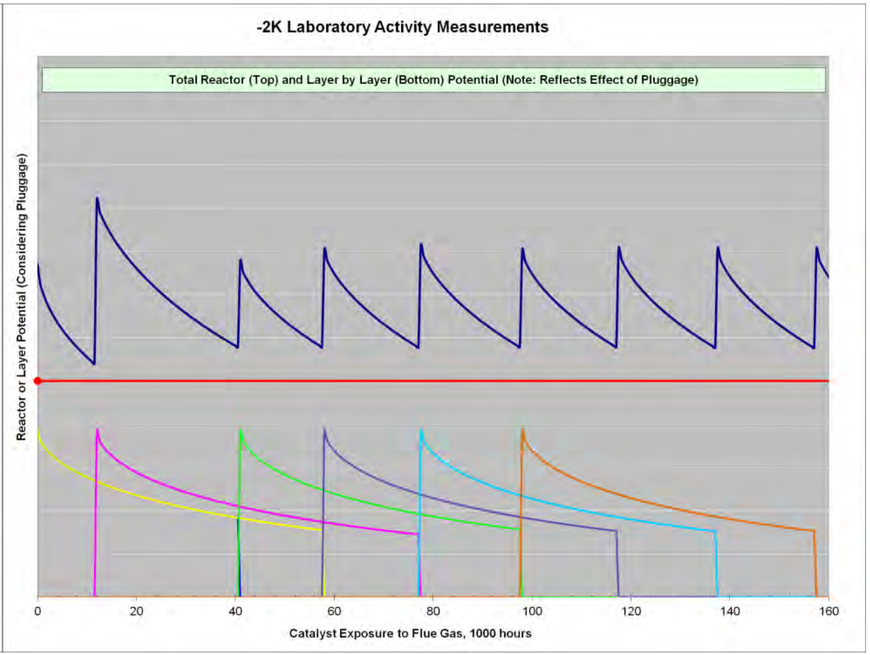
Low Bias Lab Activity Result:
Wasted Activity and Increased Catalyst Costs

Minus 1 K Bias



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

Minus 2 K Bias

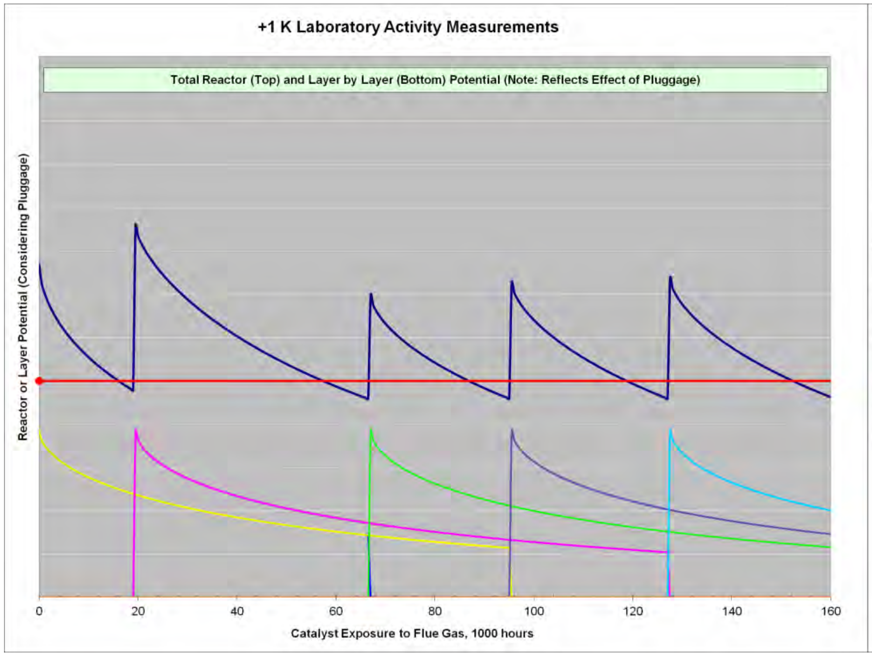


- $3.6 M (33%) more catalyst
- 8 Events (+3 to Unbiased)

CERAM

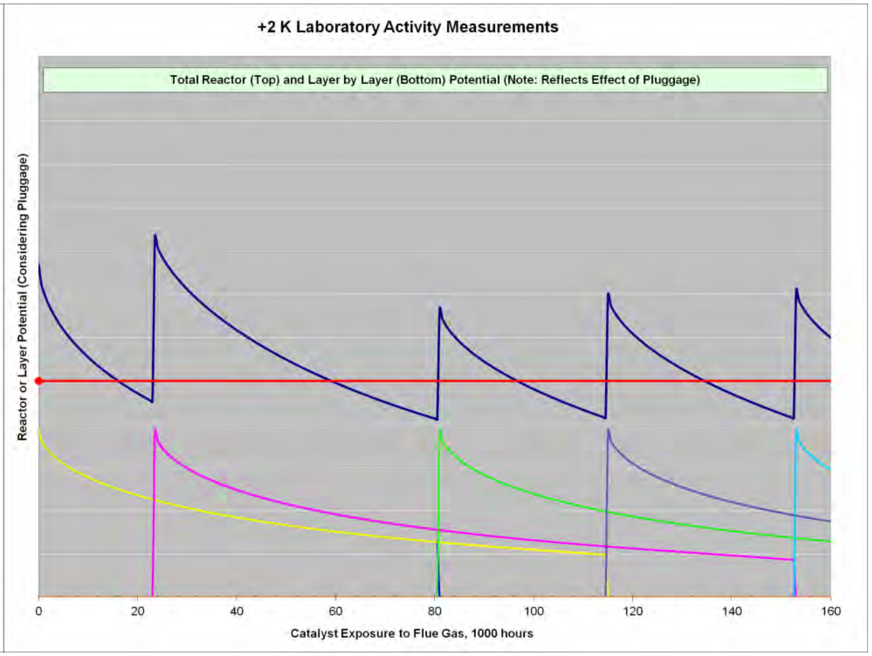
High Bias Lab Activity Result: Deficient Performance

Plus 1 K Bias



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

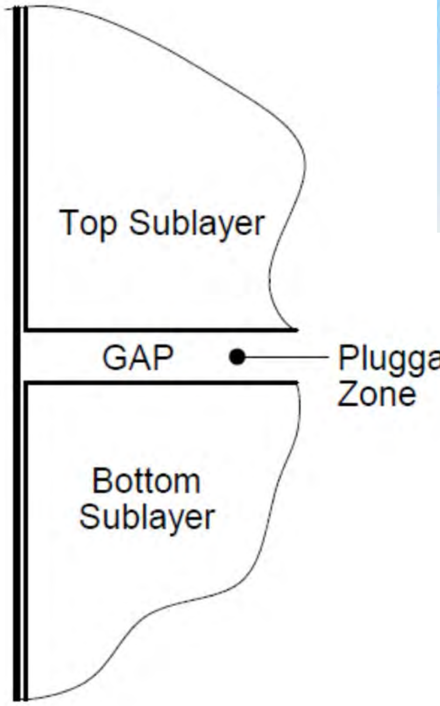
Plus 2 K Bias

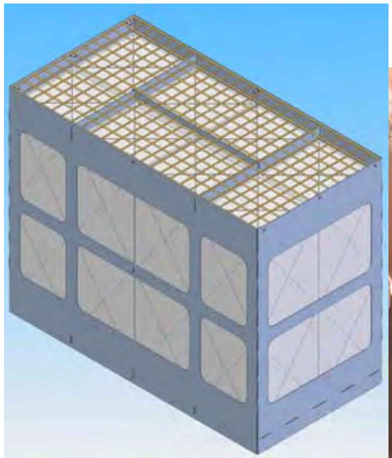


- 6 ppm NH_3 slip
- Surprise Catalyst Needs (+\$/m^3)

CERAM Plate Catalyst Reduces Potential for Sublayer Pluggage

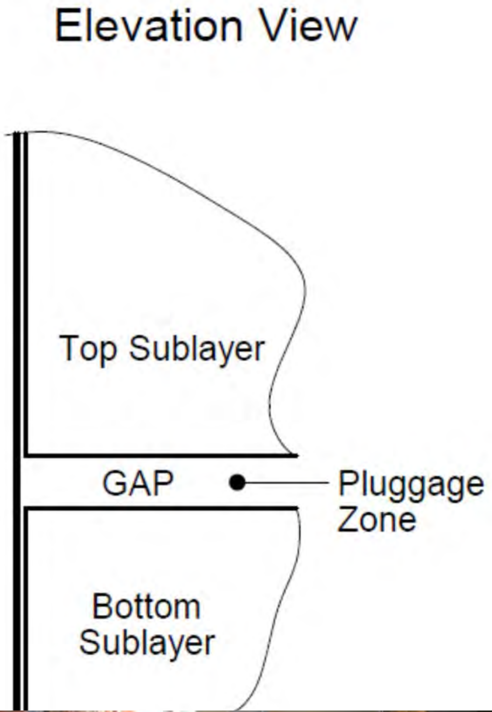
Elevation View

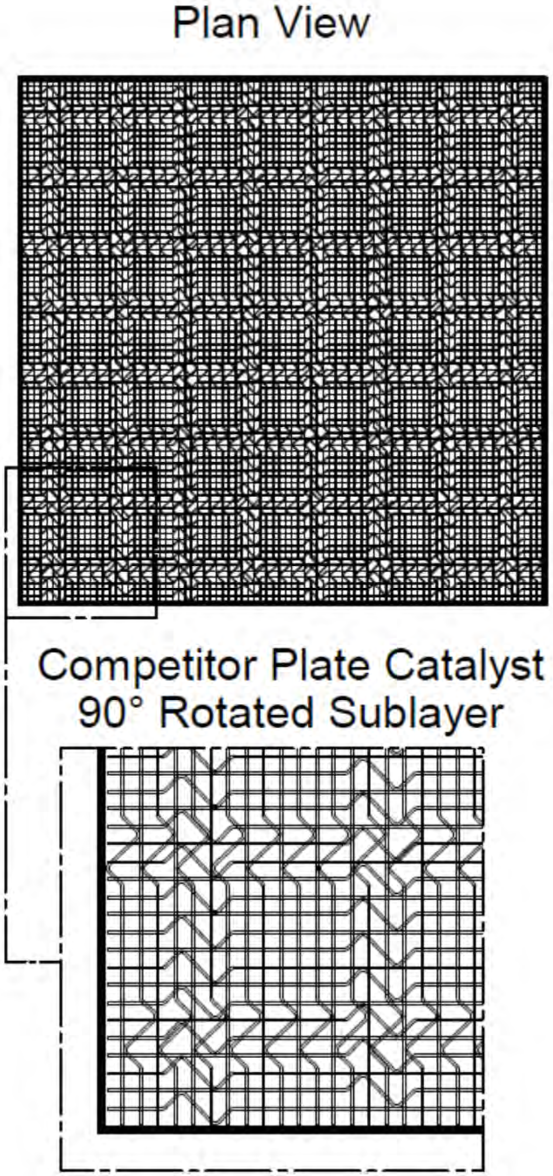




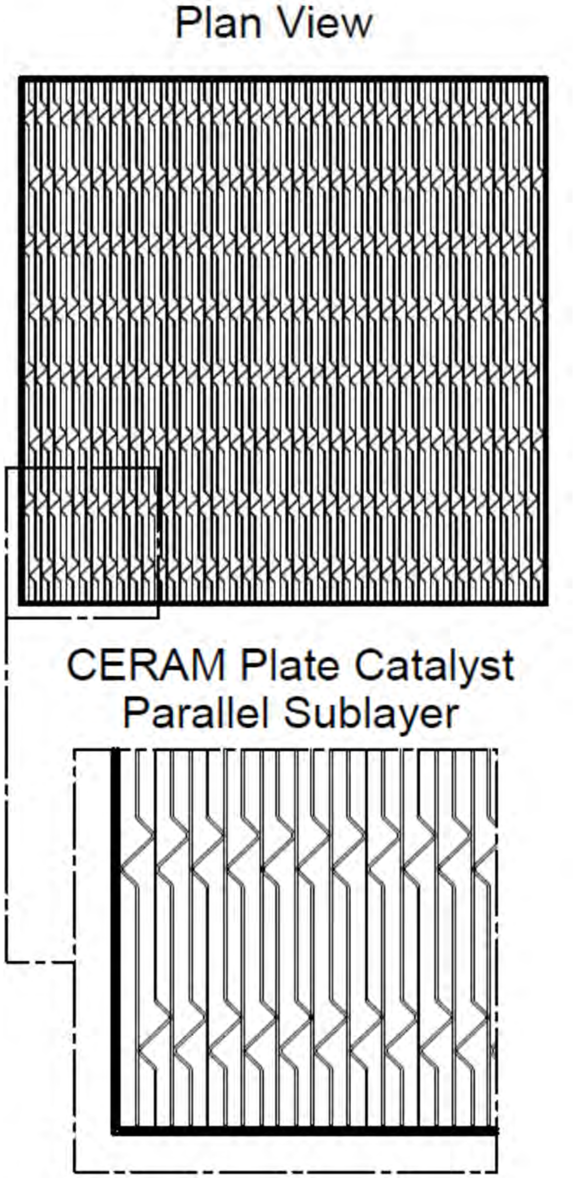
Competitor Catalyst Sublayer Pluggage Being “Dry Cleaned” Before Regeneration

CERAM Plate Catalyst Design Reduces Potential for Sublayer Pluggage





Competitor Plate Catalyst
90° Rotated Sublayer



CERAM Plate Catalyst
Parallel Sublayer

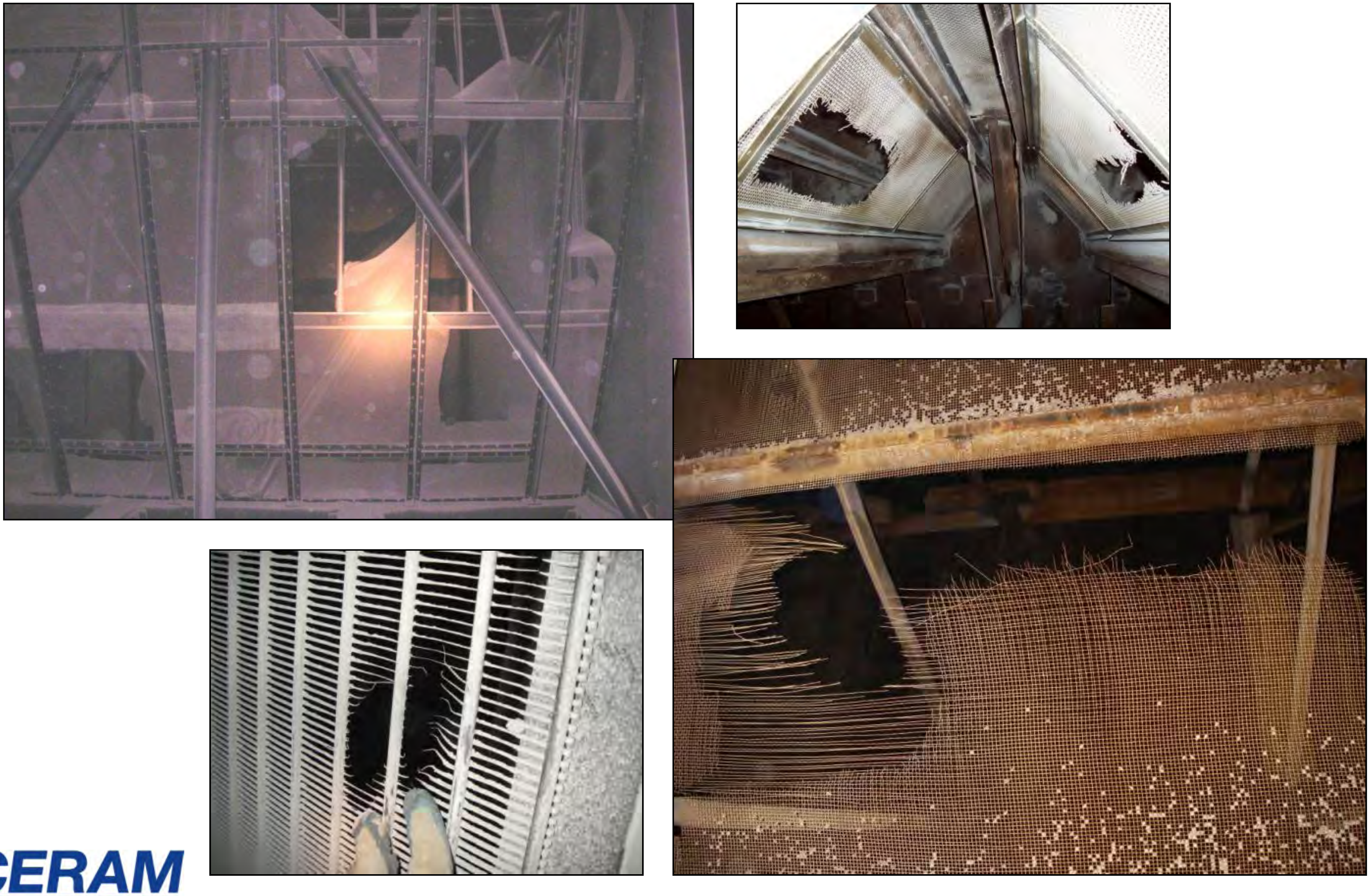
Eliminate LPA Prior to Catalyst

Large Particle Ash (LPA)

Damaged LPA Screen Material

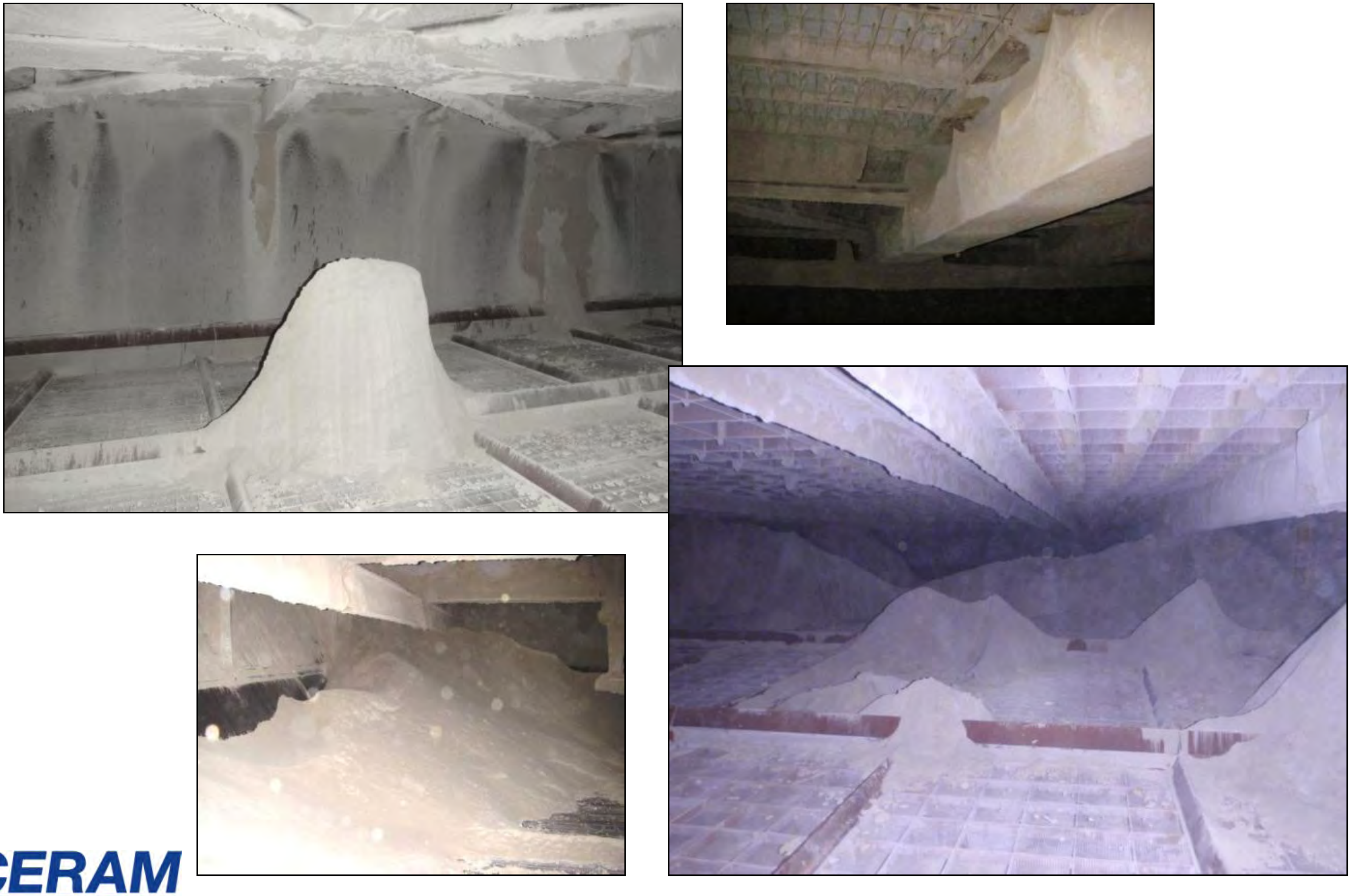
- **L**arge **P**article **A**sh Can Be Present and Should be Controlled as Part of System Design
- LPA Pluggage of Catalyst Leads to…
  - High Pressure Drops
  - Mechanical Damage
  - Reduced Performance Potential
- Effective and Durable Screen Designs are Required
  - Located With Ash Removal
  - Located at Proper Velocity
  - Simple and Advanced Designs Have Both Succeeded and Also Had Problems
- Flow Modeling and Physical Changes are Likely Necessary

LPA Screen – Damage Due to High Velocity (Local and Bulk)



Ductwork – Ash Dropout

Ash Accumulation



Minimize Carbon Carryover

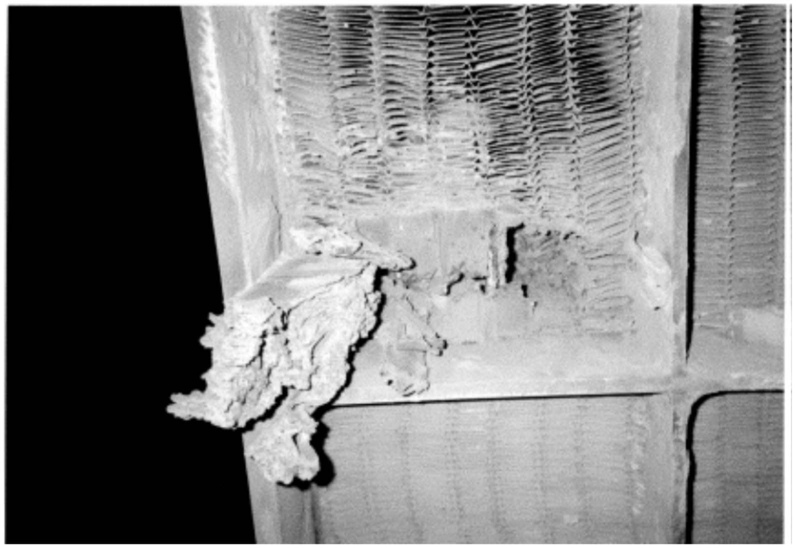
Reactor Accumulation of Unburned Carbon

Plate Catalyst With Accumulated Unburned Carbon

- The Control of Unburned Carbon is Important for Reliable DeNOx Operation
- All DeNOx Catalyst Has Oxidizing Properties and Will Tend to Oxidize Unburned Carbon
- Oxidized Carbon Sticks to Catalyst and Can Result in Pluggage
- Accumulation on Catalyst Increases Risk of Pluggage and Fires
- Increased Potential for Needing Offline, Out of Reactor Cleaning
- Homogeneous Honeycomb Catalyst Consists of Fully Oxidized Material
- Metal Substrates Can Lead to Increased Potential for Fires

Any Catalyst Type Can Be Susceptible to Fire Damage

Fused Plate Catalyst After Fire Found In Downstream Ductwork



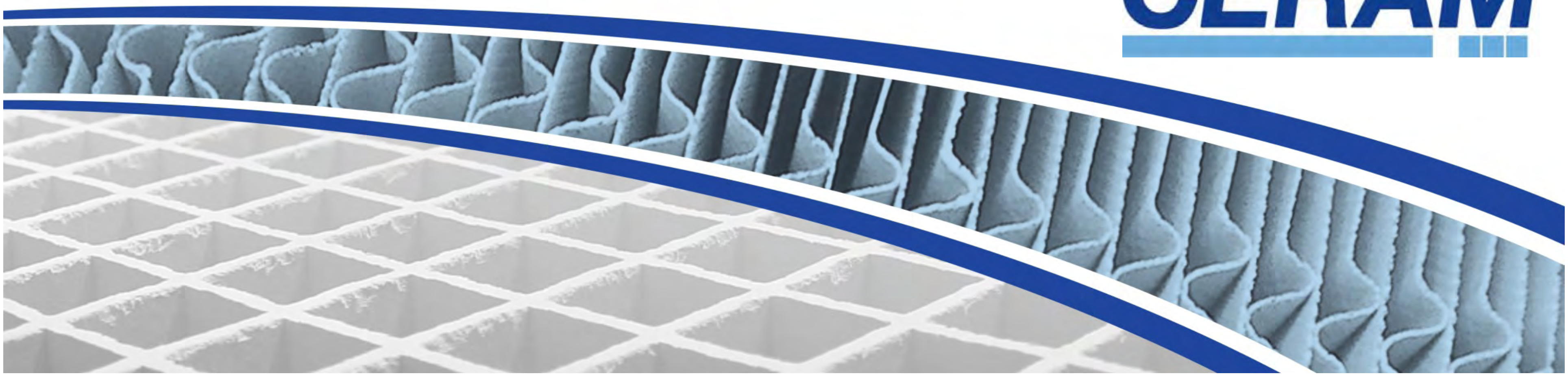
Bottom of Plate Catalyst After Fire Damage

Top of Honeycomb Catalyst After Fire Damage

- Plate Catalyst Supports Combustion (Stainless Steel Substrate)
- Molten Plate Can Start Air Heater Fire
- Honeycomb Catalyst Material is Stable After a Fire (Made of Fully Oxidized Material)

CERAM

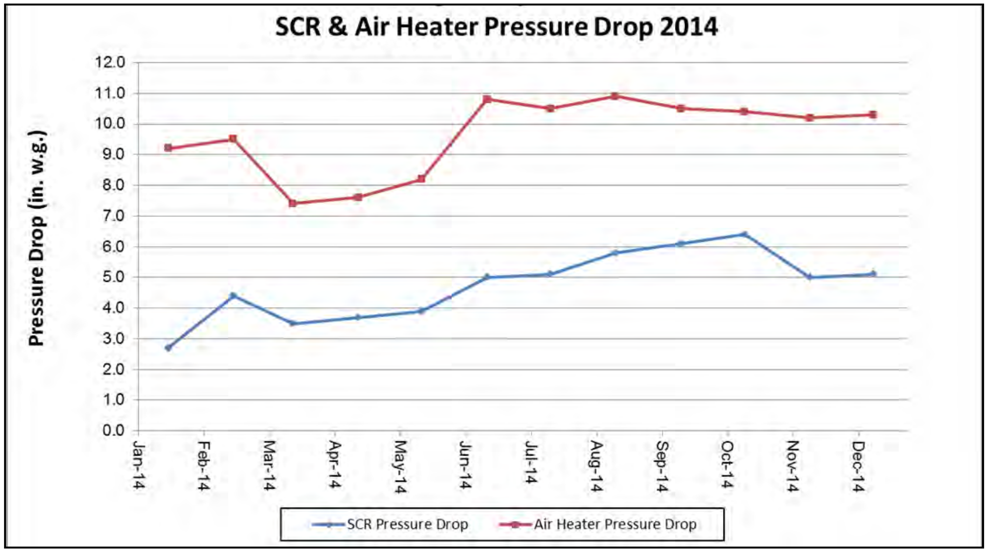
Midwest Utility 500 MW Unit Burning PRB Blend



CERAM

Case Example: Midwest 500 MW Utility

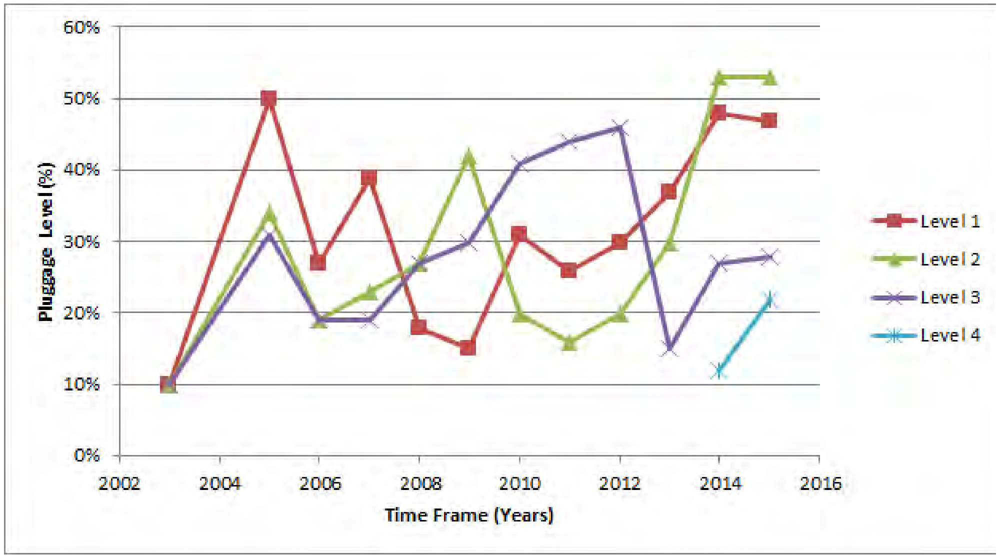
- 500 MW (gross) Cyclone that fires 85% PRB / 15% Bituminous Blend
- SCR began commercial operation in 2003
  - 3+1 Reactor (7.4 mm pitch HC)
  - 30-50% pluggage by 2005 (Fly Ash and Unburned Carbon)
- L1 replaced in 2006 due to pluggage, DP and sintering with 9.2 mm pitch HC. Combination catalyst and additional flow straightener.
- L1, L2 and L3 available aged catalyst rejuvenated in 2006; Best-of-the-best modules re-used
- From 2006 to 2009 after 27,000 hrs heavy pluggage. CFD recommended.
- 2009 new L2; 8.2 mm HC; best-of-best to L3. New L3 in 2012 & L4 in 2013 (both 8.2 mm HC)
- From 2009-15 pluggage increased
- Emission targets lowered (Increase in reactor potential)

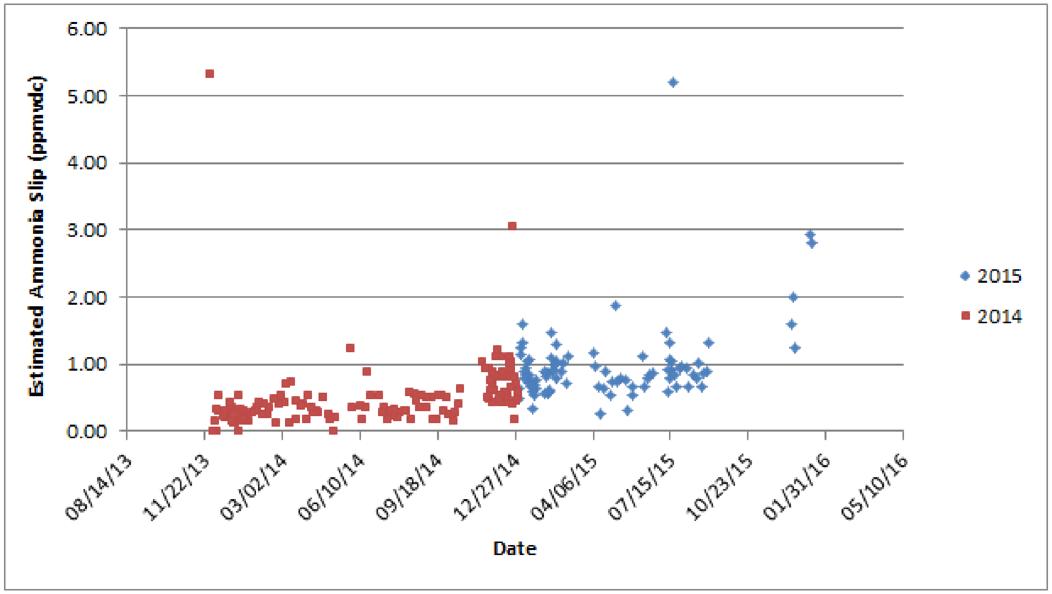


CERAM

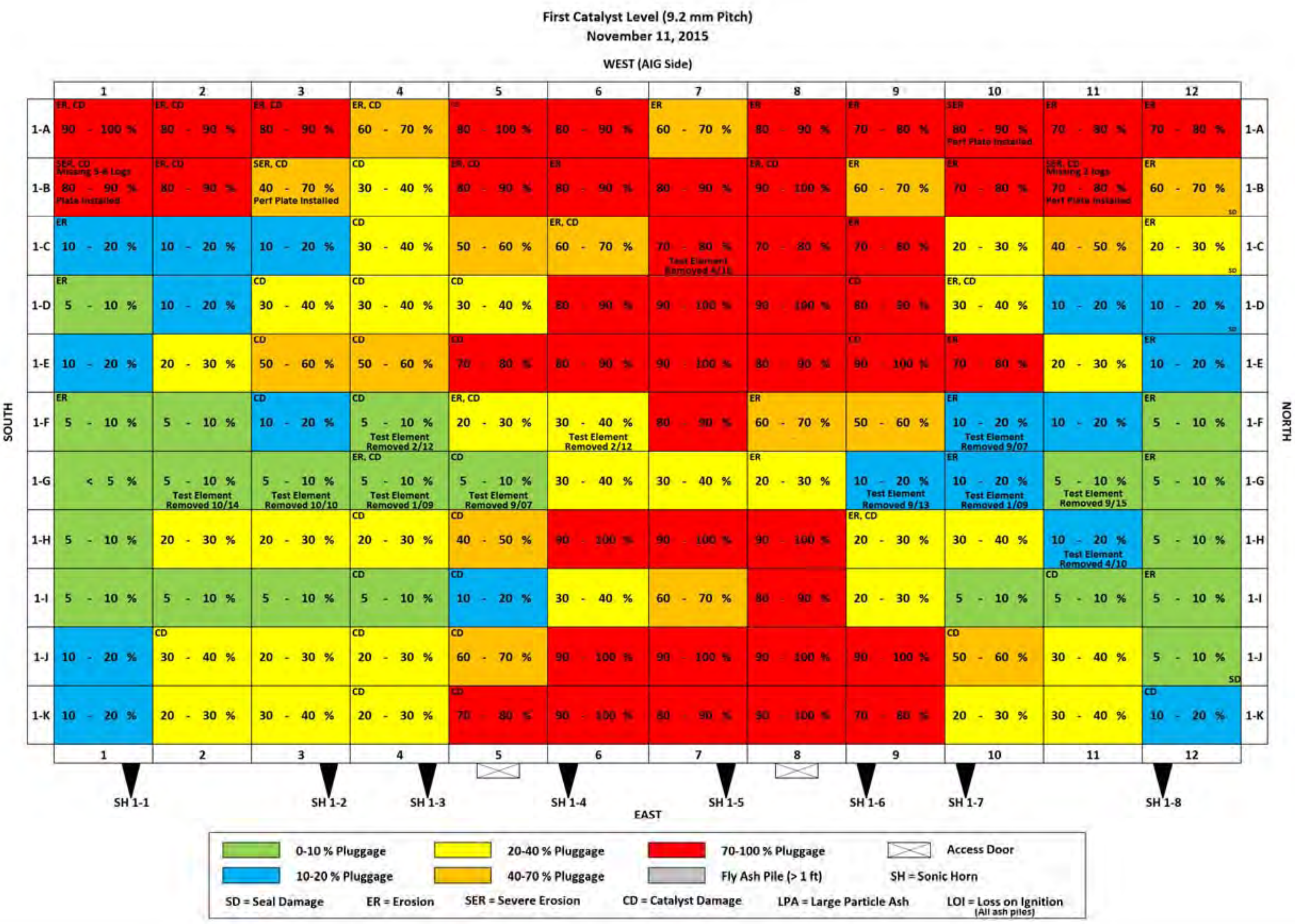
Case Example: Midwest 500 MW Utility

- 2013 revealed large pluggage increase (affects reactor potential)
- Reactor has velocity mal-distribution
  - CFD modeling investigated
  - CFD results cost prohibitive
- Unit meeting emission target at reasonable ammonia slip
- Ammonia in ash measurements taken daily





Reactor Inspection Results



First Catalyst Level (9.2 mm Pitch)
November 11, 2015

WEST (AIG Side)

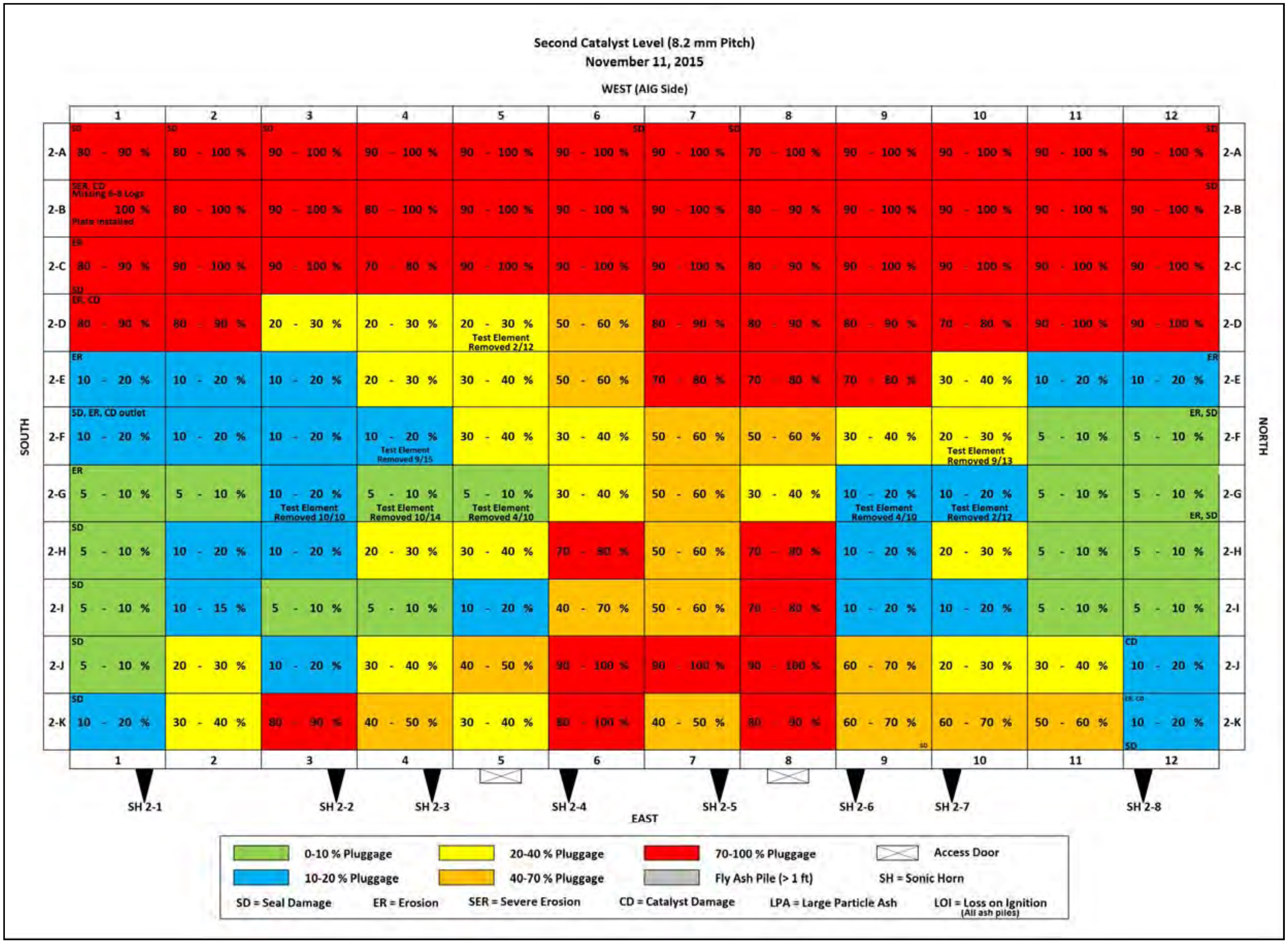
	1	2	3	4	5	6	7	8	9	10	11	12	
1-A	ER, CD 90 - 100 %	ER, CD 80 - 90 %	ER, CD 80 - 90 %	ER, CD 60 - 70 %	80 - 100 %	80 - 90 %	ER 60 - 70 %	ER 80 - 90 %	ER 70 - 80 %	SER 80 - 90 % Perf Plate Installed	ER 70 - 80 %	ER 70 - 80 %	1-A
1-B	SER, CD Missing 5-6 Logs 80 - 90 % Plate Installed	ER, CD 80 - 90 %	SER, CD 40 - 70 % Perf Plate Installed	CD 30 - 40 %	ER, CD 80 - 90 %	ER 80 - 90 %	80 - 90 %	ER, CD 90 - 100 %	ER 60 - 70 %	ER 70 - 80 %	SER, CD Missing 2 logs 70 - 80 % Perf Plate Installed	ER 60 - 70 % SD	1-B
1-C	ER 10 - 20 %	10 - 20 %	10 - 20 %	CD 30 - 40 %	50 - 60 %	ER, CD 60 - 70 %	70 - 80 % Test Element Removed 4/16	70 - 80 %	ER 70 - 80 %	20 - 30 %	40 - 50 %	ER 20 - 30 % SD	1-C
1-D	ER 5 - 10 %	10 - 20 %	CD 30 - 40 %	CD 30 - 40 %	CD 30 - 40 %	80 - 90 %	90 - 100 %	90 - 100 %	CD 80 - 90 %	ER, CD 30 - 40 %	10 - 20 %	10 - 20 % SD	1-D
1-E	10 - 20 %	20 - 30 %	CD 50 - 60 %	CD 50 - 60 %	CD 70 - 80 %	80 - 90 %	90 - 100 %	80 - 90 %	CD 90 - 100 %	ER 70 - 80 %	20 - 30 %	ER 10 - 20 %	1-E
1-F	ER 5 - 10 %	5 - 10 %	CD 10 - 20 %	CD 5 - 10 % Test Element Removed 2/12	ER, CD 20 - 30 %	30 - 40 % Test Element Removed 2/12	80 - 90 %	ER 60 - 70 %	50 - 60 %	ER 10 - 20 % Test Element Removed 9/07	10 - 20 %	ER 5 - 10 %	1-F
1-G	< 5 %	5 - 10 % Test Element Removed 10/14	5 - 10 % Test Element Removed 10/10	ER, CD 5 - 10 % Test Element Removed 1/09	CD 5 - 10 % Test Element Removed 9/07	30 - 40 %	30 - 40 %	ER 20 - 30 %	10 - 20 % Test Element Removed 9/13	ER 10 - 20 % Test Element Removed 1/09	5 - 10 % Test Element Removed 9/15	ER 5 - 10 %	1-G
1-H	5 - 10 %	20 - 30 %	20 - 30 %	CD 20 - 30 %	CD 40 - 50 %	90 - 100 %	90 - 100 %	90 - 100 %	ER, CD 20 - 30 %	30 - 40 %	10 - 20 % Test Element Removed 4/10	5 - 10 %	1-H
1-I	5 - 10 %	5 - 10 %	5 - 10 %	CD 5 - 10 %	CD 10 - 20 %	30 - 40 %	60 - 70 %	80 - 90 %	20 - 30 %	5 - 10 %	CD 5 - 10 %	ER 5 - 10 %	1-I
1-J	10 - 20 %	CD 30 - 40 %	20 - 30 %	CD 20 - 30 %	CD 60 - 70 %	90 - 100 %	90 - 100 %	90 - 100 %	90 - 100 %	CD 50 - 60 %	30 - 40 %	5 - 10 % SD	1-J
1-K	10 - 20 %	20 - 30 %	30 - 40 %	CD 20 - 30 %	CD 70 - 80 %	90 - 100 %	80 - 90 %	90 - 100 %	70 - 80 %	20 - 30 %	30 - 40 %	CD 10 - 20 %	1-K
	1	2	3	4	5	6	7	8	9	10	11	12	

EAST

🟩 0-10 % Pluggage	🟨 20-40 % Pluggage	🟥 70-100 % Pluggage	☒ Access Door
🟦 10-20 % Pluggage	🟧 40-70 % Pluggage	⬜ Fly Ash Pile (> 1 ft)	SH = Sonic Horn

SD = Seal Damage ER = Erosion SER = Severe Erosion CD = Catalyst Damage LPA = Large Particle Ash LOI = Loss on Ignition (All ash piles)

Reactor Inspection Results



Second Catalyst Level (8.2 mm Pitch)
November 11, 2015

WEST (AIG Side)

SOUTH | NORTH

	1	2	3	4	5	6	7	8	9	10	11	12	
2-A	SD 80 - 90 %	SD 80 - 100 %	SD 90 - 100 %	90 - 100 %	90 - 100 %	SD 90 - 100 %	SD 90 - 100 %	70 - 100 %	90 - 100 %	90 - 100 %	90 - 100 %	SD 90 - 100 %	2-A
2-B	SER, CD Missing 6-8 Logs 100 % Plate installed	80 - 100 %	90 - 100 %	80 - 100 %	90 - 100 %	90 - 100 %	90 - 100 %	80 - 90 %	90 - 100 %	90 - 100 %	90 - 100 %	SD 90 - 100 %	2-B
2-C	ER 80 - 90 % SD	90 - 100 %	90 - 100 %	70 - 80 %	90 - 100 %	90 - 100 %	90 - 100 %	80 - 90 %	90 - 100 %	90 - 100 %	90 - 100 %	90 - 100 %	2-C
2-D	ER, CD 80 - 90 %	80 - 90 %	20 - 30 %	20 - 30 %	20 - 30 % Test Element Removed 2/12	50 - 60 %	80 - 90 %	80 - 90 %	80 - 90 %	70 - 80 %	90 - 100 %	90 - 100 %	2-D
2-E	ER 10 - 20 %	10 - 20 %	10 - 20 %	20 - 30 %	30 - 40 %	50 - 60 %	70 - 80 %	70 - 80 %	70 - 80 %	30 - 40 %	10 - 20 %	ER 10 - 20 %	2-E
2-F	SD, ER, CD outlet 10 - 20 %	10 - 20 %	10 - 20 %	10 - 20 % Test Element Removed 9/15	30 - 40 %	30 - 40 %	50 - 60 %	50 - 60 %	30 - 40 %	20 - 30 % Test Element Removed 9/13	5 - 10 %	ER, SD 5 - 10 %	2-F
2-G	ER 5 - 10 %	5 - 10 %	10 - 20 % Test Element Removed 10/10	5 - 10 % Test Element Removed 10/14	5 - 10 % Test Element Removed 4/10	30 - 40 %	50 - 60 %	30 - 40 %	10 - 20 % Test Element Removed 4/10	10 - 20 % Test Element Removed 2/12	5 - 10 %	5 - 10 % ER, SD	2-G
2-H	SD 5 - 10 %	10 - 20 %	10 - 20 %	20 - 30 %	30 - 40 %	70 - 80 %	50 - 60 %	70 - 80 %	10 - 20 %	20 - 30 %	5 - 10 %	5 - 10 %	2-H
2-I	SD 5 - 10 %	10 - 15 %	5 - 10 %	5 - 10 %	10 - 20 %	40 - 70 %	50 - 60 %	70 - 80 %	10 - 20 %	10 - 20 %	5 - 10 %	5 - 10 %	2-I
2-J	SD 5 - 10 %	20 - 30 %	10 - 20 %	30 - 40 %	40 - 50 %	90 - 100 %	90 - 100 %	90 - 100 %	60 - 70 %	20 - 30 %	30 - 40 %	CD 10 - 20 %	2-J
2-K	SD 10 - 20 %	30 - 40 %	80 - 90 %	40 - 50 %	30 - 40 %	80 - 100 %	40 - 50 %	80 - 90 %	60 - 70 % SD	60 - 70 %	50 - 60 %	ER, CD 10 - 20 % SD	2-K
	1	2	3	4	5	6	7	8	9	10	11	12	

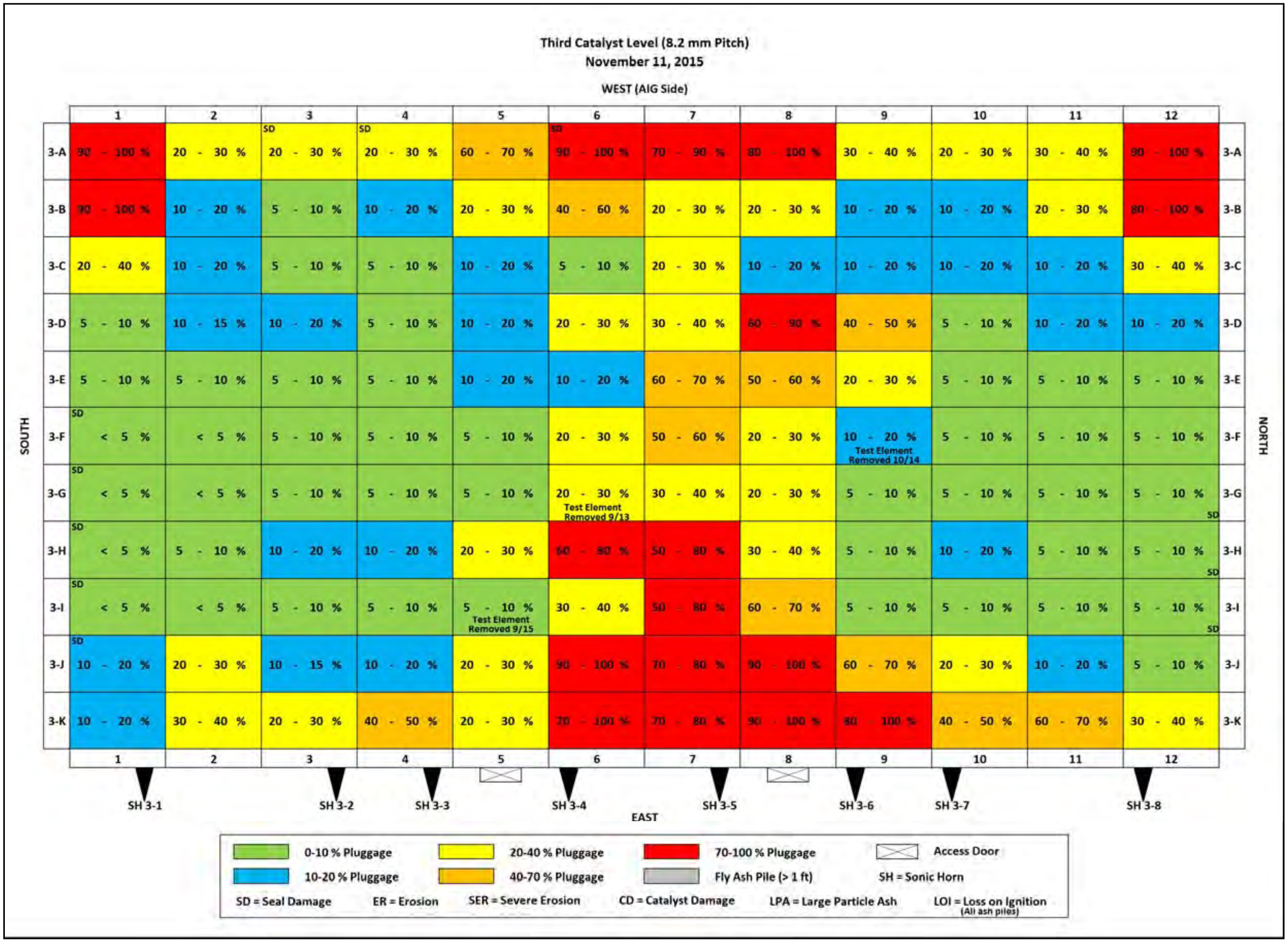
SH 2-1 SH 2-2 SH 2-3 SH 2-4 SH 2-5 SH 2-6 SH 2-7 SH 2-8

EAST

🟩	0-10 % Pluggage	🟨	20-40 % Pluggage	🟥	70-100 % Pluggage	☒	Access Door
🟦	10-20 % Pluggage	🟧	40-70 % Pluggage	⬜	Fly Ash Pile (> 1 ft)		SH = Sonic Horn

SD = Seal Damage
ER = Erosion
SER = Severe Erosion
CD = Catalyst Damage
LPA = Large Particle Ash
LOI = Loss on Ignition (All ash piles)

Reactor Inspection Results



Third Catalyst Level (8.2 mm Pitch)
November 11, 2015

WEST (AIG Side)

	1	2	3	4	5	6	7	8	9	10	11	12	
3-A	90 - 100 %	20 - 30 %	SD 20 - 30 %	SD 20 - 30 %	60 - 70 %	SD 90 - 100 %	70 - 90 %	80 - 100 %	30 - 40 %	20 - 30 %	30 - 40 %	90 - 100 %	3-A
3-B	90 - 100 %	10 - 20 %	5 - 10 %	10 - 20 %	20 - 30 %	40 - 60 %	20 - 30 %	20 - 30 %	10 - 20 %	10 - 20 %	20 - 30 %	80 - 100 %	3-B
3-C	20 - 40 %	10 - 20 %	5 - 10 %	5 - 10 %	10 - 20 %	5 - 10 %	20 - 30 %	10 - 20 %	10 - 20 %	10 - 20 %	10 - 20 %	30 - 40 %	3-C
3-D	5 - 10 %	10 - 15 %	10 - 20 %	5 - 10 %	10 - 20 %	20 - 30 %	30 - 40 %	60 - 90 %	40 - 50 %	5 - 10 %	10 - 20 %	10 - 20 %	3-D
3-E	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	10 - 20 %	10 - 20 %	60 - 70 %	50 - 60 %	20 - 30 %	5 - 10 %	5 - 10 %	5 - 10 %	3-E
3-F	SD < 5 %	< 5 %	5 - 10 %	5 - 10 %	5 - 10 %	20 - 30 %	50 - 60 %	20 - 30 %	10 - 20 % Test Element Removed 10/14	5 - 10 %	5 - 10 %	5 - 10 %	3-F
3-G	SD < 5 %	< 5 %	5 - 10 %	5 - 10 %	5 - 10 %	20 - 30 % Test Element Removed 9/13	30 - 40 %	20 - 30 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 % SD	3-G
3-H	SD < 5 %	5 - 10 %	10 - 20 %	10 - 20 %	20 - 30 %	60 - 80 %	50 - 80 %	30 - 40 %	5 - 10 %	10 - 20 %	5 - 10 %	5 - 10 % SD	3-H
3-I	SD < 5 %	< 5 %	5 - 10 %	5 - 10 %	5 - 10 % Test Element Removed 9/15	30 - 40 %	50 - 80 %	60 - 70 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 % SD	3-I
3-J	SD 10 - 20 %	20 - 30 %	10 - 15 %	10 - 20 %	20 - 30 %	90 - 100 %	70 - 80 %	90 - 100 %	60 - 70 %	20 - 30 %	10 - 20 %	5 - 10 %	3-J
3-K	10 - 20 %	30 - 40 %	20 - 30 %	40 - 50 %	20 - 30 %	70 - 100 %	70 - 80 %	90 - 100 %	80 - 100 %	40 - 50 %	60 - 70 %	30 - 40 %	3-K
	1	2	3	4	5	6	7	8	9	10	11	12	

SOUTH

NORTH

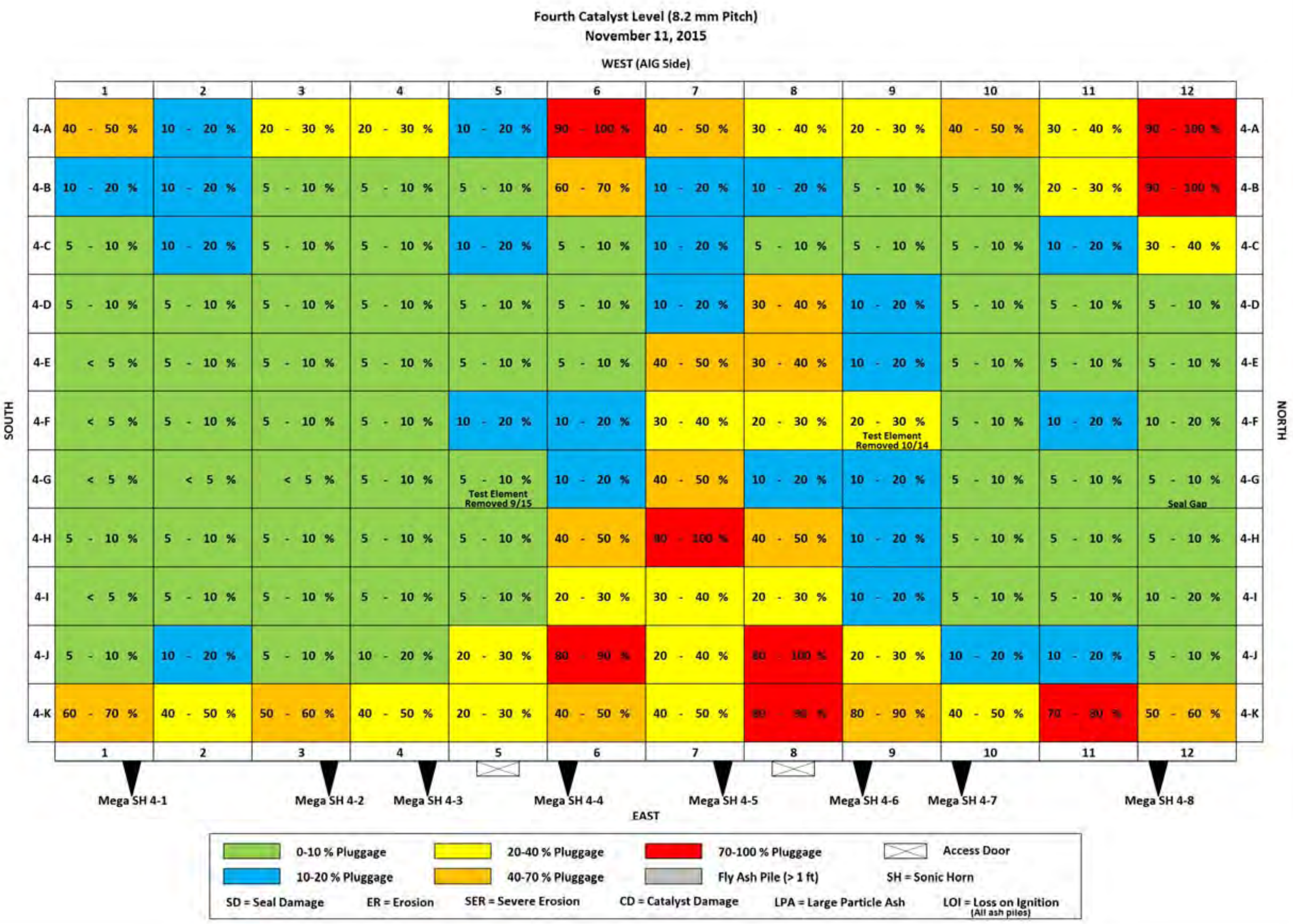
SH 3-1
SH 3-2
SH 3-3
SH 3-4
SH 3-5
SH 3-6
SH 3-7
SH 3-8

EAST

- 🟩 0-10 % Pluggage
- 🟦 10-20 % Pluggage
- 🟨 20-40 % Pluggage
- 🟧 40-70 % Pluggage
- 🟥 70-100 % Pluggage
- ⬜ Fly Ash Pile (> 1 ft)
- ☒ Access Door
- SH = Sonic Horn

SD = Seal Damage
ER = Erosion
SER = Severe Erosion
CD = Catalyst Damage
LPA = Large Particle Ash
LOI = Loss on Ignition (All ash piles)

Reactor Inspection Results



Fourth Catalyst Level (8.2 mm Pitch)
November 11, 2015

WEST (AIG Side)

	1	2	3	4	5	6	7	8	9	10	11	12	
4-A	40 - 50 %	10 - 20 %	20 - 30 %	20 - 30 %	10 - 20 %	90 - 100 %	40 - 50 %	30 - 40 %	20 - 30 %	40 - 50 %	30 - 40 %	90 - 100 %	4-A
4-B	10 - 20 %	10 - 20 %	5 - 10 %	5 - 10 %	5 - 10 %	60 - 70 %	10 - 20 %	10 - 20 %	5 - 10 %	5 - 10 %	20 - 30 %	90 - 100 %	4-B
4-C	5 - 10 %	10 - 20 %	5 - 10 %	5 - 10 %	10 - 20 %	5 - 10 %	10 - 20 %	5 - 10 %	5 - 10 %	5 - 10 %	10 - 20 %	30 - 40 %	4-C
4-D	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	10 - 20 %	30 - 40 %	10 - 20 %	5 - 10 %	5 - 10 %	5 - 10 %	4-D
4-E	< 5 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	40 - 50 %	30 - 40 %	10 - 20 %	5 - 10 %	5 - 10 %	5 - 10 %	4-E
4-F	< 5 %	5 - 10 %	5 - 10 %	5 - 10 %	10 - 20 %	10 - 20 %	30 - 40 %	20 - 30 %	20 - 30 % Test Element Removed 10/14	5 - 10 %	10 - 20 %	10 - 20 %	4-F
4-G	< 5 %	< 5 %	< 5 %	5 - 10 %	5 - 10 % Test Element Removed 9/15	10 - 20 %	40 - 50 %	10 - 20 %	10 - 20 %	5 - 10 %	5 - 10 %	5 - 10 % Seal Gap	4-G
4-H	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	40 - 50 %	80 - 100 %	40 - 50 %	10 - 20 %	5 - 10 %	5 - 10 %	5 - 10 %	4-H
4-I	< 5 %	5 - 10 %	5 - 10 %	5 - 10 %	5 - 10 %	20 - 30 %	30 - 40 %	20 - 30 %	10 - 20 %	5 - 10 %	5 - 10 %	10 - 20 %	4-I
4-J	5 - 10 %	10 - 20 %	5 - 10 %	10 - 20 %	20 - 30 %	80 - 90 %	20 - 40 %	80 - 100 %	20 - 30 %	10 - 20 %	10 - 20 %	5 - 10 %	4-J
4-K	60 - 70 %	40 - 50 %	50 - 60 %	40 - 50 %	20 - 30 %	40 - 50 %	40 - 50 %	80 - 90 %	80 - 90 %	40 - 50 %	70 - 80 %	50 - 60 %	4-K
	1	2	3	4	5	6	7	8	9	10	11	12	

SOUTH

NORTH

EAST

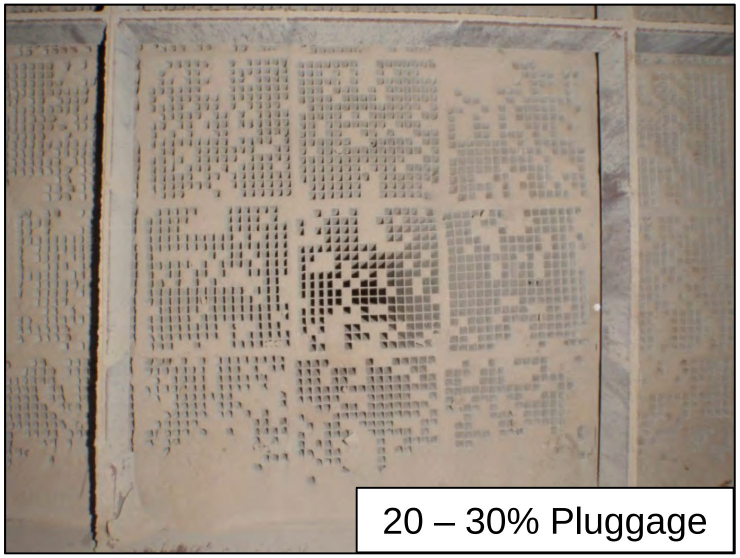
🟩	0-10 % Pluggage	🟨	20-40 % Pluggage	🟥	70-100 % Pluggage	☒	Access Door
🟦	10-20 % Pluggage	🟧	40-70 % Pluggage	⬜	Fly Ash Pile (> 1 ft)		SH = Sonic Horn

SD = Seal Damage
ER = Erosion
SER = Severe Erosion
CD = Catalyst Damage
LPA = Large Particle Ash
LOI = Loss on Ignition (All ash piles)

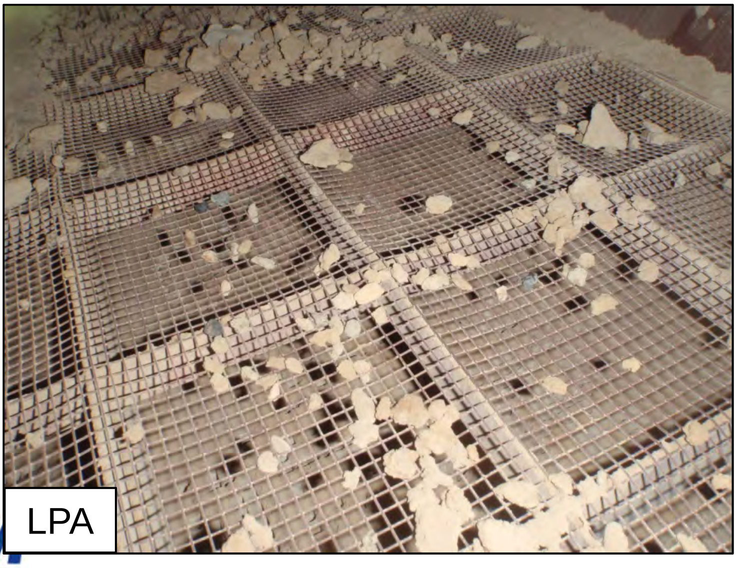
Reactor Inspection Results

AIG (West) Side

Level 1



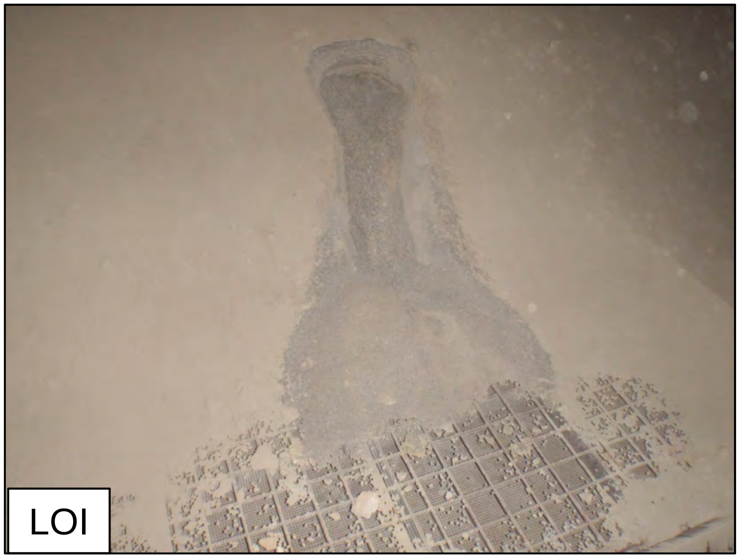
20 – 30% Pluggage



LPA

LOI

Reactor Inspection Results


LOI

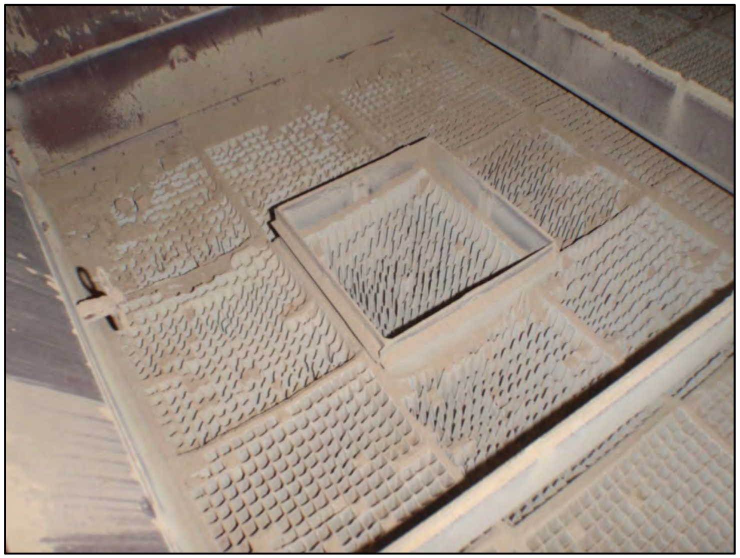
Level 2


Center Section


LPA


Ash AIG Side

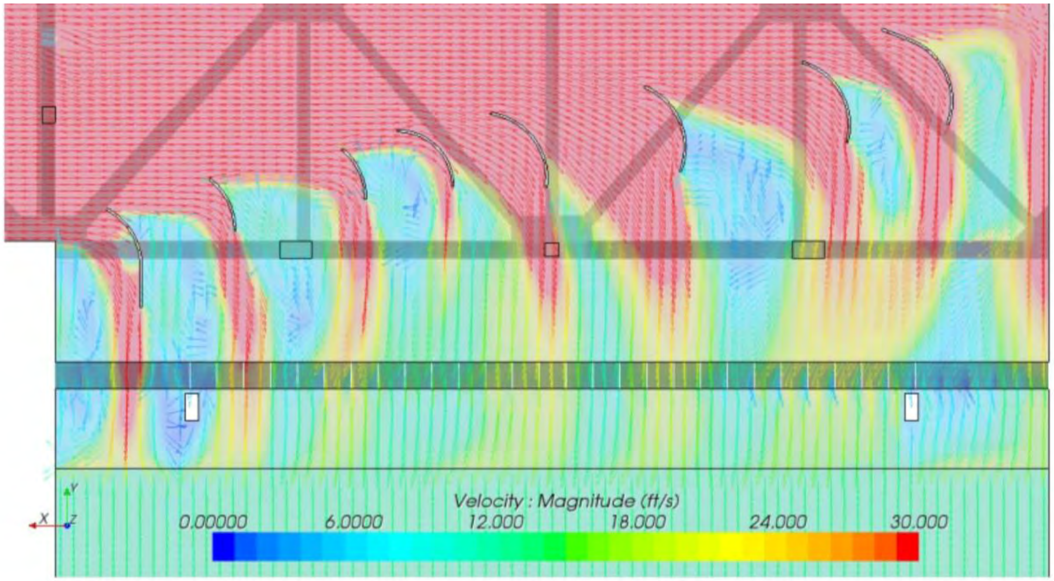
Reactor Inspection Results

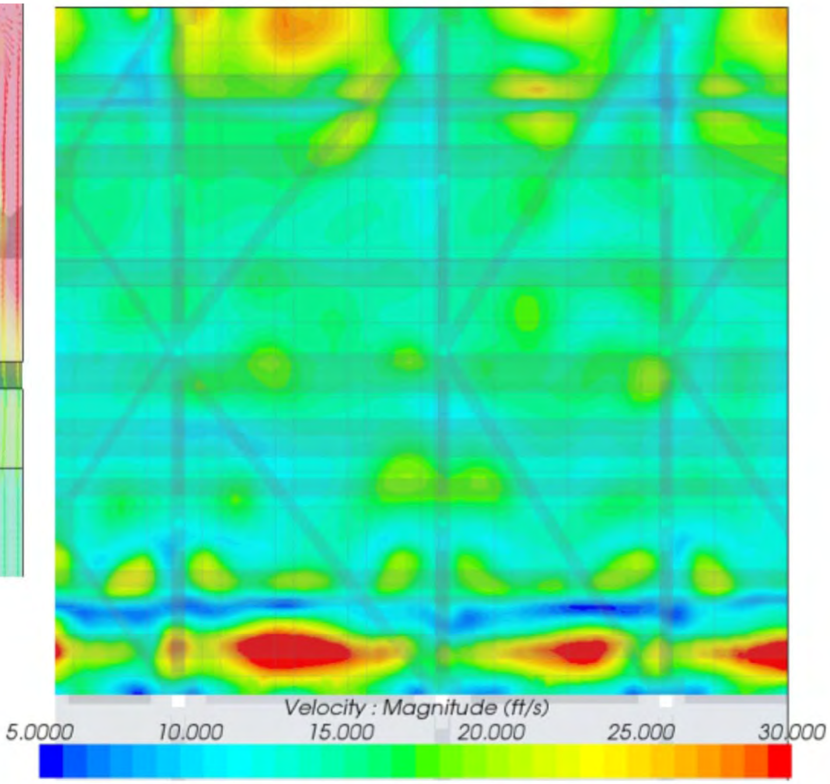


Outlet Ash Buildup

CFD Modeling Study by Fuel Tech 2010

- Reduce flow behind 3rd turning vane
- Increase in low flow behind 1st vane
- 51% of points within 15% of mean (25% RMS)





Operating Reactor Potential; 500 MW Unit

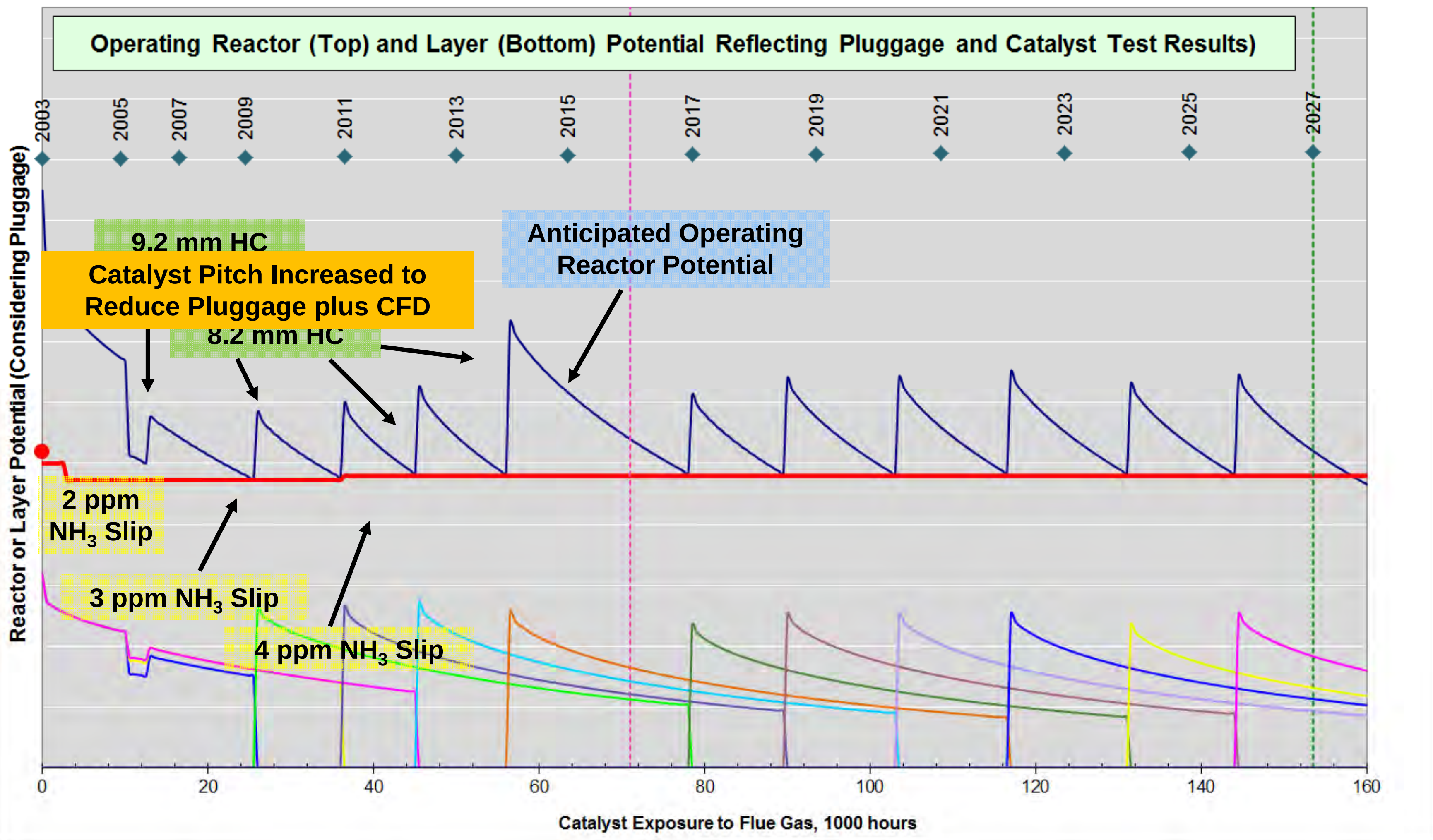


Figure 1 - Catalyst Management Plan (Reactor Potential)

Operating Reactor (Top) and Layer (Bottom) Potential Reflecting Pluggage and Catalyst Test Results)

9.2 mm HC

Catalyst Pitch Increased to Reduce Pluggage plus CFD

8.2 mm HC

Anticipated Operating Reactor Potential

2 ppm NH_3 Slip

3 ppm NH_3 Slip

4 ppm NH_3 Slip

Anticipated Operating Reactor Potential and Original Plan; 500 MW Unit

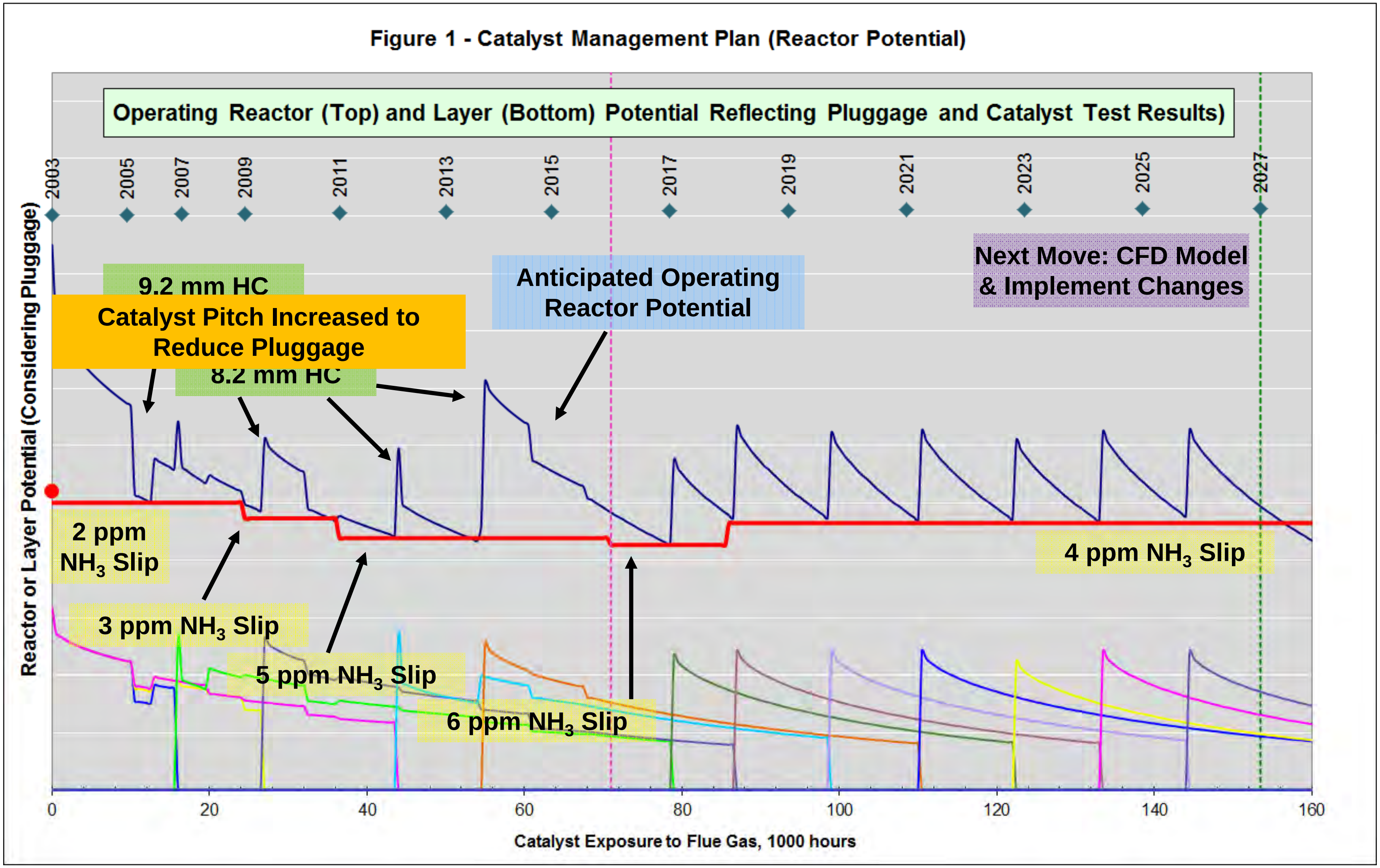


Figure 1 - Catalyst Management Plan (Reactor Potential)

Operating Reactor (Top) and Layer (Bottom) Potential Reflecting Pluggage and Catalyst Test Results)

9.2 mm HC

Catalyst Pitch Increased to Reduce Pluggage

8.2 mm HC

Anticipated Operating Reactor Potential

Next Move: CFD Model & Implement Changes

2 ppm NH$_3$ Slip

3 ppm NH$_3$ Slip

5 ppm NH$_3$ Slip

6 ppm NH$_3$ Slip

4 ppm NH$_3$ Slip

Operating Reactor Potential; 500 MW Unit

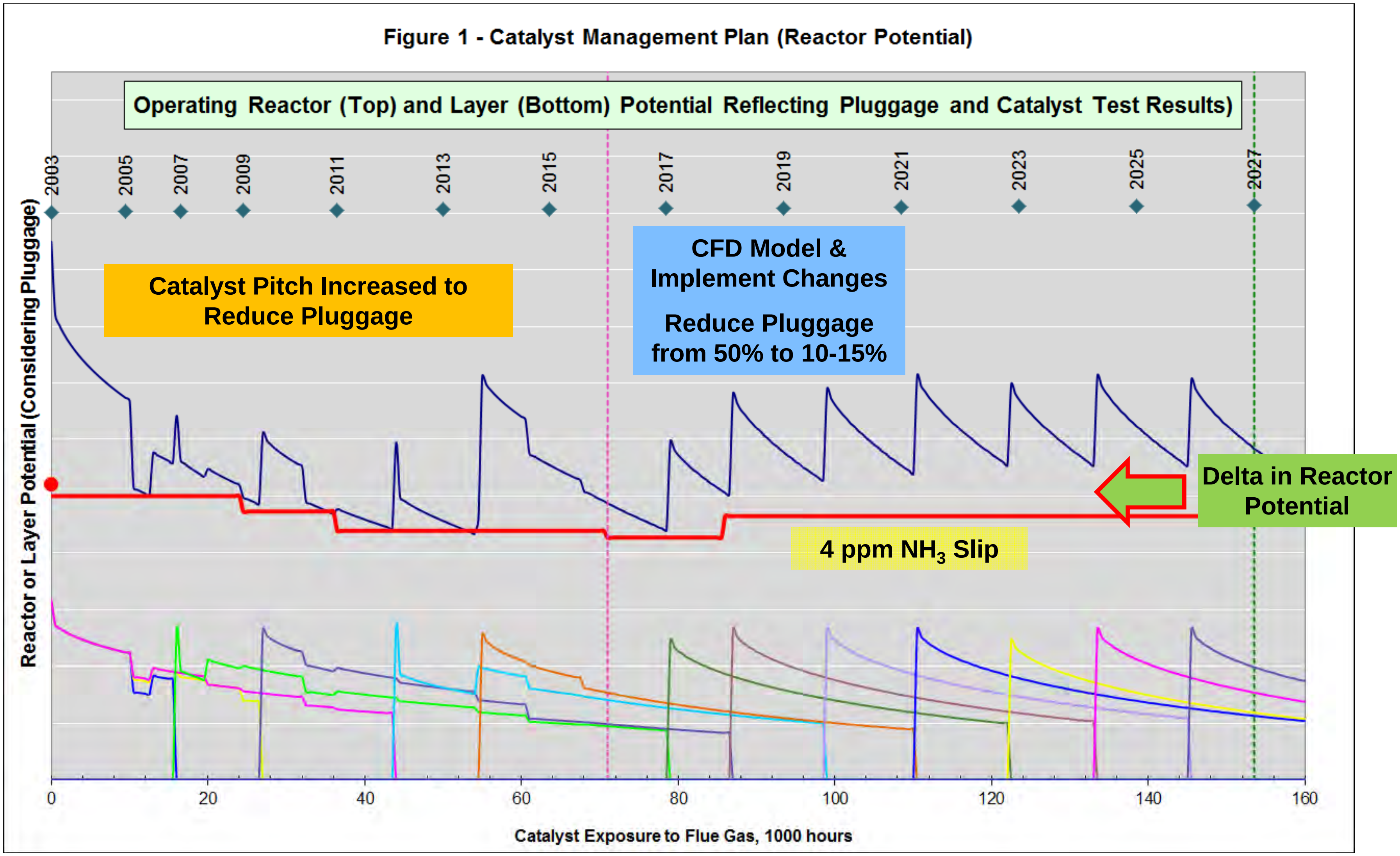


Figure 1 - Catalyst Management Plan (Reactor Potential)

Operating Reactor (Top) and Layer (Bottom) Potential Reflecting Pluggage and Catalyst Test Results)

Catalyst Pitch Increased to Reduce Pluggage

CFD Model & Implement Changes

Reduce Pluggage from 50% to 10-15%

Delta in Reactor Potential

4 ppm NH_3 Slip

Anticipated Operating Reactor Potential and Original Plan (2016-2026); 500 MW Unit

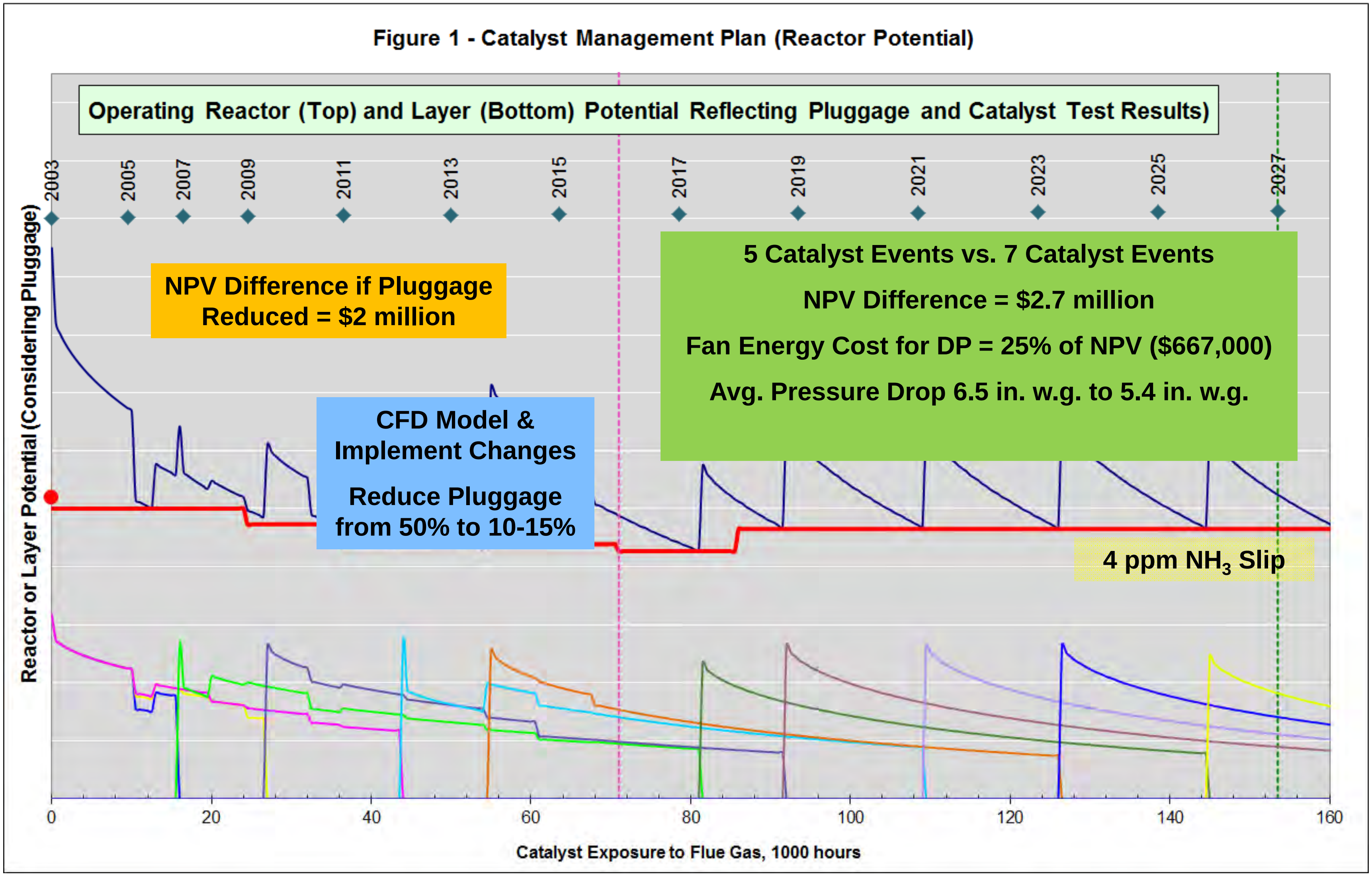


Figure 1 - Catalyst Management Plan (Reactor Potential)

Operating Reactor (Top) and Layer (Bottom) Potential Reflecting Pluggage and Catalyst Test Results)

NPV Difference if Pluggage Reduced = $2 million

CFD Model & Implement Changes

Reduce Pluggage from 50% to 10-15%

5 Catalyst Events vs. 7 Catalyst Events

NPV Difference = $2.7 million

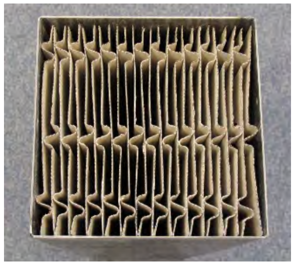
Fan Energy Cost for DP = 25% of NPV ($667,000)

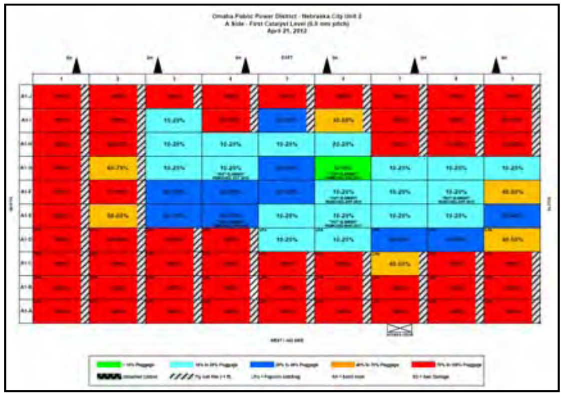
Avg. Pressure Drop 6.5 in. w.g. to 5.4 in. w.g.

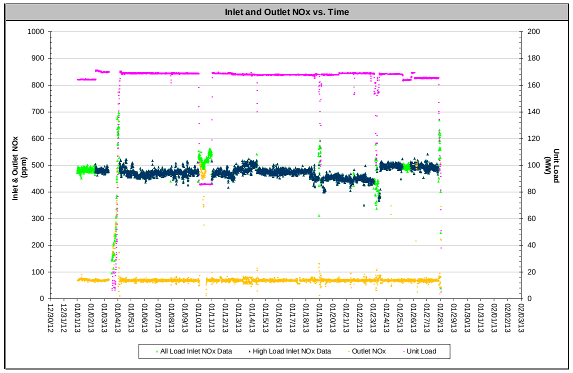
4 ppm NH_3 Slip

CERAM

Assuring Reactor Potential is a Key Aspect of Effective Catalyst Management Planning







- Catalyst Testing:
  - Accuracy and Consistency
  - Benchmarking
  - Consider Activity Measurement Bias
    - Low – Premature Catalyst Additions
    - High – Increased Operating Risks/Costs
  - Plate Geometric Uniformity
- 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